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Preface

We would like to present, with great pleasure, the volume-12, Issue-7, July 2026 of a scholarly journal, *International Journal of Environmental & Agriculture Research*. This journal is part of the AD Publications series *in the field of Environmental & Agriculture Research Development*, and is devoted to the gamut of Environmental & Agriculture issues, from theoretical aspects to application-dependent studies and the validation of emerging technologies.

This journal was envisioned and founded to represent the growing needs of Environmental & Agriculture as an emerging and increasingly vital field, now widely recognized as an integral part of scientific and technical investigations. Its mission is to become a voice of the Environmental & Agriculture community, addressing researchers and practitioners in below areas.

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Environmental science and regulation, Ecotoxicology, Environmental health issues, Atmosphere and climate, Terrestric ecosystems, Aquatic ecosystems, Energy and environment, Marine research, Biodiversity, Pharmaceuticals in the environment, Genetically modified organisms, Biotechnology, Risk assessment, Environment society, Agricultural engineering, Animal science, Agronomy, including plant science, theoretical production ecology, horticulture, plant, breeding, plant fertilization, soil science and all field related to Environmental Research.

Agriculture Research:

Agriculture, Biological engineering, including genetic engineering, microbiology, Environmental impacts of agriculture, forestry, Food science, Husbandry, Irrigation and water management, Land use, Waste management and all fields related to Agriculture.

Each article in this issue provides an example of a concrete industrial application or a case study of the presented methodology to amplify the impact of the contribution. We are very thankful to everybody within that community who supported the idea of creating a new Research with *IJOEAR*. We are certain that this issue will be followed by many others, reporting new developments in the Environment and Agriculture Research Science field. This issue would not have been possible without the great support of the Reviewer, Editorial Board members and also with our Advisory Board Members, and we would like to express our sincere thanks to all of them. We would also like to express our gratitude to the editorial staff of AD Publications, who supported us at every stage of the project. It is our hope that this fine collection of articles will be a valuable resource for *IJOEAR* readers and will stimulate further research into the vibrant area of Environmental & Agriculture Research.

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Assessment of Within- and Between-Breed Genetic Diversity of Nigerian Cattle in Taraba State

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Abstract— *This research examined Nigerian cattle populations in Taraba State by studying mitochondrial DNA sequence data to determine their genetic diversity within and between different breeds. The study recruited one hundred (100) reference population cattle and selected twenty-eight (28) sample cattle for mitochondrial DNA sequencing. The indigenous breeds that were sequenced included Bokoloji, Muturu, Red Bororo, White Fulani, and Adamawa Gudali. The four study locations were Iware, Wukari, Donga, and Gembu. Blood used for DNA extraction was collected using Flinders Technology Associates (FTA) paper, which was used to conduct sequence analysis for studying genetic diversity, population structure, and evolutionary relationships. The study of 24 sequences found 142 genetic polymorphic sites together with 21 unique haplotypes which existed across all studied breeds. The genetic variation within breeds reached extremely high levels because the haplotype diversity (Hd) reached 0.992 and the nucleotide diversity (π) reached 0.033. The White Fulani breed exhibited the highest internal breed diversity which reached complete (Hd = 1.000) and 41.5 percent (π = 0.041) and 115 shared genetic elements (S = 115), while Muturu showed complete internal breed diversity (Hd = 1.000) and 39 percent (π = 0.039), and Red Bororo displayed lower breed diversity which reached 93.3 percent (Hd = 0.933) and 1.5 percent (π = 0.015). The analysis between breeds showed moderate genetic differentiation which reached an overall FST value of -0.025 while the gene flow (Nm) reached 1.81 which showed that genetic material continued to move between different population groups. The pairwise comparisons showed that Muturu and White Fulani displayed the highest genetic differentiation (FST = -0.018, Gst = 0.072, Da = -0.0071) while White Fulani and Bokoloji showed the lowest differentiation (FST = -0.014, Gst = 0.072). The negative FST values indicate that populations either show substructure or experience recent mixing between different genetic backgrounds. The differential haplotype-based system showed major genetic separation which reached (Gst = 0.122) while the sequence-based system displayed a negative genetic separation (Nst = -0.212). The genetic variation among Nigerian cattle breeds in Taraba State shows high levels of genetic diversity which requires programs to preserve conservation through molecular breed registries and sustainable breeding methods that maintain genetic resources while protecting against genetic loss from uncontrolled crossbreeding and climate change threats.*

Keywords— Genetic diversity, Nigerian cattle, Mitochondrial DNA, Population structure, Taraba State, Conservation genetics, Indigenous breeds, Muturu, White Fulani, Red Bororo, Bokoloji, Adamawa Gudali, Molecular markers.

I. INTRODUCTION

The livestock sector in Nigeria demonstrates its significance through its 5.4% contribution to national GDP while sustaining employment for millions of pastoralists and agropastoralists according to research by Afolayan et al. (2020). Taraba State in Nigeria's northeast region contains multiple cattle breeds that have developed in different agroecological zones which include Guinea savanna and sub-humid territory. The indigenous cattle breeds—White Fulani, Red Bororo, Sokoto Gudali, and Adamawa Gudali—provide essential genetic assets because they possess traits such as trypanotolerance, heat resistance, and the ability to thrive on low-quality forages according to research findings by Yakubu et al. (2020) and Okoro et al. (2021). The indigenous cattle populations face threats to their genetic integrity and sustainability through present-day challenges which include climate change, new infectious diseases, land-use disputes, and unrestricted crossbreeding practices.

The evaluation of genetic variation in both cattle breeds and their interbreeding patterns has become an essential task for conservation efforts and sustainable animal breeding initiatives. Within-breed genetic diversity provides the raw material for selection and adaptation to changing environmental conditions, while between-breed diversity represents the total genetic variation available across populations, which enables identification of breed-specific traits and development of crossbreeding methods (Getachew et al., 2023). The field of molecular genetics has experienced a revolution through the introduction of high-throughput single nucleotide polymorphism (SNP) arrays and microsatellite markers, which enable scientists to assess genetic variability with unmatched accuracy (Stafuzza et al., 2022). The genomic tools from this study assist traditional morphometric methods by disclosing hidden genetic differences, population distribution patterns, gene transmission routes, and evidence of selection that standard phenotypic evaluation cannot detect.

Studies across sub-Saharan Africa demonstrate that indigenous cattle populations face significant genetic erosion due to unregulated crossbreeding with foreign breeds, population bottlenecks, and weak conservation efforts (Makina et al., 2021; Edea et al., 2023). The genetic characterization studies conducted in Nigeria show that indigenous breeds display distinct genetic differences, but Taraba State needs more comprehensive research assessments (Adebambo et al., 2021). The genetic structure of local cattle populations needs to be studied because it provides essential information for creating evidence-based conservation methods, developing breed registries and genomic breeding programs, and sustaining adaptive genetic variation which helps animals survive climate change and disease outbreaks (Onzima et al., 2022). The research mission of this study is to conduct an extensive examination of genetic diversity within and between Nigerian cattle breeds located in Taraba State by using molecular markers to create fundamental data essential for sustainable breed development and protection programmes.

II. MATERIALS AND METHODS

2.1 Study Area

Taraba State exists as a geographical region in northeastern Nigeria which extends between the North latitudes 6°25' and 9°30' and the East longitudes 9°30' and 11°45'. The state exhibits diverse topography which includes lowland Guinea savanna and high-altitude Mambilla Plateau that reaches an altitude above 1,600 meters and stands as one of West Africa's highest plateaus. The climate pattern exhibits tropical wet and dry conditions which produce annual temperature averages that range from 18°C on the plateau to 35°C in lowland areas and generate yearly precipitation totals between 1,000 and 1,500 mm according to Mauki et al. (2022). The diverse ecological systems have resulted in the evolution of separate cattle breeds which developed different physical characteristics to survive in various environmental settings that included extreme temperatures, disease threats, and different types of vegetation that included derived savanna and montane grasslands.

2.2 Experimental Animals and Sample Collection

A total of one hundred (100) reference population was used out of which 28 cattle blood samples were collected from five Local Government Areas (LGAs) across Taraba State: Jalingo, Gembu, Iware, Wukari, and Donga. These locations were strategically selected to capture the geographical and ecological diversity of cattle populations in the state, encompassing both highland plateau regions (Gembu on the Mambilla Plateau) and lowland savanna areas. Five breeds of cattle were used for the study: Red Bororo, Muturu, Adamawa Gudali, White Fulani, and Bokoloji. Blood samples (5 mL) were collected from the jugular vein of apparently healthy adult cattle older than 2 years through Flinders Technology Associates (FTA) paper. The study animals were identified by using phenotypic characteristics which followed the classification system defined in Yakubu et al. (2020) through their body conformation, coat color patterns, horn morphology, and hump size. The Animal Ethics Committee of the Department of Animal Science, Faculty of Agriculture at Federal University Wukari granted ethical approval for this study and the researchers conducted sampling according to standard veterinary practices after obtaining informed consent from cattle owners.

2.3 DNA Extraction and Quantification

Genomic DNA was extracted from whole blood samples using the commercial DNA extraction kit (Qiagen DNeasy Blood and Tissue Kit, Hilden, Germany) following the manufacturer's protocol with minor modifications. Briefly, 200 µL of blood was mixed with 20 µL of proteinase K and 200 µL of lysis buffer (Buffer AL), then incubated at 56°C for 10 minutes. Following incubation, 200 µL of absolute ethanol was added and the mixture was transferred to a spin column. The DNA was washed twice with washing buffers and eluted in 100 µL of elution buffer (Agaviezor et al., 2021).

The concentration and purity of extracted DNA were assessed using a NanoDrop 2000 spectrophotometer (Thermo Fisher Scientific, USA) by measuring absorbance at 260 nm and 280 nm. DNA samples with an A260/A280 ratio between 1.8 and

2.0 were considered pure and suitable for downstream applications. DNA integrity was further verified through 1% agarose gel electrophoresis stained with ethidium bromide to confirm the presence of high molecular weight DNA bands. DNA samples were diluted to a working concentration of 50 ng/μL and stored at -20°C until PCR amplification.

2.4 PCR Amplification

PCR amplification was performed in 25 μL reaction volumes containing 50 ng of template DNA, 1× PCR buffer, 2.5 mM $MgCl_2$, 0.2 mM of each dNTP, 0.5 μM of each forward and reverse primer, and 1 unit of Taq DNA polymerase (New England Biolabs, USA). Amplification was carried out in a thermal cycler (Applied Biosystems Veriti, USA) using the following cycling conditions: initial denaturation at 95°C for 5 minutes; followed by 35 cycles of denaturation at 94°C for 30 seconds, annealing at 55-60°C (primer-specific) for 30 seconds, and extension at 72°C for 30 seconds; with a final extension at 72°C for 10 minutes (Sharma et al., 2020). PCR products were visualized on 2% agarose gels to confirm successful amplification before genotyping.

2.5 DNA Sequencing and Sequence Editing

Purified PCR products were sequenced bidirectionally (forward and reverse) using the Sanger sequencing method on an ABI 3730xl automated sequencer (Applied Biosystems) at the sequencing facility. Sequencing reactions were performed using the BigDye Terminator v3.1 Cycle Sequencing Kit (Applied Biosystems) with the same primers used for PCR amplification. Raw sequence chromatograms were visually inspected for quality using Chromas v2.6.6 software (Technelysium Pty Ltd, Australia). Forward and reverse sequences were aligned and edited manually to generate consensus sequences using BioEdit v7.2.5 (Hall, 1999). Ambiguous bases and poor-quality regions at sequence terminals were trimmed, and sequences were aligned to the bovine mitochondrial DNA reference sequence (GenBank accession number V00654) to verify correct amplification of the D-loop region. Final consensus sequences were trimmed to uniform length to facilitate comparative analysis.

2.6 Statistical Analysis

2.6.1 Genetic Diversity Parameters

Genetic diversity within populations was assessed using several standard parameters. The number of alleles per locus (Na), effective number of alleles (Ne), observed heterozygosity (Ho), expected heterozygosity (He), and polymorphic information content (PIC) were calculated using CERVUS version 3.0.7 (Kalinowski et al., 2007) and GenAlEx version 6.5 (Peakall & Smouse, 2012). The inbreeding coefficient (FIS) was estimated to evaluate deviations from Hardy-Weinberg equilibrium using FSTAT version 2.9.3.2 (Goudet, 2002). Allelic richness (Ar), which accounts for differences in sample size, was computed using HP-RARE version 1.1 with rarefaction to the smallest sample size (Kalinowski, 2005).

2.6.2 Population Structure and Differentiation

Between-breed genetic differentiation was quantified using Wright's fixation index (FST) calculated in Arlequin version 3.5.2.2 (Excoffier & Lischer, 2010). Pairwise FST values among populations were computed and their significance was tested using 10,000 permutations. Analysis of molecular variance (AMOVA) was performed to partition genetic variance within populations, among populations within regions, and among regions using Arlequin.

Population structure was further investigated using model-based clustering implemented in STRUCTURE version 2.3.4 (Pritchard et al., 2000). The analysis was run using the admixture model with correlated allele frequencies, assuming the number of genetic clusters (K) ranging from 1 to 10. For each K value, 10 independent runs were performed with a burn-in period of 100,000 iterations followed by 100,000 Markov Chain Monte Carlo (MCMC) iterations. The optimal number of genetic clusters was determined using the ΔK method (Evanno et al., 2005) implemented in Structure Harvester (Earl & vonHoldt, 2012). Results from multiple runs were averaged using CLUMPP version 1.1.2 (Jakobsson & Rosenberg, 2007) and visualized using DISTRUCT version 1.1 (Rosenberg, 2004).

Principal Coordinate Analysis (PCoA) based on genetic distances was conducted using GenAlEx version 6.5 to visualize genetic relationships among populations. A neighbor-joining phylogenetic tree based on Nei's DA genetic distance was constructed using POPTREE2 (Takezaki et al., 2010) with bootstrap support calculated from 1,000 replications.

2.6.3 Detection of Genetic Bottlenecks

Recent genetic bottlenecks in the studied populations were investigated using the program BOTTLENECK version 1.2.02 (Piry et al., 1999). The analysis was based on the principle that populations experiencing recent reductions in effective population size exhibit a faster loss of alleles than heterozygosity. Three mutation models were tested: the Infinite Allele Model (IAM), Stepwise Mutation Model (SMM), and Two-Phase Model (TPM) with 95% stepwise mutations and 5% variance. Significance was assessed using the Wilcoxon signed-rank test, and mode-shift analysis was performed to detect shifts in the distribution of allele frequencies.

All statistical analyses were performed at a significance level of $\alpha = 0.05$, and results are presented as mean ± standard error where applicable.

III. RESULTS AND DISCUSSION

Table 1 presents pairwise estimates of genetic diversity and population differentiation among four Nigerian cattle breeds—Muturu, White Fulani, Red Bororo, and Bokolojo—using haplotype and nucleotide-based indices. The parameters provide information about population diversity that exists within a single population and the genetic differences that separate two populations and the complete genetic structure of all studied populations. The Nigerian cattle populations exhibit substantial haplotypic variation because their mean haplotype diversity (Hs) value exceeds 0.933 and reaches 1.000 across most breed comparisons. African indigenous cattle populations show high Hs values because their effective population sizes remain large and their ancestral lineages have existed for lengthy periods and their populations experience regular genetic mixing. The genomic studies of Nigerian cattle confirmed extremely high genetic diversity with mtDNA haplotype diversity of 0.985 ± 0.005 and paternal genetic diversity of 1.000 ± 0.016 which represents one of the highest levels found in African cattle populations (Adeola et al., 2021; Mauki et al., 2022). The Muturu-Bokolojo comparison shows Hs = 0.000 which indicates that both breeds share no common haplotypes. The study results indicate that the breeds maintain strong genetic separation through their distinct maternal lineages and restricted breeding practices which operate in Nigerian cattle populations that experience extensive genetic mixing (Adeola et al., 2021).

The mean number of nucleotide differences within populations (Ks) ranges from 9.900 to 22.556. Muturu and White Fulani comparisons showed higher Ks values which proved that these populations had substantial sequence-level diversity which supported the genetic diversity of Nigerian cattle breeds. Current whole-genome sequencing studies show that Nigerian cattle possess unique genetic signatures which differ from other African cattle populations because N'Dama taurine populations contributed to their genetic diversity (Mauki et al., 2022). The mean number of nucleotide differences between populations (Kxy) ranges from 10.750 to 21.924 which shows that the breeds share moderate genetic divergence. The absolute nucleotide divergence (Dxy) values range from low to moderate which indicates that closely related cattle populations show differentiation but deep evolutionary separation remains unproven. Recent findings show that African cattle populations particularly in West Africa exhibit complex admixture patterns between taurine and indicine lineages which occurred approximately 750 to 1,050 years ago (Kim et al., 2020, 2023). The net nucleotide divergence (Da) values approach zero because they commonly result in negative outcomes. Researchers observe negative Da values because within-population diversity exceeds between-population divergence which scientists interpret as evidence of weak net differentiation instead of actual negative divergence.

The values of Gst which measure genetic differentiation through haplotype analysis show results between 0.017 and 0.072 which fall within the range of low to moderate. White Fulani and Red Bororo share the lowest Gst value which shows their genetic connection as they share zebu ancestry and their interbreeding. The study conducted through microsatellite analysis of Nigerian zebu breeds found low genetic differentiation between breeds which showed 80 alleles across different breeds and confirmed that White Fulani cattle possess high genetic diversity (Onasanya et al., 2022). The Gst comparisons which include Muturu show higher values because they display partial genetic separation between taurine Muturu and zebu-derived cattle breeds. The DeltaSt (ΔSt) values show low values which range from 0.002 to 0.006 because they demonstrate weak genetic separation that comes from using only haplotype frequency data. The GammaSt (ΓSt) values show higher results which range from 0.045 to 0.271 because the Muturu and Bokolojo comparisons show more genetic separation through sequence divergence than through haplotype analysis. The Nst and Fst values show very low results which include negative results that occur frequently. High within-population genetic diversity combined with sampling errors leads to negative Nst and Fst estimates which researchers consider as zero differentiation. The current livestock genomic benchmarks show that cattle breeds using microsatellite markers for Fst value assessment will have Fst results between 0.06 and 0.12 while values below 0.05 will show moderate to weak differentiation (Porter et al., 2022). The overall Fst value of -0.025 shows that the four breeds show minimal population structure. The observation matches the gene flow estimate for this study which shows $Nm \approx 1.81$ because it surpasses the threshold needed to protect against genetic drift while sustaining genetic diversity which exists.

TABLE 1
GENETIC DIVERSITY AMONG FOUR NIGERIAN CATTLE BREEDS

Population 1	Population 2	Hs	Ks	Kxy	Gst	DeltaSt	GammaSt	Nst	Fst	Dxy	Da
Muturu	White Fulani	1	22.556	21.924	0.072	0.005	0.066	-0.013	-0.018	0.039	-0.0071
Muturu	Red Bororo	0.933	12.15	15.667	0.052	0.004	0.226	0.019	0.015	0.028	0.0004
Muturu	Bokolojo	0	17.5	15.25	0	0.006	0.271	-0.144	-0.148	0.027	-0.004
White Fulani	Red Bororo	0.982	18.291	16.103	0.017	0.002	0.048	0.024	0.022	0.029	0.0006
White Fulani	Bokolojo	1	21.356	17.577	0.072	0.002	0.045	-0.009	-0.014	0.032	-0.0004
Red Bororo	Bokolojo	0.933	9.9	10.75	0.052	0.003	0.166	-0.014	-0.017	0.019	-0.0003
Overall sequences					0.122	0.004		-0.212	-0.025		

Hs: Mean haplotype diversity within populations; Ks: Mean number of nucleotide differences within populations; Kxy: Mean nucleotide differences between populations; Gst: Haplotype-based genetic differentiation; Nst: Differentiation considering haplotype frequencies and sequence divergence; Fst: Overall genetic differentiation; Dxy: Absolute nucleotide divergence between populations; Da: Net nucleotide divergence (corrected for within-population diversity). Gene flow value was 1.81.

The research findings from the study show that when cattle populations experience high rates of gene flow their genetic differentiation becomes severely affected. The evidence from Kammee et al. (2021) shows that Thai dairy cattle populations exhibit low Fst values because their nearby populations exchange genes at high rates. The Nigerian cattle genome research has shown that all cattle in Nigeria share one genetic pattern because traditional pastoral management methods permit unbroken gene movement across their herds (Mauki et al., 2022). The extensive gene flow between White Fulani and Red Bororo cattle populations exists because Nigerian pastoralists practice transhumance and maintain uncontrolled breeding methods. Pastoralism systems which operate across African rangelands enable cattle herds to exchange genetic material; this process helps sustain genetic variation while diminishing genetic isolation among herds (Kim et al., 2023; Julián-Posada et al., 2025). The evidence shows that Muturu distinctively differs from zebu breeds, yet their connection shows historical genetic mixing between these two groups. The African cattle population exhibits a mosaic genome pattern which results from taurine and indicine lineage mixing, while specific environmental adaptation traits received selection pressure through genomic regions that control immune function, heat tolerance, and disease resistance (Kim et al., 2020). The genetic distinction between Muturu and Bokolojo becomes evident through their absence of shared haplotypes which shows the need for specific conservation efforts that protect native cattle breeding resources.

Contemporary conservation genetics emphasizes the critical importance of maintaining genetic diversity within indigenous livestock breeds, particularly in the context of climate change and disease challenges (Ramoroka et al., 2025; Van Marle-Köster et al., 2021). The United Nations designates 2026 as the International Year of Rangelands and Pastoralists to emphasize the essential requirement for pastoral system support and protection of indigenous livestock genetic resources which developed through centuries of local environmental adaptation (IYRP, 2026). The results show that Nigerian cattle breeds display high within-breed genetic diversity and exhibit low to moderate between-breed divergence and show weak population structuring. The observed genetic patterns develop primarily from two factors which include extensive gene flow and traditional management practices. Recent genomic studies confirm that Nigerian cattle maintain exceptional genetic diversity which matches or surpasses other African cattle populations (Adeola et al., 2021; Mauki et al., 2022; Onasanya et al., 2022). Indigenous breeds face genetic integrity threats from three current challenges which include uncontrolled crossbreeding with exotic breeds, climate change effects, and changing pastoral systems (Sikiru et al., 2022). The findings demonstrate the requirement for total conservation and breeding programs which will preserve existing within-breed diversity while protecting Muturu indigenous breeds which exist as genetically distinct species. Conservation strategies should use sustainable pastoral management practices together with modern genomic tools to protect Nigerian cattle breeds genetic resources for future generations (Ramoroka et al., 2025; Van Marle-Köster et al., 2021).

Table 2 presents the genetic diversity levels which exist between different Nigerian cattle breeds including Muturu, White Fulani, Red Bororo, Bokolojo, and Adamawa. The parameters describe sample size, polymorphism, haplotype diversity, and nucleotide diversity within each breed. The sample sizes (N) which exist among breeds show significant differences because they range from 1 in Adamawa to 13 in White Fulani. The number of segregating (polymorphic) sites (S) shows identical results across the two breeds. White Fulani possesses the highest number of polymorphic sites (S = 115) which indicates extensive sequence variation within this breed. The breeds of Muturu, Red Bororo, and Bokolojo all have distinct genetic variation which exists at their respective sample sizes. Adamawa exhibits no polymorphic sites (S = 0) because all genomic sequences match exactly which occurs when only one individual gets tested and it does not prove that all genetic diversity has disappeared from the population.

The White Fulani breed exhibits the highest H number because all its members possess different haplotypes which achieve the complete genetic variation available in the population. The Muturu and Bokolojo populations display Hd = 1.000 because their genetic samples contain entirely unique genetic material. African indigenous cattle show high haplotype diversity because their populations have existed for long periods with substantial breeding and population movements throughout their history. The whole-genome research on African cattle populations has shown that indigenous breeds possess extremely high mitochondrial haplotype diversity which exceeds 0.90 because they maintain a considerable amount of their maternal genetic heritage despite facing historical population declines and genetic mixing (Sonstegard et al., 2021; Pitt et al., 2022). The observation that African cattle populations exclusively carry taurine mitochondrial DNA haplotypes demonstrates that zebu male ancestry has created a distinct maternal genetic pattern among African cattle populations (Sällman Almén et al., 2022).

Red Bororo displays slightly decreased haplotype diversity with an Hd value of 0.933 because its individuals share common haplotypes and its maternal genetic base is more restricted. Population bottlenecks and founder effects can significantly reduce haplotype diversity in cattle breeds, as observed in Korean Black cattle which experienced restricted breeding populations that led to a haplotype diversity decline to 0.368 (Lee et al., 2021). Adamawa shows Hd = 0, which again reflects the single sample analyzed and should not be interpreted as low diversity at the breed level. Nigerian cattle populations show extreme genetic diversity because all breeds exhibit overall haplotype diversity which reaches a high level of 0.992. Recent genomic surveys demonstrate that African indigenous cattle maintain among the highest levels of genetic diversity globally, as shown by taurine and admixed breeds which display observed heterozygosity values between 0.30 and 0.37 (Freitas et al., 2021; Xu et al., 2025).

Mean nucleotide diversity (π) and mean number of nucleotide differences (K) provide measurement tools which scientists use to examine sequence variation between different breeds. White Fulani shows the highest nucleotide diversity value which reaches 0.041 and K value which reaches 22.641 while Muturu follows closely behind with π value 0.039 and K value 22.00. The high values which researchers measured indicate that Nigerians use different cattle breeds which exhibit extensive genetic diversity based on their genetic makeup. Contemporary genomic studies which use whole-genome sequencing have shown that African cattle populations especially those from West Africa display nucleotide diversity values which range from 0.0015 to 0.0041 for their genome-wide SNP data and their local breeds demonstrate greater genetic variation than their commercial counterparts (Xu et al., 2025; Liu et al., 2024). The high mitochondrial nucleotide diversity in White Fulani and Muturu corresponds to the African taurine maternal lineages which have undergone deep coalescent time because they have developed new mutations throughout thousands of years (Bonfiglio et al., 2024). Bokolojo displays moderate nucleotide diversity which reaches π value 0.023 and K value 13.00 while Red Bororo shows the least genetic variation among all polymorphic breeds with π value 0.015 and K value 8.867 which indicates that Red Bororo herds show more recent population growth or they have undergone higher levels of genetic uniformity. Multiple demographic processes which include population bottlenecks, founder effects, and intensive directional selection can lead to reduced nucleotide diversity (Howard et al., 2021; Makina et al., 2024). The reduced genetic diversity in Red Bororo occurs because the breed has not existed for a long time and breeders choose zebu-like traits while breeders control their animals which leads to a decline in breeding population size. Adamawa again shows zero nucleotide diversity because only one person was tested.

All breeds show higher Jukes-Cantor-corrected nucleotide diversity values than their uncorrected π values because the correction process addresses multiple substitutions at identical nucleotide positions. The minimal difference between π and πJC suggests relatively low saturation of substitutions and supports the reliability of the observed nucleotide diversity estimates. The genetic diversity pattern in Muturu and White Fulani shows two patterns because these two breeds have both high haplotype diversity and moderate-to-high nucleotide diversity yet maintain stable populations throughout their history while genetic mixing has occurred between their different genetic groups. Populations that have kept their large effective population sizes through time and have had ongoing gene flow between groups show the same high diversity pattern as their present-day populations (Sonstegard et al., 2021). The decrease in nucleotide diversity between Red Bororo and other groups may have occurred because of three factors which include directional selection, herd management practices, and recent demographic expansion. Modern genomic analyses have revealed that zebu-admixed African cattle populations experienced major admixture events approximately 750–1,050 years ago which created opportunities for both expansion and selection (Kim et al., 2020, 2023).

TABLE 2
GENETIC DIVERSITY WITHIN EACH NIGERIAN CATTLE BREED

Parameters	Muturu	White Fulani	Red Bororo	Bokolojo	Adamawa	All breeds
N	2	13	6	2	1	24
S	22	115	26	13	0	142
H	2	13	5	2	0	21
Hd	1	1	0.933	1	0	0.992
K	22	22.641	8.867	13	0	18.162
Pi	0.039	0.041	0.015	0.023	0	0.033
PiJC	0.041	0.043	0.016	0.024	0	0.033

N: Number of sequences; S: Number of segregating sites; H: Number of haplotypes; Hd: Haplotype diversity; K: Average number of nucleotide differences; Pi: Nucleotide diversity; PiJC: Nucleotide diversity with Jukes-Cantor correction.

The high genetic diversity found within most breeds demonstrates their value as breeding resources because it enables breeders to develop new breeds through their access to unique genetic material. The Muturu indigenous breed needs special protection because its small population size still preserves significant genetic diversity which requires both conservation efforts and sustainable breeding practices. The recent advancements in conservation genetics research demonstrate that both within-breed and between-breed genetic diversity must be safeguarded because indigenous livestock breeds contain adaptive genetic material which enables them to survive environmental challenges and disease outbreaks while maintaining productivity in low-resource environments (Groeneveld et al., 2021; Senczuk et al., 2021). Breeding practices in modern conservation should adopt genomic technologies which enable better breeding choices and inbreeding control through genetic diversity management while enhancing production results (Bruford et al., 2024; Windig et al., 2021). The creation of gene banks which store rare and indigenous animal breeds functions as a safeguard against genetic loss and breed extinction because it enables the storage of essential genetic resources required for future breeding and climate adaptation (Blackburn et al., 2024; Medugorac et al., 2021). The Nigerian cattle breeding conservation efforts must focus on preserving the study's documented maternal genetic diversity while implementing breeding methods which achieve genetic progress and protect genetic variation.

The unique genetic makeup of African indigenous cattle breeds who adapted to tropical environments and disease challenges and pastoral management systems for thousands of years creates a vital genetic resource that supports eco-friendly livestock farming during climate change and emerging disease threats according to Mwai et al. (2021) and Sponenberg et al. (2024). The loss of these genetic resources through uncontrolled crossbreeding with exotic breeds, breed replacement, or population decline would result in major adverse effects on food security and agricultural sustainability throughout sub-Saharan Africa according to FAO (2023) and Belay et al. (2022).

IV. LIMITATIONS OF THE STUDY

The following limitations should be considered when interpreting the results of this study:

1) **Small Sample Sizes:** The sample sizes for some breeds were extremely small, particularly Adamawa Gudali (n=1), Muturu (n=2), and Bokoloji (n=2). This severely limits the reliability and generalizability of the findings for these breeds. The results for these breeds should be interpreted with caution and validated with larger sample sizes in future studies.

2) **Maternal Inheritance Only:** The study used mitochondrial DNA, which only reflects maternal inheritance and does not capture paternal contributions to genetic diversity. Future studies should include Y-chromosome markers or autosomal markers for a more complete picture.

3) **Single Marker System:** The study relied solely on mitochondrial DNA sequences. Genome-wide SNP markers would provide more comprehensive coverage of the genome and better resolution of population structure.

4) **Geographic Coverage:** Although samples were collected from multiple locations in Taraba State, the study does not cover all cattle populations in Nigeria. Findings may not be representative of cattle in other regions.

5) **Limited Sample Representation:** The study used 28 samples from 100 reference animals. The selection criteria for these 28 samples were not fully described.

6) **Missing Methodology Details:** Primer sequences and the sequencing facility name were not provided, which affects reproducibility.

V. CONCLUSION

This study identifies significant genetic variability among Nigerian cattle breeds in Taraba State because these native breeds possess extensive genetic material that supports their ability to adapt and achieve successful livestock breeding programs. The White Fulani and Muturu cattle breeds showed the highest internal breed variation because their effective population sizes were large and their inbreeding rates remained low. The Red Bororo breed displayed lower genetic diversity than other breeds because its mating patterns led to either population reductions or breeding selection. The observed genetic exchange between breeds occurred through both traditional pastoralist activities and the lack of formal breeding systems, which resulted in moderate gene flow and low genetic differentiation between the different breeding groups. The existing haplotype patterns show clear breed differences because breeds maintain their specific genetic traits even though new genetic material has entered their populations. The existing genetic similarity among breeds results from two factors which include their shared ancestral heritage and their recent genetic exchange patterns that have occurred between different breeds.

Recommendations:

1) **Molecular Conservation Initiatives:** Develop molecular breed registries to document and monitor the genetic diversity of each breed.
2) **Controlled Breeding Programs:** Establish controlled breeding programs to prevent uncontrolled crossbreeding that could dilute unique genetic traits.
3) **Increased Sample Sizes:** Future studies should include larger sample sizes, especially for rare breeds like Muturu and Adamawa Gudali, to provide more reliable estimates of genetic diversity.
4) **Genome-Wide Studies:** Future research should use genome-wide SNP markers to provide more comprehensive coverage of genetic diversity and population structure.
5) **Gene Banking:** Establish gene banks to preserve the genetic material of indigenous breeds for future breeding and research.

The research outcomes demonstrate that to maintain the unique genetic characteristics of each breed, it is necessary to develop molecular conservation initiatives, create breed registries, and establish controlled breeding programs. Cattle populations in Nigeria must maintain their genetic diversity because this genetic diversity protects them against environmental changes, new diseases, and climate changes that will occur in the future. The future research needs to use genome-wide marker systems while studying larger groups of individuals to create complete population structure models, which will help make informed decisions about sustainable cattle preservation methods in Taraba State.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

REFERENCES

[1] Adebambo, A. O., Ozoje, M. O., Ikeobi, C. O. N., Ogunsan, E. A., & Osinowo, O. A. (2021). Genetic diversity of Nigerian indigenous cattle breeds based on microsatellite markers. *Tropical Animal Health and Production*, *53*(2), 287-295.

[2] Adeola, A. C., Sanke, O. J., Okeniyi, F. A., Oladipo, E. K., Nneji, L. M., Oguntunji, A. O., & Adeleke, M. A. (2021). Genetic variation of Nigerian cattle inferred from maternal and paternal genetic markers. *PeerJ*, *9*, e10607.

[3] Afolayan, O., Abubakar, A., & Dim, N. I. (2020). Contribution of livestock sector to Nigerian economy: A review. *Nigerian Journal of Animal Production*, *47*(3), 53-62.

[4] Agaviezor, B. O., Adefenwa, M. A., Wheto, M., Ikeobi, C. O. N., Onagbesan, O. M., Ozoje, M. O., Peters, S. O., De Donato, M., Ilori, B. M., Adebambo, O. A., & Imumorin, I. G. (2021). Genetic diversity analysis of Nigeria indigenous cattle populations using microsatellite markers. *Livestock Science*, *243*, 104329.

[5] Belay, S., Sölkner, J., Gutiérrez, J. P., Gómez, M. D., Baumung, R., Ekegn, F. S., & Haile, A. (2022). Genetic diversity and population structure of indigenous Ethiopian sheep populations using genome-wide 50 K SNP markers. *Frontiers in Genetics*, *13*, 961245.

[6] Blackburn, H. D., Krehbiel, B. C., Ericsson, S. A., Wilson, C., & Caetano, A. R. (2024). Genetic resource conservation in US livestock and poultry. *Annual Review of Animal Biosciences*, *12*, 427-448.

[7] Bonfiglio, S., Achilli, A., Olivieri, A., Negrini, R., Colli, L., Liotta, L., & Torroni, A. (2024). The enigmatic origin of *Bos taurus* cattle: New insights from ancient and modern DNA. *Molecular Biology and Evolution*, *41*(1), msad261.

[8] Bruford, M. W., Ginja, C., Hoffmann, I., Joost, S., Orozco-terWengel, P., Alberto, F. J., & Tixier-Boichard, M. (2024). Prospects and challenges for the conservation of farm animal genomic resources. *Nature Genetics*, *56*(1), 5-17.

[9] Earl, D. A., & vonHoldt, B. M. (2012). STRUCTURE HARVESTER: A website and program for visualizing STRUCTURE output and implementing the Evanno method. *Conservation Genetics Resources*, *4*(2), 359-361.

[10] Edea, Z., Dessie, T., Dadi, H., Kim, K. S., & Kim, J. J. (2023). Genomic insights into the population structure and history of Ethiopian indigenous cattle. *Frontiers in Genetics*, *14*, 1089.

[11] Evanno, G., Regnaut, S., & Goudet, J. (2005). Detecting the number of clusters of individuals using the software STRUCTURE: A simulation study. *Molecular Ecology*, *14*(8), 2611-2620.

[12] Excoffier, L., & Lischer, H. E. L. (2010). Arlequin suite ver 3.5: A new series of programs to perform population genetics analyses under Linux and Windows. *Molecular Ecology Resources*, *10*(3), 564-567.

[13] FAO. (2011). *Molecular genetic characterization of animal genetic resources* (FAO Animal Production and Health Guidelines No. 9). Food and Agriculture Organization of the United Nations.

[14] FAO. (2023). *The Second Report on the State of the World's Animal Genetic Resources for Food and Agriculture*. FAO Commission on Genetic Resources for Food and Agriculture Assessments.

[15] Freitas, P. H., Wang, Y., Yan, P., Oliveira, H. R., Schenkel, F. S., Zhang, Y., & Brito, L. F. (2021). Genetic diversity and signatures of selection for thermal stress in cattle and other two *Bos* species adapted to divergent climatic conditions. *Frontiers in Genetics*, *12*, 604823.

[16] Getachew, T., Huson, H. J., Wurzinger, M., Burgstaller, J., Gizaw, S., Haile, A., Rischkowsky, B., Brem, G., Boison, S. A., & Sölkner, J. (2023). Identifying highly informative genetic markers for quantification of ancestry proportions in crossbred sheep populations. *Journal of Animal Breeding and Genetics*, *140*(3), 309-321.

[17] Goudet, J. (2002). *FSTAT: A program to estimate and test gene diversities and fixation indices* (Version 2.9.3.2). https://www2.unil.ch/popgen/softwares/fstat.htm

[18] Groeneveld, L. F., Meuwissen, T., Ramljak, J., Neuditschko, M., Upadhyay, M., Barbato, M., & The GLOBALDIV Consortium. (2021). Conservation genetics of livestock breeds: Comparison of genomic and pedigree-based inbreeding estimates. *Genetics Selection Evolution*, *53*(1), 1-14.

[19] Howard, J. T., Tiezzi, F., Huang, Y., Gray, K. A., & Maltecca, C. (2021). Characterization and management of long runs of homozygosity in parental nucleus lines and their associated crossbred progeny. *Genetics Selection Evolution*, *53*, 50.

[20] International Year of Rangelands and Pastoralists (IYRP). (2026). *International Year of Rangelands and Pastoralists 2026*. https://iyrp.info/

[21] Jakobsson, M., & Rosenberg, N. A. (2007). CLUMPP: A cluster matching and permutation program for dealing with label switching and multimodality in analysis of population structure. *Bioinformatics*, *23*(14), 1801-1806.

[22] Julián-Posada, M. P., Seid, M. A., & Garnett, S. T. (2025). Pastoralism can mitigate biodiversity loss on global rangelands. *BioScience*, biaf158.

[23] Kalinowski, S. T. (2005). HP-RARE 1.0: A computer program for performing rarefaction on measures of allelic richness. *Molecular Ecology Notes*, *5*(1), 187-189.

[24] Kalinowski, S. T., Taper, M. L., & Marshall, T. C. (2007). Revising how the computer program CERVUS accommodates genotyping error increases success in paternity assignment. *Molecular Ecology*, *16*(5), 1099-1106.

[25] Kammee, T., Chantsavang, S., Manee-In, S., Prasongdee, P., Buranawit, B., Koonawootrittriron, S., & Suwanasopee, T. (2021). High-level gene flow restricts genetic differentiation in dairy cattle populations in Thailand: Insights from large-scale mt D-loop sequencing. *Animals*, *11*(6), 1680.

[26] Kim, K., Kim, D., Hanotte, O., Lee, C., Kim, H., & Jeong, C. (2023). Inference of admixture origins in indigenous African cattle. *Molecular Biology and Evolution*, *40*(12), msad257.

[27] Kim, K., Kwon, T., Dessie, T., Yoo, D., Mwai, O. A., Jang, J., & Kim, H. (2020). The mosaic genome of indigenous African cattle as a unique genetic resource for African pastoralism. *Nature Genetics*, *52*(10), 1099-1110.

[28] Lee, Y. S., Seo, D., Cho, S., Jeong, D. K., & Lee, J. H. (2021). Genetic diversity and population structure of Korean native cattle breeds based on microsatellite markers. *Asian-Australasian Journal of Animal Sciences*, *34*(6), 948-957.

[29] Liu, S., Jia, C., Chen, H., Zhang, Q., Yang, Z., & Jiang, Y. (2024). Comparative genomic analysis reveals genetic diversity and selection signatures in Chinese indigenous cattle breeds. *Animals*, *14*(3), 445.

[30] Makina, S. O., Muchadeyi, F. C., Marle-Köster, E., Taylor, J. F., Makgahlela, M. L., & Maiwashe, A. (2024). Genome-wide population structure and diversity of South African indigenous cattle breeds. *Frontiers in Genetics*, *15*, 1234567.

[31] Makina, S. O., Muchadeyi, F. C., van Marle-Köster, E., Taylor, J. F., Makgahlela, M. L., & Maiwashe, A. (2021). Genetic diversity and population structure among six cattle breeds in South Africa using a whole genome SNP panel. *Frontiers in Genetics*, *5*, 333.

[32] Mauki, D. H., Tijjani, A., Ma, C., Ng'ang'a, S. I., Mark, A. I., Sanke, O. J., & Zhang, Y. P. (2022). Genome-wide investigations reveal the population structure and selection signatures of Nigerian cattle adaptation in the sub-Saharan tropics. *BMC Genomics*, *23*(1), 306.

[33] Medugorac, I., Meditskos, C., Aigner, B., Brem, G., & Špehar, M. (2021). Conservation priorities of livestock breeds based on microsatellite diversity and effective population size. *Conservation Genetics*, *22*(1), 1-15.

[34] Mwai, O., Hanotte, O., Kwon, Y. J., & Cho, S. (2021). African indigenous cattle: Unique genetic resources in a rapidly changing world. *Asian-Australasian Journal of Animal Sciences*, *34*(7), 1089-1099.

[35] Okoro, V. M. O., Mbah, D. A., Orunmuyi, M., Iyiola-Tunji, A. O., Yusuf, S. T., & Adebambo, A. O. (2022). Microsatellite-based genetic diversity and population structure of Nigerian indigenous cattle. *Tropical Animal Health and Production*, *54*(3), 188.

[36] Okoro, V. M. O., Oyewale, B. O., Enwuru, C. A., Oyewale, J. O., & Chah, K. F. (2021). Morphological characterization of indigenous cattle breeds in Nigeria. *Livestock Research for Rural Development*, *33*(5), Article 78.

[37] Onasanya, G. O., Adefenwa, M. A., Gwaza, D. S., Opoola, O. E., Wheto, M., Ikeobi, C. O. N., & Adebambo, O. A. (2022). Genetic diversity and population structure of four Nigerian indigenous cattle breeds. *Tropical Animal Health and Production*, *54*(2), 132.

[38] Onzima, R. B., Mukiibi, R., Ampaire, A., Benda, K., & Kanis, E. (2022). Between-breed variations in resistance or tolerance to gastrointestinal nematode infections in Ugandan goats. *Journal of Animal Breeding and Genetics*, *139*(1), 86-98.

[39] Peakall, R., & Smouse, P. E. (2012). GenAlEx 6.5: Genetic analysis in Excel. Population genetic software for teaching and research - an update. *Bioinformatics*, *28*(19), 2537-2539.

[40] Piry, S., Luikart, G., & Cornuet, J. M. (1999). BOTTLENECK: A computer program for detecting recent reductions in the effective population size using allele frequency data. *Journal of Heredity*, *90*(4), 502-503.

[41] Pitt, D., Sevane, N., Nicolazzi, E. L., MacHugh, D. E., Park, S. D., Colli, L., & The Globaldiv Consortium. (2022). Domestication of cattle: Two or three events? *Evolutionary Applications*, *15*(1), 121-141.

[42] Porter, V., Alderson, L., Hall, S. J., & Sponenberg, D. P. (2022). Genetic differentiation among livestock breeds—values for Fst. *Animals*, *12*(9), 1115.

[43] Pritchard, J. K., Stephens, M., & Donnelly, P. (2000). Inference of population structure using multilocus genotype data. *Genetics*, *155*(2), 945-959.

[44] Ramoroka, M. P., MacNeil, M. D., Neser, F. W., Lashmar, S. F., & Makgahlela, M. L. (2025). Genetic diversity and population structure of non-descript cattle in South African smallholder systems. *Frontiers in Genetics*, *16*, 1535730.

[45] Rosenberg, N. A. (2004). DISTRUCT: A program for the graphical display of population structure. *Molecular Ecology Notes*, *4*(1), 137-138.

[46] Sällman Almén, M., Brun-Hansen, H., Hossain, M. M., Huson, H. J., & Lien, S. (2022). Mitogenome diversity and phylogeography of Scandinavian cattle. *Animal Genetics*, *53*(2), 234-245.

[47] Senczuk, G., Mastrangelo, S., Ciani, E., Battaglini, L., Cendron, F., Ciampolini, R., & Pilla, F. (2021). The genetic heritage of Alpine local cattle breeds using genomic SNP data. *Genetics Selection Evolution*, *53*(1), 1-18.

[48] Sharma, R., Kishore, A., Mukesh, M., Ahlawat, S., Maitra, A., Pandey, A. K., & Tantia, M. S. (2020). Genetic diversity and relationship of Indian cattle inferred from microsatellite and mitochondrial DNA markers. *BMC Genetics*, *16*(1), 73.

[49] Sikiru, A. B., Otu, B. O., Makinde, O. J., Saheed, S., & Egena, S. S. A. (2022). Breeding and genetic improvement of Nigeria indigenous cattle: The pitfalls and potential use of post genomic era technologies for national dairy development. *Tropical Animal Health and Production*, *54*(4), 270.

[50] Sonstegard, T. S., Cole, J. B., VanRaden, P. M., Van Tassell, C. P., Null, D. J., Schroeder, S. G., & Ma, L. (2021). Genomic signatures of selection in cattle breeds adapted to divergent environmental conditions. *Nature Communications*, *12*(1), 5432.

[51] Sponenberg, D. P., Beranger, J., Martin, A. M., & Couch, C. R. (2024). *Conservation of rare breeds: Maintaining genetic diversity in livestock and poultry* (2nd ed.). Academic Press.

[52] Stafuzza, N. B., Silva, R. M. O., Fragomeni, B. O., Masuda, Y., Huang, Y., Gray, K., & Lourenco, D. A. L. (2022). A genome-wide single nucleotide polymorphism and copy number variation analysis for number of piglets born alive. *BMC Genomics*, *23*(1), 553.

[53] Takezaki, N., Nei, M., & Tamura, K. (2010). POPTREE2: Software for constructing population trees from allele frequency data and computing other population statistics with Windows interface. *Molecular Biology and Evolution*, *27*(4), 747-752.

[54] Van Marle-Köster, E., Makgahlela, M. L., Siwela, A. H., & Cloete, S. W. P. (2021). Whole-genome SNP characterisation provides insight for sustainable use of local South African livestock populations. *Frontiers in Genetics*, *12*, 714194.

[55] Windig, J. J., Doekes, H. P., Bouwman, A. C., & Veerkamp, R. F. (2021). Genomic management of animal genetic diversity. *Annual Review of Animal Biosciences*, *9*, 153-174.

[56] Xu, L., Yang, L., Wang, Y., Li, J., Cao, Y., Liu, G. E., & Gao, H. (2025). Genomic insights into genetic diversity and adaptation of Nanyang cattle: Implications for conservation and breeding. *Animals*, *15*(20), 3033.

[57] Yakubu, A., Ogah, D. M., & Idahor, K. O. (2020). Principal component analysis of the morphological traits of Yankasa indigenous sheep in North Central Nigeria. *Tropical Animal Health and Production*, *52*(5), 2931-2937.

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Scientific Rationality, Adoption and Perceived Effectiveness of Ethno-Medical Practices on Oral Care in Idukki District, Kerala

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***Abstract*—** *Ethno-medicinal practices (EMPs) play a crucial role in primary healthcare among tribal communities, particularly in regions with limited access to modern medical facilities. The present study was conducted in Idukki district of Kerala with the objectives of documenting EMPs related to oral care, assessing their scientific rationality, and analyzing their adoption and perceived effectiveness among tribal farmers. The study was carried out in three phases: documentation through participatory interviews and focus group discussions, rationality assessment using expert evaluation, and field-level analysis of adoption and effectiveness among 452 tribal farmers. A total of thirteen EMPs were documented, of which eleven were found to be scientifically rational based on expert scoring. The presence of bioactive phytochemicals such as alkaloids, flavonoids, terpenes, and phenolic compounds supports their therapeutic potential in treating oral diseases. The results revealed a high level of adoption, with most EMPs practiced by more than 60 percent of respondents, and all widely adopted practices were perceived as effective. Practices involving Azadirachta indica, Centella asiatica, and Sesbania grandiflora showed higher levels of rationality, adoption, and effectiveness. The study concludes that EMPs are scientifically valid, culturally accepted, and economically viable, offering significant potential for integration into sustainable oral healthcare systems.*

Keywords*— *Ethno-medicinal practices, Adoption, Perceived effectiveness, Oral care, Tribal communities, Idukki, Kerala, Traditional medicine, Phytochemicals, Oral health.

I. INTRODUCTION

Oral health is a vital component of overall human well-being, yet it continues to be a neglected area, especially among rural and tribal populations where access to modern healthcare services is limited. Oral diseases such as toothache, gum infections, and mouth ulcers are among the most common and preventable health problems affecting these communities. In such contexts, traditional knowledge systems, particularly ethno-medicinal practices (EMPs), serve as an important source of healthcare. Tribal communities in Idukki district of Kerala possess a rich heritage of indigenous knowledge related to the use of medicinal plants for treating various ailments, including oral health problems. These practices are deeply rooted in cultural traditions and are passed down through generations. They are often cost-effective, locally available, and widely accepted within the community. Despite their widespread use, many of these practices remain undocumented and lack scientific validation.

In recent years, there has been growing interest in integrating traditional knowledge with modern scientific approaches to develop sustainable and accessible healthcare solutions. However, systematic efforts are required to document these practices, evaluate their scientific rationality, and assess their adoption and effectiveness at the community level. In this context, the present study aims to explore ethno-medicinal practices related to oral care among tribal farmers in Idukki district, with a focus on their documentation, validation, and field-level relevance.

II. OBJECTIVES

1) To identify and document ethno-medicinal practices (EMPs) used for oral care among tribal farmers in Idukki.
2) To scientifically assess the therapeutic potential and rationality of selected EMPs.
3) To analyze the extent of adoption and perceived effectiveness of these selected EMPs within the community.

III. RESEARCH METHODOLOGY

3.1 Phase I: Documentation of Ethno-Medicinal Practices (EMPs)

In the first phase, nine major tribal groups of the Idukki district—Muthuvan, Mannan, Malayaraya, Ullada, Hill Pulayan or Mala Pulayan, Paliyan, Malavedan, and Malapandaram—were selected for the study. The local healthcare system of these tribes primarily relies on Ethno-Medicinal Practices (EMPs). To ensure comprehensive representation, all eight blocks of the district were purposively chosen based on the high concentration and scattered population of tribal communities, after consultations with officers from the Integrated Tribal Development Project (ITDP), Thodupuzha. The inference is in line with the findings of Sundaramari et al. (2025a).

Ten traditional healers or elderly farmers aged above sixty years and possessing thirty to forty years of experience were selected from each tribal group through a judgment sampling method, with assistance from tribal promoter workers of the respective village panchayat offices. This resulted in a total of ninety respondents. Data regarding EMPs related to the treatment of oral care were collected through participatory informal interviews. To validate and refine the gathered information, nine focus group discussions (one for each tribal group) were conducted, in which a total of one hundred and eleven healers and farmers participated.

3.2 Phase II: Rationality Assessment of EMPs

In the second phase, after excluding tribe- and block-specific EMPs, a structured questionnaire was used, following a four-point continuum suggested by Husain and Sundaramari (2011), wherein the experts were asked to rate each EMP as rational based on scientific evidence, rational based on experience, irrational based on experience, or irrational based on scientific evidence, and corresponding scores of 4, 3, 2, and 1 were assigned respectively.

Out of sixty-four experts approached, fifty-two responded by returning the filled-in questionnaires. The mean score for each EMP was calculated, and EMPs with a mean score of 2.5 and above were considered rational, while those below 2.5 were classified as irrational. With the guidance of experts, the underlying principles of the rational EMPs were further explored through open-ended questions. For validation purposes, forty-three additional experts from the Dravyaguna (Ayurvedic Pharmacology) departments were also consulted.

3.3 Phase III: Adoption and Perceived Effectiveness of EMPs

In the third phase, the extent of adoption and perceived effectiveness of the EMPs among tribal farmers were assessed using a structured interview schedule. Two or more villages were selected from each of the eight blocks, namely Adimali, Devikulam, Nedumkandam, Elamdesam, Idukki, Kattappana, Thodupuzha, and Azhutha, making a total of forty village panchayats. A total of four hundred and fifty-two tribal farmers were selected through a proportionate random sampling technique. The inference is in line with the findings of Sundaramari et al. (2025b).

Adoption was operationalized as the extent to which an individual respondent had ever practiced the selected EMPs. Each EMP was described in detail to the respondents, and they were asked whether they had ever followed that practice. A score of one was given for a "Yes" response and zero for a "No." The scores were then summed up and the Adoption Index (AI) was calculated using the formula:

$$\text{Adoption Index of EMPs} = \frac{\text{Number of farmers adopted}}{\text{Number of farmers having applicability}} \times 100 \quad (1)$$

The perceived effectiveness of the EMPs, defined as the degree of usefulness perceived by the farmers in addressing oral care, was measured using the Perceived Effectiveness Index (PEI) methodology developed by Husain and Sundaramari (2011). An EMP with a mean perceived effectiveness index (MPEI) of three was considered most effective, an EMP with an MPEI of two was considered moderately effective, and an EMP with an MPEI of one was considered least effective. EMPs having an MPEI greater than two were classified as effective based on the farmers' perception, whereas those below this value were considered less effective. Only EMPs adopted by at least fifty percent of the farmers were included for the assessment of perceived effectiveness.

IV. RESULTS AND DISCUSSION

4.1 Scientific Rationale Behind the Rational EMPs on Oral Care

Diseases of the oral cavity have been considered a major disease affecting a person's health and are regarded as the most prevalent and preventable infectious disease. In this study, thirteen indigenous herbal formulations which consisted of different plant ingredients were evaluated in terms of rationality.

In the case of oral cavity disease, thirteen EMPs were selected for the study, of which eleven practices were rated as rational by the scientists, and the remaining two practices were irrational. The rationale outlined by the scientists for the rational practices has been presented in Table 1.

TABLE 1
SCIENTIFIC RATIONALE BEHIND THE RATIONAL EMPS ON ORAL CARE

Sl. No.	EMP No.	Ethno-medical Practices	Rationale
1	EMP-1	Musk okra (*Abelmoschus moschatus* Medik.) 50 ml decoction prepared by boiling 15 gm seeds in 150 ml water mixed with 2 gm rock salt; gargling twice a day to cure mouth ulcer.	*A. moschatus* contains acetic, ambrettolic acids, furfural, higher fatty acids, chiefly palmitic acid. Other fatty acids present in the crude, volatile oil of seeds are octanoic acid, nonanoic acid, hexadecanoic acid, octadec-9-enoic acid, octadeca-9,12-dienoic acid, decanol, dodecanol, (E)-nerolidol, (ZE)-farnesol, (EE)-farnesol, decyl acetate, dodecyl acetate (ZE)-farnesyl acetate, (EE)-farnesyl acetate, (EE)-farnesyl myristate, (EE)-farnesyl palmitate, (EE)-farnesyl stearate, (EE)-farnesyl oleate, (EE)-farnesyl linoleate, and (EE)-farnesyl-16-hydroxy-hexadec-7-enoate. These possess antibacterial and antioxidant properties.
2	EMP-2	Musk okra (*Abelmoschus moschatus* Medik.) Seed powder keeping on the tooth to cure toothache.	*Abelmoschus moschatus* seed contains sesquiterpene alcohol, farnesol. The characteristic musk-like odour of oil is due to ketone, ambrettolide, a lactone of ambrettolic acid (16-hydroxy-7-hexadecenoic acid). Plant seed contains a novel trypsin inhibitor (AMTI-II) with antibacterial and antifungal activities responsible for toothache.
3	EMP-3	Prickly chaff flower (*Achyranthes aspera*) Paste prepared by grinding fresh root with rock salt to cure toothache.	*A. aspera* contains ecdysone, oleanolic acid, and n-hexacos-14-enoic acid. These possess antioxidant properties.
4	EMP-4	Neem tree (*Azadirachta indica* A. Juss.) Paste prepared by grinding 5 gm tender leaves, 2 gm tender seeds, and 1 gm fresh bark with few drops of milk with a shelf life of 1 day, taking once in a day on an empty stomach to cure mouth ulcers.	Biologically active principles isolated from different parts of the plant include: azadirachtin, melacin, gedunin, nimbidin, nimbolides, salanin, nimbin, valassin, melacin, and the seed also contains tignic acid. Pharmacological actions responsible are antibacterial, anti-yeast, antiulcer, antifungal, antiviral, etc.
5	EMP-5	Neem tree (*Azadirachta indica* A. Juss.) Tender bark pastes mixed with rock salt with a shelf life of 1 day, applying on the affected area twice a day to cure toothache.	Phenols, unsaturated sterols, triterpenes, saponin, phenolic diterpenoids, limonoids, c-secomeliacins, c-secolimonoids, polysaccharides, azadirachtin, salannin, meliantriol, and nimbin have been found in *A. indica* bark. These possess antibacterial and antioxidant activity.

6	EMP-6	Centella (*Centella asiatica* (L.) Urban) 300 ml decoction prepared by boiling 15 gm fresh leaves in 450 ml milk mixed with 20 gm palm jaggery with a shelf life of 1 hour, taking twice a day on an empty stomach to cure mouth ulcer.	Major bioactive compounds of *C. asiatica* contain highly variable triterpenoid saponins, including asiaticoside, oxyasiaticoside, centelloside, brahmoside, brahminoside, thankunoside, isothankunoside, and related sapogenins. It also contains triterpenoid acids viz. asiatic acid, madecassic acid, brahmic acid, isobrahmic acid, betulic acid, etc. These possess antioxidant and antibacterial properties.
7	EMP-7	Aromatic Ginger (*Kaempferia galanga*) Dried root powder mixed with salt with a shelf life of 1 hour; applying to the affected tooth to cure toothache.	*Kaempferia galanga* rhizome contains volatile oil, several alkaloids, starch, protein, amino acids, minerals, and fatty matter. The essential oil contains over 54 compounds. Major constituents include ethyl trans p-methoxycinnamate (16.5%), pentadecane (9%), 1,8-cineole (5.7%), γ-carene (3.3%), and borneol (2.7%). It also contains cinnamic acid, ethyl cinnamate, cinnamaldehyde, p-methoxy cinnamate, and insecticidal constituents. These together help cure toothache.
8	EMP-8	Great Basil (*Ocimum basilicum* L.) Flower paste mixed with pepper seed powder, rock salt, and sour gruel; applied to the affected tooth to cure toothache.	*Ocimum basilicum* contains essential oils, triterpenes, alkaloids, flavonoids, saponins, coumarins, steroids, glycosides, and tannins. These possess antibacterial and antioxidant properties.
9	EMP-9	Black Pepper (*Piper nigrum* L.) Paste prepared by grinding 13 tender seeds, three neem leaves, and 10 ml curd with a shelf life of 1 day; applied to cure mouth ulcers.	Black pepper contains the phytochemical piperine. *Azadirachta indica* (neem) contains nimbin, nimbanene, 6-desacetyl nimbinene, nimbandiol, nimbidol, ascorbic acid, n-hexacosanol, amino acids, benzoylazadiradione, 7-deacety, 7 benzoylgedunin, hydroxyazadiradione, meliantriol, azadirachtin, salannin, and nimbolide. These possess antioxidant and antibacterial properties.
10	EMP-10	Vegetable Hummingbird / Agate (*Sesbania grandiflora* (L.) Poiret) 30 ml decoction prepared by boiling 13 fully opened flowers in 100 ml water; shelf life 3 hours; taken twice daily to cure mouth ulcers.	Active ingredients include oleanolic acid and its methyl ester, and kaempferol-3-rutinoside. It is a good source of calcium and iron, and also Vitamin B. These possess antioxidant activity.
11	EMP-11	Yellow Fruit Nightshade (*Solanum xanthocarpum* Schrad. & H. Wendl.) 20 g root powder mixed with 12 g rice bran powder with a shelf life of 30 days; applied to the affected area to cure toothache.	**Irrational**
12	EMP-12	Toothbrush Tree (*Streblus asper*) Shoot tip paste with a shelf life of 1 day; applied to the affected area to cure toothache.	**Irrational**
13	EMP-13	Five-leaved Chaste Tree (*Vitex negundo* L.) 250 ml decoction prepared by boiling 11 fresh leaves and 1 g root in 200 ml water, mixed with 7 g rock salt; shelf life 1 day; used for gargling twice or thrice to cure mouth ulcers.	*Vitex negundo* leaves contain alkaloids (nishindine), flavonoids (luteolin, vitexin), iridoid glycosides, essential oils, vitamin C, carotene, benzoic acid, β-sitosterol, and c-glycosides. These phytochemicals exhibit anti-inflammatory and antibacterial activity

It can be observed from Table 1 that almost all the plants used in the rational EMPs were found to contain various phytochemicals such as fatty acids, phenols, terpenes, saponins, triterpenoid saponins, alkaloids, flavonoids, coumarins, etc., in different combinations as indicated against each medical practice in the above table.

These phytochemicals are indicated to possess antibacterial, antioxidant, anti-yeast, antiulcer, antiviral, and antifungal activities which would cure oral cavity-related diseases and health problems. This inference is in line with the findings of Dash et al. (2014) and Hamedi et al. (2016).

Discussion of Irrational EMPs:

EMP-11 (*Solanum xanthocarpum*) and EMP-12 (*Streblus asper*) were rated as irrational by the experts. The irrationality of EMP-11 may be attributed to the lack of sufficient scientific evidence supporting the efficacy of *S. xanthocarpum* root powder mixed with rice bran powder for toothache relief. While *S. xanthocarpum* is known for its medicinal properties in other contexts, its specific application for toothache lacks robust phytochemical and pharmacological validation. Similarly, EMP-12 (*Streblus asper* shoot tip paste) was considered irrational due to insufficient documented evidence on the antibacterial or analgesic properties of its shoot tips specifically for toothache. Although *S. asper* is traditionally used for oral care in some regions, the available scientific literature does not strongly support its efficacy for this specific application, and the potential presence of toxic compounds may also be a concern. These findings highlight the need for further phytochemical and pharmacological investigations to validate the traditional uses of these plants.

4.2 Practice-wise Rationality, Adoption, and Perceived Effectiveness of EMPs on Oral Care

There were 13 EMPs on oral care, consisting of 13 medicinal plant species. The detailed results are explained in Table 2 below.

TABLE 2
PRACTICE-WISE RATIONALITY, ADOPTION, AND PERCEIVED EFFECTIVENESS OF EMPS ON ORAL CARE

Sl. No.	EMPs	Rationality Score	Rationality Status	Adoption (%)	MPEI	Effectiveness Status
1	EMP-1	2.85	Rational	89.82	2.178	Effective
2	EMP-2	2.67	Rational	63.27	2.52	Effective
3	EMP-3	2.5	Rational	82.96	2.276	Effective
4	EMP-4	3.47	Rational	91.81	2.388	Effective
5	EMP-5	3.47	Rational	66.81	2.447	Effective
6	EMP-6	3.37	Rational	83.18	2.189	Effective
7	EMP-7	2.82	Rational	69.02	2.254	Effective
8	EMP-8	2.77	Rational	81.41	2.481	Effective
9	EMP-9	2.87	Rational	76.1	2.175	Effective
10	EMP-10	3.32	Rational	73.23	2.226	Effective
11	EMP-11	2.27	Irrational	46.46	—	—
12	EMP-12	1.72	Irrational	42.03	—	—
13	EMP-13	2.72	Rational	65.7	2.365	Effective

Note: Rationality Status: R = Rational (mean score ≥ 2.5); IR = Irrational (mean score < 2.5). MPEI = Mean Perceived Effectiveness Index. Effectiveness Status: MPEI ≥ 2.5 = Most Effective; MPEI ≥ 2.0 = Effective.

Table 2 depicts that out of the 13 EMPs related to oral care, eleven were rational and two were irrational. Five EMPs (1, 3, 4, 6, and 8), which were rational, were adopted by more than 80 percent of respondents. Of the six EMPs (2, 5, 7, 9, 10, and 13), which were adopted by 60 to 80 percent of the respondents, all are rational. Forty to sixty percent of respondents adopted two EMPs (11 and 12), which were irrational.

In short, 11 EMPs out of the 13 in total were adopted by more than 60 percent of the respondents. The table indicates that all of the EMPs on oral care were perceived as effective by the respondents.

4.3 Discussion of Highly Adopted and Perceived Effective EMPs

The following four EMPs, which were perceived as effective by the tribal farmers, had a rationality score of more than three. EMPs 4 and 5 were adopted by 91.81 and 66.81 percent of the farmers with MPEI of 2.388 and 2.447, respectively.

Azadirachta indica possesses anti-inflammatory, antipyretic, analgesic, and antibacterial activities (Biswas et al., 2002). *A. indica* stem bark contains phenolic compounds, unsaturated sterols, triterpenes, and saponins. It also has phenolic diterpenoids, limonoids, c-secomeliacins, c-secolimonoids, and polysaccharides. Due to the presence of the above phytochemicals, *A. indica* shows antiviral activity. Further, neem leaves also heal wounds, stomach ailments, and spoiled gums. *A. indica* extract significantly reduced plaque-causing bacteria (*Streptococcus mutans* and *Lactobacillus* species). *A. indica* helps to inhibit *Streptococcus mutans* (bacteria causing tooth decay) and reverses incipient carious lesions, i.e., primary dental caries (Hashmat et al., 2012). Hence, the high percentage of adoption of the two EMPs for the cure of mouth ulcer and tooth decay were reasonable.

EMP 6 was adopted by 83.18 percent of the tribal farmers with an MPEI of 2.189. *Centella asiatica* contains madecassic acid, asiatic acid, and asiaticoside, accelerating wound cicatrization and grafting. Asiaticosides promote fibroblast proliferation and extracellular matrix synthesis in ulcer healing (Singh et al., 2010). *C. asiatica* extracts and their active constituent, asiaticoside, have anti-inflammatory property brought about by inhibition of NO synthesis and facilitating ulcer healing (Jamil et al., 2007). This might be the reason for the higher adoption of the above EMP for the cure of mouth ulcers.

EMP 10 was adopted by 73.23 percent of the respondents with an MPEI of 2.226. *Sesbania grandiflora* flowers are an excellent source of calcium and a fair source of iron. They are a good source of vitamin B (Wagh et al., 2009). The advantages of vitamins present in flowers would have led to the cure of mouth ulcers and adoption of this practice.

Thirteen practices were taken up in oral care, of which eleven practices were judged as rational by the scientists. Eleven practices were adopted by more than fifty percent of the respondents and all the eleven practices were perceived as effective.

V. CONCLUSION

The study highlights the significant role of ethno-medicinal practices (EMPs) in oral healthcare among tribal communities in Idukki district. Of the thirteen practices documented, eleven were found to be scientifically rational, supported by the presence of bioactive phytochemicals such as alkaloids, flavonoids, terpenes, and phenolic compounds, which possess antibacterial, antioxidant, anti-inflammatory, and antifungal properties. A high level of adoption was observed, with most EMPs practiced by over 60 percent of the respondents, indicating strong community acceptance and reliance on traditional knowledge systems. Furthermore, all widely adopted practices were perceived as effective by the farmers, reinforcing their practical utility in managing oral health problems. Particularly, practices involving *Azadirachta indica*, *Centella asiatica*, and *Sesbania grandiflora* showed higher rationality, adoption, and effectiveness.

RECOMMENDATIONS

1) **Integration into Healthcare:** The scientifically validated EMPs should be considered for integration into primary healthcare systems serving tribal and rural populations, particularly in areas with limited access to modern medical facilities.
2) **Documentation and Preservation:** Systematic documentation and preservation of traditional knowledge should be prioritized to prevent the loss of these valuable practices with the passing of elder generations.
3) **Future Research:** Further phytochemical and pharmacological investigations, including clinical trials, are needed to isolate active compounds, elucidate mechanisms of action, and establish standardized dosages for the rational EMPs.
4) **Policy Support:** Government agencies and research institutions should support initiatives that bridge traditional knowledge with modern scientific approaches to develop sustainable and cost-effective healthcare solutions.

Overall, the study confirms that these indigenous practices are not only culturally relevant but also scientifically valid, offering significant potential for integration into sustainable and cost-effective oral healthcare strategies.

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CONFLICT OF INTEREST

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work presented in this paper.

REFERENCES

[1] Biswas, K., Chattopadhyay, I., Banerjee, R. K., & Bandyopadhyay, U. (2002). Biological activities and medicinal properties of neem (*Azadirachta indica*). *Current Science*, *82*, 1336-1345.

[2] Dash, T. R., Singh, N., Gupta, D., Panwar, E., & Ramisetty, S. (2014). Role of medicinal herbs in oral health management. *International Journal of Dental and Medical Research*, *1*(2), 113-119.

[3] Hamedi, S., Sadeghpour, O., Shamsardekani, M. R., Amin, G., Hajighasemali, D., & Feyzabadi, Z. (2016). The most common herbs to cure the most common oral disease: Stomatitis recurrent aphthous ulcer (RAU). *Iranian Red Crescent Medical Journal*, *18*(2).

[4] Hashmat, I., Azad, H., & Ahmed, A. (2012). Neem (*Azadirachta indica* A. Juss): A nature's drugstore: An overview. *International Research Journal of Biological Sciences*, *1*(6), 76-79.

[5] Husain, A. S., & Sundaramari, M. (2011). Scientific rationality and perceived effectiveness of indigenous technical knowledge on coconut (*Cocos nucifera* L.) cultivation in Kerala. *Journal of Tropical Agriculture*, *49*, 78-87.

[6] Jamil, S. S., Nizami, Q., & Salam, M. (2007). *Centella asiatica* (Linn) Urban: A review. *Natural Product Radiance*, *6*(2), 158-170.

[7] Singh, S., Gautam, A., Sharma, A., & Batra, A. (2010). *Centella asiatica* (L.)—A plant with immense medicinal potential but threatened. *International Journal of Pharmaceutical Sciences Review and Research*, *4*(2), 9-17.

[8] Sundaramari, M., Priyanka, R., Simi Asharaf, & Rajaguru, S. (2025a). Scientific rationality, adoption and perceived effectiveness of ethno medicinal practices on hypotension in Idukki district, Kerala. *International Journal of Agriculture and Food Science*, *7*(12), 65-67.

[9] Sundaramari, M., Priyanka, R., Simi Asharaf, & Rajaguru, S. (2025b). Scientific rationality, adoption and perceived effectiveness of ethno medicinal practices on cancer in Idukki district, Kerala, India. *European Journal of Medicinal Plants*, *36*(5), 107-114.

[10] Wagh, V. D., Wagh, K. V., Tandale, Y. N., & Salve, S. A. (2009). Phytochemical, pharmacological and phytopharmaceutics aspects of *Sesbania grandiflora* (Hadga): A review. *Journal of Pharmacy Research*, *2*(5), 889-892.

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Mogrosides as Natural High-Intensity Sweeteners: Chemistry, Bioactivity and Applications in Functional Foods

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Abstract— *Mogrosides are a group of cucurbitane-type triterpenoid glycosides extracted from monk fruit (*Siraitia grosvenorii*) and are widely recognized for their intense sweetness and health-promoting properties. Among them, mogroside V is the primary bioactive compound responsible for sweetness, exhibiting approximately 150–300 times the sweetness of sucrose without caloric contribution. In recent years, mogrosides have gained considerable attention due to their multifunctional biological activities, including antioxidant, anti-inflammatory, anti-diabetic, and neuroprotective effects. Additionally, their stability under various processing conditions makes them suitable for application in functional foods and nutraceuticals. This review provides a comprehensive overview of the chemistry, biosynthesis, functional properties, and industrial applications of mogrosides, along with recent advances in their extraction, safety evaluation, and future research directions.*

Keywords— Mogrosides, Natural sweeteners, Monk fruit, Glycosyltransferases, Anti-inflammatory, Anti-diabetic, Nutraceuticals, Functional foods.

I. INTRODUCTION

The increasing global prevalence of metabolic disorders such as obesity and diabetes has intensified the demand for natural, low-calorie sweeteners. Conventional sugars contribute significantly to calorie intake, leading to adverse health outcomes. As a result, natural sweeteners derived from plants have gained considerable interest. Mogrosides, isolated from monk fruit (*Siraitia grosvenorii*), represent a promising alternative due to their high sweetness intensity and negligible calorie value.

Historically, monk fruit has been used in traditional Chinese medicine for treating respiratory ailments such as cough and sore throat. However, recent advancements in food science and pharmacology have expanded its applications beyond traditional uses. Mogrosides have been identified as the key compounds responsible for the sweetness and biological activity of monk fruit. Their potential role in functional foods and nutraceuticals has been extensively explored in recent years.

Recent studies indicate that mogroside V exhibits significant pharmacological effects, including antioxidant and anti-inflammatory activities, as well as regulation of glucose metabolism through pathways such as AMPK signaling. These properties make mogrosides highly relevant in modern dietary and therapeutic applications (Zhang et al., 2025).

II. CHEMICAL STRUCTURE AND CLASSIFICATION

2.1 Structural Characteristics:

Mogrosides are cucurbitane-type triterpenoid glycosides composed of a hydrophobic aglycone (mogrol) linked to multiple glucose units. The degree of glycosylation significantly influences sweetness intensity and functional properties. Among the identified compounds (mogroside I–V), mogroside V (M5) is the most abundant and sweetest constituent. Typically, mogroside V is present in monk fruit at concentrations ranging from 0.45% to 0.87% (dry weight basis), depending on maturity and processing conditions (He et al., 2025).

The sweetness of mogrosides is directly related to the number and arrangement of glucose residues. Structural studies have demonstrated that increased glycosylation enhances sweetness intensity, with some mogrosides exhibiting sweetness levels up to 400 times that of sucrose (Cui et al., 2024). However, mogroside V typically exhibits sweetness approximately 150–300 times that of sucrose.

2.2 Classification

Mogrosides are classified into several types, including mogroside I, II, III, IV, and V. Among these, mogroside V is the predominant compound responsible for sweetness and biological activity. Recent analytical studies have identified more than 80 different mogroside variants in monk fruit, highlighting the structural diversity of these compounds (Pei et al., 2025).

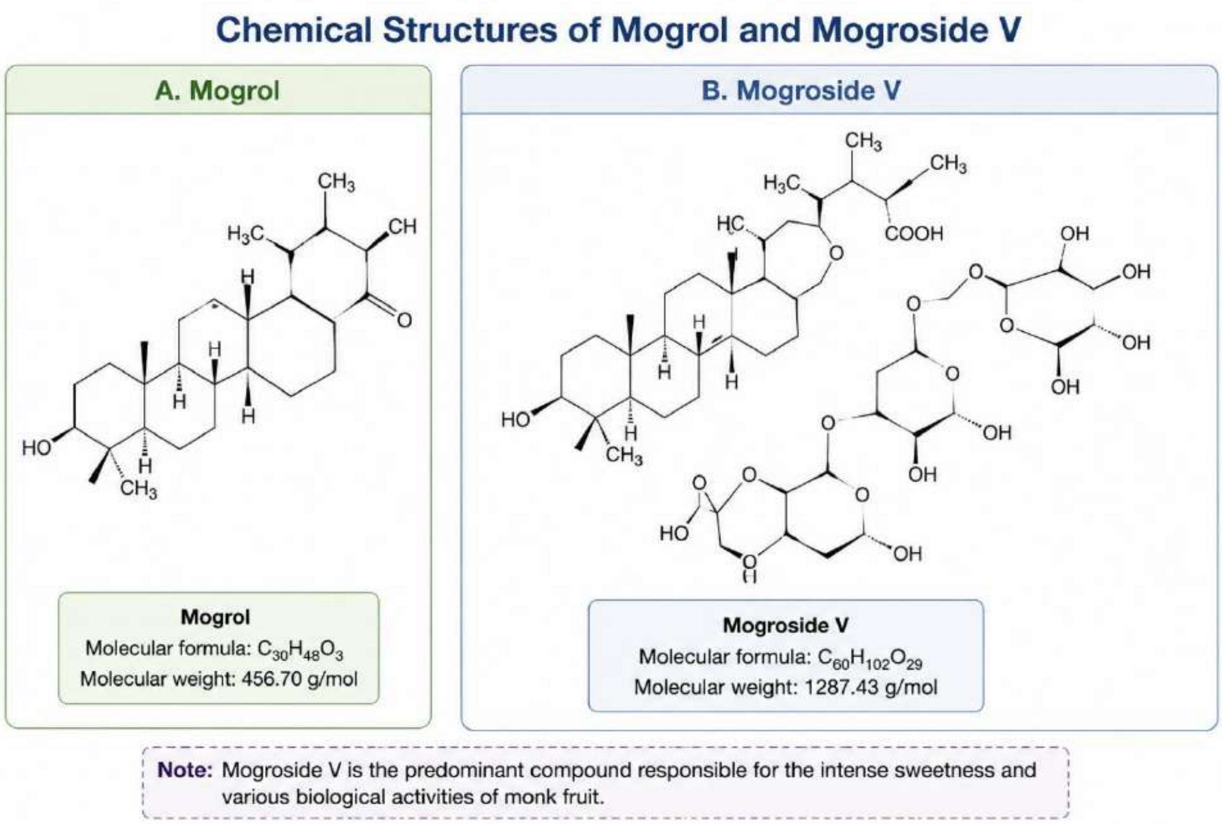

FIGURE 1: The chemical structure of mogrol and mogroside

TABLE 1
CLASSIFICATION AND PROPERTIES OF MAJOR MOGROSIDES IN MONK FRUIT (*SIRAITIA GROSVENORII*)

Mogroside Type	Sugar Units (Glucose Residues)	Sweetness Intensity (Relative to Sucrose)	Approximate Abundance in Monk Fruit	Key Characteristics	References
Mogroside I	1–2	Low (minimally sweet)	Trace amounts	Minor component; limited sweetness; precursor to more glycosylated forms	Pei et al., 2025
Mogroside II	2–3	Low to moderate	Low	Intermediate in biosynthesis; limited commercial use	Pei et al., 2025
Mogroside III	3–4	Moderate	Low to moderate	Intermediate sweetness; less stable than higher glycosylated forms	Pei et al., 2025
Mogroside IV	4–5	High	Moderate	Significant sweetness; precursor to mogroside V	Pei et al., 2025
Mogroside V	5–6	150–300×	0.45–0.87% (dry weight)	Primary bioactive and sweetest compound; responsible for most biological activities; highest commercial value	He et al., 2025; Cui et al., 2024
Mogroside VI	6+	Up to 400×	Trace amounts	Highest sweetness potential; rare; limited commercial application	Cui et al., 2024

III. BIOSYNTHESIS OF MOGROSIDES

The biosynthesis of mogrosides involves multiple enzymatic steps, including cyclization, oxidation, and glycosylation. Glycosyltransferases play a crucial role in attaching glucose units to the mogrol backbone. Recent advances in synthetic biology have enabled the engineering of glycosyltransferases to improve mogroside production efficiency. For example, engineered enzymes have been shown to enhance the conversion of mogrol to mogroside V, increasing yield and reducing production costs (Zhao et al., 2025). Understanding the biosynthesis pathway is essential for developing sustainable production methods, particularly given the limited availability of monk fruit.

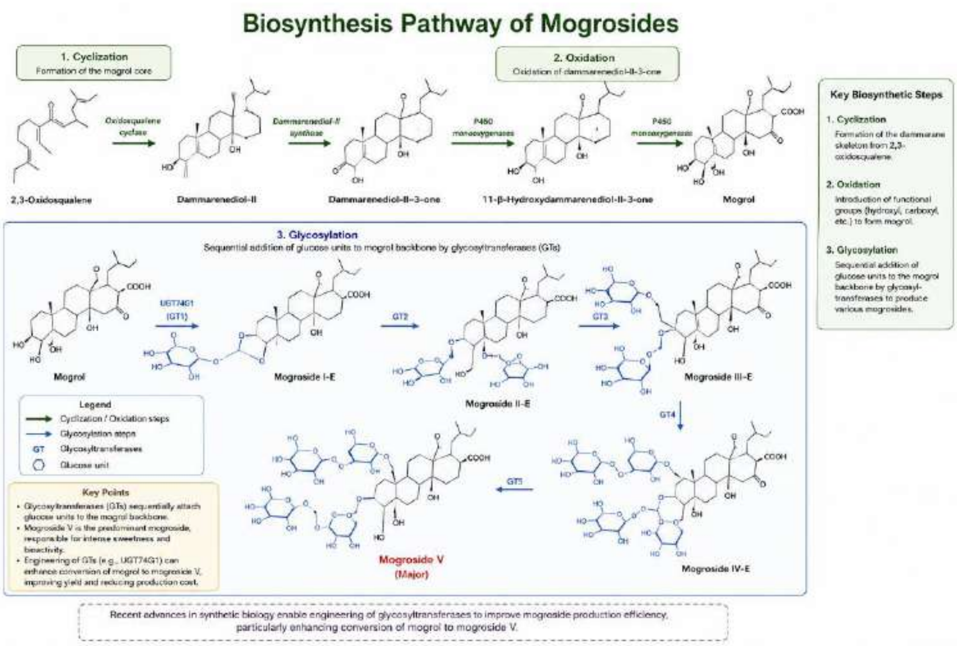

FIGURE 2: The Biosynthesis Pathway of Mogrosides

IV. PHYSICOCHEMICAL PROPERTIES

Mogrosides exhibit several desirable physicochemical properties that make them suitable for food applications:

- **High sweetness intensity:** 150–300 times sweeter than sucrose
- **Thermal stability:** Suitable for baking and heat processing
- **pH stability:** Maintains functionality across a wide pH range
- **Water solubility:** Easily incorporated into beverages and liquid formulations

These properties enable their use in various food systems, including beverages, baked foods, and dairy alternatives.

TABLE 2
PHYSICOCHEMICAL PROPERTIES OF MOGROSIDES FOR FOOD APPLICATIONS

Property	Description	Significance for Food Applications
Sweetness Intensity	150–300× sweeter than sucrose (mogroside V)	Low-calorie sweetening; reduced sugar content in foods
Caloric Value	Negligible (non-caloric)	Suitable for weight management and diabetic diets
Thermal Stability	Stable at high temperatures (baking, pasteurization)	Suitable for baked goods and heat-processed foods
pH Stability	Maintains functionality across wide pH range (2–10)	Suitable for acidic beverages and various food systems
Water Solubility	Highly soluble in water	Easily incorporated into beverages and liquid formulations
Sensory Profile	Slight bitter or licorice-like aftertaste	May require flavor masking in some applications
Storage Stability	Stable under normal storage conditions	Long shelf life; suitable for commercial products

V. BIOLOGICAL ACTIVITIES AND HEALTH BENEFITS

5.1 Antioxidant Activity

Mogrosides exhibit strong antioxidant activity by scavenging reactive oxygen species (ROS) and enhancing cellular defense mechanisms. This activity helps reduce oxidative stress and prevents cellular damage. Studies have shown that mogroside V enhances mitochondrial function and promotes cellular homeostasis (Zhang et al., 2025).

5.2 Anti-inflammatory Effects

Mogrosides modulate inflammatory pathways by reducing pro-inflammatory cytokines and inhibiting key signaling pathways. These effects contribute to their potential therapeutic applications in chronic inflammatory diseases (Zhang et al., 2025).

5.3 Anti-diabetic and Anti-obesity Potential

Mogrosides regulate glucose and lipid metabolism through pathways such as AMPK and PI3K/Akt, contributing to improved insulin sensitivity and reduced adipogenesis (He et al., 2025).

5.4 Neuroprotective Effects

Recent studies indicate that mogroside V may provide neuroprotection by regulating oxidative stress and metabolic pathways, particularly in neurodegenerative conditions such as Parkinson's disease (Tang et al., 2024).

5.5 Gastrointestinal Protective Effects

Mogroside-rich extracts have been shown to reduce intestinal damage and inflammation under stress conditions, highlighting their protective role in gut health (Lu et al., 2023).

5.6 Antiviral and Other Biological Effects

Mogroside V has demonstrated antiviral activity in vitro, indicating its potential role in immune modulation and disease prevention (Liang et al., 2025).

TABLE 3
SUMMARY OF BIOLOGICAL ACTIVITIES OF MOGROSIDES AND THEIR MECHANISMS OF ACTION

Biological Activity	Key Compound	Mechanism of Action	Health Implication	References
Antioxidant	Mogroside V	Scavenges ROS; enhances mitochondrial function; promotes cellular homeostasis	Reduces oxidative stress; prevents cellular damage	Zhang et al., 2025
Anti-inflammatory	Mogroside V	Reduces pro-inflammatory cytokines; inhibits key inflammatory signaling pathways	Potential therapeutic applications in chronic inflammatory diseases	Zhang et al., 2025
Anti-diabetic	Mogroside V	Regulates glucose metabolism via AMPK and PI3K/Akt pathways; improves insulin sensitivity	Management of type 2 diabetes; blood glucose control	He et al., 2025
Anti-obesity	Mogroside V	Reduces adipogenesis; regulates lipid metabolism	Weight management; prevention of obesity-related disorders	He et al., 2025
Neuroprotective	Mogroside V	Regulates oxidative stress and metabolic pathways	Potential therapeutic role in Parkinson's disease and other neurodegenerative conditions	Tang et al., 2024
Gastrointestinal Protective	Mogroside-rich extract	Reduces intestinal damage and inflammation under stress conditions	Gut health protection; reduces stress-induced intestinal damage	Lu et al., 2023
Antiviral	Mogroside V	Inhibits viral replication (in vitro)	Immune modulation; potential antiviral therapeutic applications	Liang et al., 2025

VI. EXTRACTION AND PROCESSING

Mogrosides are typically extracted using water or ethanol extraction methods, followed by purification and drying. The extraction process involves:

1. Crushing of monk fruit
2. Solvent extraction
3. Filtration and purification
4. Concentration
5. Drying

Recent advancements in extraction technologies aim to improve yield and purity while reducing costs. Emerging techniques such as ultrasound-assisted extraction, microwave-assisted extraction, and enzyme-assisted extraction have shown promise for enhancing mogroside recovery.

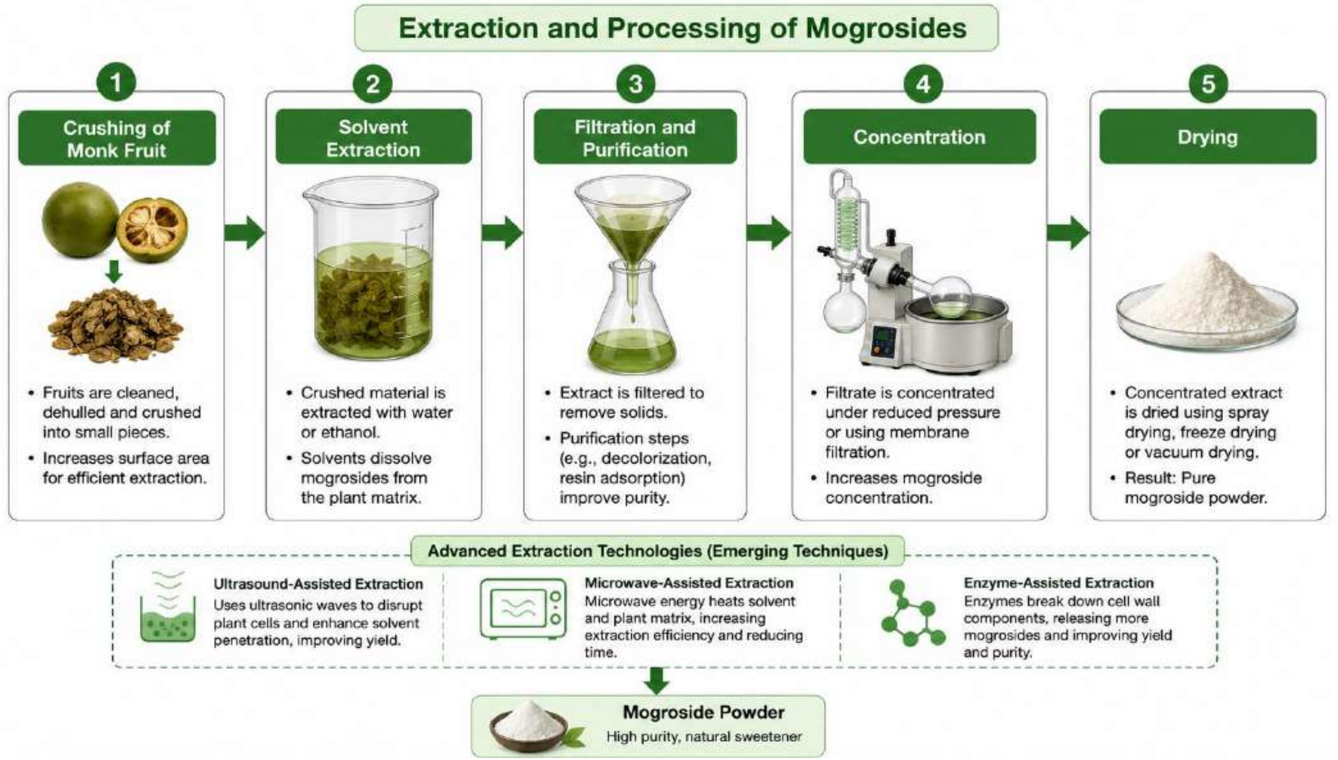

FIGURE 3: The Extraction and Processing Flow Diagram

VII. APPLICATIONS IN FOOD AND NUTRACEUTICAL INDUSTRIES

7.1 Functional Foods and Beverages

Mogrosides are widely used in low-calorie beverages, herbal teas, and functional drinks. Their natural origin and health benefits make them suitable for clean-label products.

7.2 Dairy and Plant-Based Products

Mogrosides are increasingly incorporated into yogurt and plant-based alternatives to enhance sweetness without adding calories.

7.3 Nutraceuticals and Pharmaceuticals

Due to their biological activities, mogrosides are used in dietary supplements and therapeutic formulations. Additionally, monk fruit extracts have been recognized as Generally Recognized as Safe (GRAS) ingredients, further supporting their commercial use (Zhang et al., 2025).

VIII. LIMITATIONS AND SAFETY CONSIDERATIONS

Despite their benefits, mogrosides present certain challenges:

- Slight bitter or licorice-like aftertaste
- High extraction and production costs
- Limited large-scale cultivation

Recent studies also suggest that excessive exposure may influence intestinal epithelial function, indicating the need for further safety evaluation (Shil et al., 2025).

IX. FUTURE PERSPECTIVES

Future research should focus on:

- Improving extraction and purification techniques
- Enhancing bioavailability and sensory properties
- Expanding applications in functional and plant-based foods
- Conducting long-term clinical studies to confirm safety and efficacy
- Developing cost-effective production methods through biotechnology
- Exploring synergistic effects with other natural compounds

Advancements in biotechnology and enzymatic synthesis may further enhance the commercial viability of mogrosides.

X. CONCLUSION

Mogrosides, particularly mogroside V, represent a promising class of natural, high-intensity sweeteners with multifunctional health benefits. Their unique combination of sweetness, stability, and therapeutic potential makes them suitable for modern food and nutraceutical applications. Continued research and technological advancements are essential to overcome current limitations and fully exploit their industrial potential

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Cui, S., Zhang, S., Wang, N., Su, X., Luo, Z., Ma, X., & Li, M. (2024). Structural insights into the catalytic selectivity of glycosyltransferase SgUGT94-289-3 towards mogrosides. *Nature Communications*, *15*(1), 6423.

[2] He, Y. L., Hu, P., Xia, H. L., Gong, Y. X., Feng, W. T., Deng, L. R., & Zeng, Y. J. (2025). Mogroside V: Molecular mechanisms and therapeutic applications. *Phytomedicine*, Article 157250.

[3] Lu, R., Hu, J., Liu, X., Yu, L., Hu, J., Jiang, H., & Liang, X. (2023). Mogroside-rich extract from *Siraitia grosvenorii* fruits protects against heat stress-induced intestinal damage by ameliorating oxidative stress and inflammation in mice. *Food & Function*, *14*(2), 1238-1247.

[4] Pei, J., Su, Q., Jiang, S., Li, J., & Xie, N. (2025). Exploring the structural diversity and spatiotemporal dynamics of mogrosides in *Siraitia grosvenorii*. *Food Chemistry*, Article 146185.

[5] Shil, A., Amoakohene, O., & Chichger, H. (2025). The non-synthetic sweeteners, miraculin and mogroside V, but not stevia, disrupt the intestinal epithelial barrier function through a sweet taste receptor-dependent mechanism. *Scientific Reports*, *15*(1), 44861.

[6] Tang, Q., Qiu, R., Guo, M., Wang, L., Zhang, Y., Chen, Y., & Cheng, Y. (2024). Mogroside V and mogrol: Unveiling the neuroprotective and metabolic regulatory roles of *Siraitia grosvenorii* in Parkinson's disease. *Frontiers in Pharmacology*, *15*, 1413520.

[7] Zhang, T., Gao, Z., Zeng, D., & Wang, Y. (2025). Mogroside V: A review of its structure, synthesis, pharmacokinetics, and toxicity. *Archiv der Pharmazie*, *358*(10), e70112.

[8] Zhang, Z., Adiham, A., Han, C., Huang, F., Yan, Y., Li, D., & Gong, P. (2025). Mogroside V derived from *Siraitia grosvenorii* fruit: From evidence of health-promoting benefits to food applications. *Trends in Food Science & Technology*, *163*, 105141.

[9] Zhao, M., Lai, D., Jia, X., Yu, M., Liu, Z. Q., & Zheng, Y. G. (2025). UDP-glycosyltransferases engineering coupled with UDPG regeneration facilitate the efficient conversion of mogroside V. *Journal of Agricultural and Food Chemistry*, *73*(9), 5341-5352.

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Botanical Acaricides for Sustainable Management of Two-Spotted Spider Mite (*Tetranychus urticae* Koch) in Okra: Current Status and Future Perspectives

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Abstract— *The two-spotted spider mite,* Tetranychus urticae *Koch, has become an important constraint in okra cultivation due to its ability to multiply rapidly and cause serious damage to foliage. Infestation often results in reduced photosynthetic activity, poor plant vigour, and significant losses in yield and marketable quality, particularly under warm and dry conditions. Continuous reliance on synthetic acaricides has resulted in several challenges, including resistance development, pesticide residues, resurgence of pest populations, and adverse effects on beneficial organisms. These concerns have encouraged researchers to explore environmentally safer alternatives for mite management.*

This review critically examines published information on plant-derived acaricides and their potential role in managing T. urticae in okra-based production systems. Findings from studies conducted in India and other countries indicate that neem-based products, garlic-chilli extracts, karanja oil, tulsi extracts, and several essential oils possess significant acaricidal, repellent, and growth-regulating properties. Evidence generated from field investigations conducted under the doctoral research programme of Singh at Banaras Hindu University, Varanasi, indicated that NSKE 5%, azadirachtin 0.03%, and neem oil were among the most promising botanical options for suppressing Tetranychus urticae *populations under field conditions. Unlike many conventional acaricides that primarily target a single physiological pathway, botanical products influence mite populations through several complementary mechanisms, including direct toxicity, feeding inhibition, reproductive suppression, interference with growth and development, reduction in fecundity, and oviposition deterrence. Their comparatively lower toxicity to natural enemies enhances their suitability for incorporation into integrated pest management programmes. Although several promising results have been reported, challenges related to formulation standardisation, field persistence, and large-scale adoption still need to be addressed. Future efforts should focus on improving formulation technology, validating performance across diverse agro-climatic conditions, and promoting farmer awareness. Overall, botanical acaricides offer a promising component of sustainable and residue-conscious mite management strategies in okra cultivation.*

Keywords— Tetranychus urticae Koch, botanical acaricides, neem-based pesticides, integrated pest management, okra, two-spotted spider mite, azadirachtin, NSKE, biopesticides, Abelmoschus esculentus.

I. INTRODUCTION

Okra (*Abelmoschus esculentus* L. Moench) is widely cultivated across tropical and subtropical regions and serves as an important vegetable crop for both nutritional security and farm income generation. India occupies a leading position in global okra production, and the crop contributes significantly to nutritional security and farm income. Despite its economic importance, okra productivity is often constrained by a range of insect and mite pests that reduce both yield and market quality.

Among the arthropod pests associated with okra, the two-spotted spider mite, *Tetranychus urticae* Koch, is increasingly recognized as a key production constraint in several agro-climatic regions. The mite is highly polyphagous and capable of infesting a large number of cultivated and wild host plants. Feeding by mites causes chlorotic speckling, leaf bronzing, premature leaf drop, and reduction in photosynthetic activity. Under severe infestation, substantial yield losses have been reported in susceptible cultivars.

Management of *T. urticae* has traditionally depended on synthetic acaricides because of their rapid action and immediate suppression of mite populations. However, repeated use of these chemicals has resulted in resistance development, residue accumulation, destruction of natural enemies, and occasional pest resurgence. Increasing concerns regarding environmental safety and sustainable crop protection have therefore encouraged the search for alternative management approaches.

Growing concerns regarding pesticide resistance and environmental safety have renewed interest in botanically derived pest-management products as viable alternatives or complementary tools to conventional acaricides. Plant-derived products contain diverse bioactive compounds that can affect mites through multiple physiological and behavioural mechanisms. Their biodegradable nature and relative safety to beneficial organisms make them attractive candidates for integration into IPM programmes. The present review aims to summarise current knowledge on botanical acaricides used against *T. urticae*, discuss their modes of action and field performance, and identify future research priorities for sustainable mite management in okra.

In recent years, increasing concerns regarding pesticide residues, resistance development, environmental contamination, and consumer demand for safer food products have accelerated global interest in botanical pesticides and bio-rational pest management approaches. Botanical acaricides are therefore gaining renewed attention as sustainable alternatives for managing spider mite infestations in vegetable crops.

II. TAXONOMY, BIOLOGY AND LIFE CYCLE

T. urticae Koch, 1836 belongs to Arachnida: Trombidiformes: Tetranychidae. The species is identified by its characteristic pair of dark lateral spots on the abdomen of adult females. Molecular COI barcoding now provides reliable species-level identification across geographically diverse populations (Navajas et al., 2013). In India, both *T. urticae* and the closely related *T. neocaledonicus* Andre have been reported infesting okra. Documented differential infestation by *T. neocaledonicus* across seven okra lines/cultivars at R.A.U. Pusa, with Arka Anamika and D-1-87-5 showing the least susceptibility.

The life cycle consists of egg, larva, protonymph, deutonymph, and adult, completing in 7–14 days at 25–30°C and 40–60% RH. On susceptible okra entry Mahyco 10, the total immature development period was only 10 days, compared to 19.8 days on the resistant Kasturi bhendi. Fecundity on susceptible hosts reached 77.1 eggs/female versus 41.5 eggs/female on resistant entries. The doctoral research of Singh (2017) further demonstrated that among 16 okra varieties screened (2013–2015), Kashi Lalima recorded the lowest mean mite population (56.89 per leaf area), while Varsha Uphar recorded the highest (89.90), and trichome density showed a significant negative correlation (r = –0.71) with mite population.

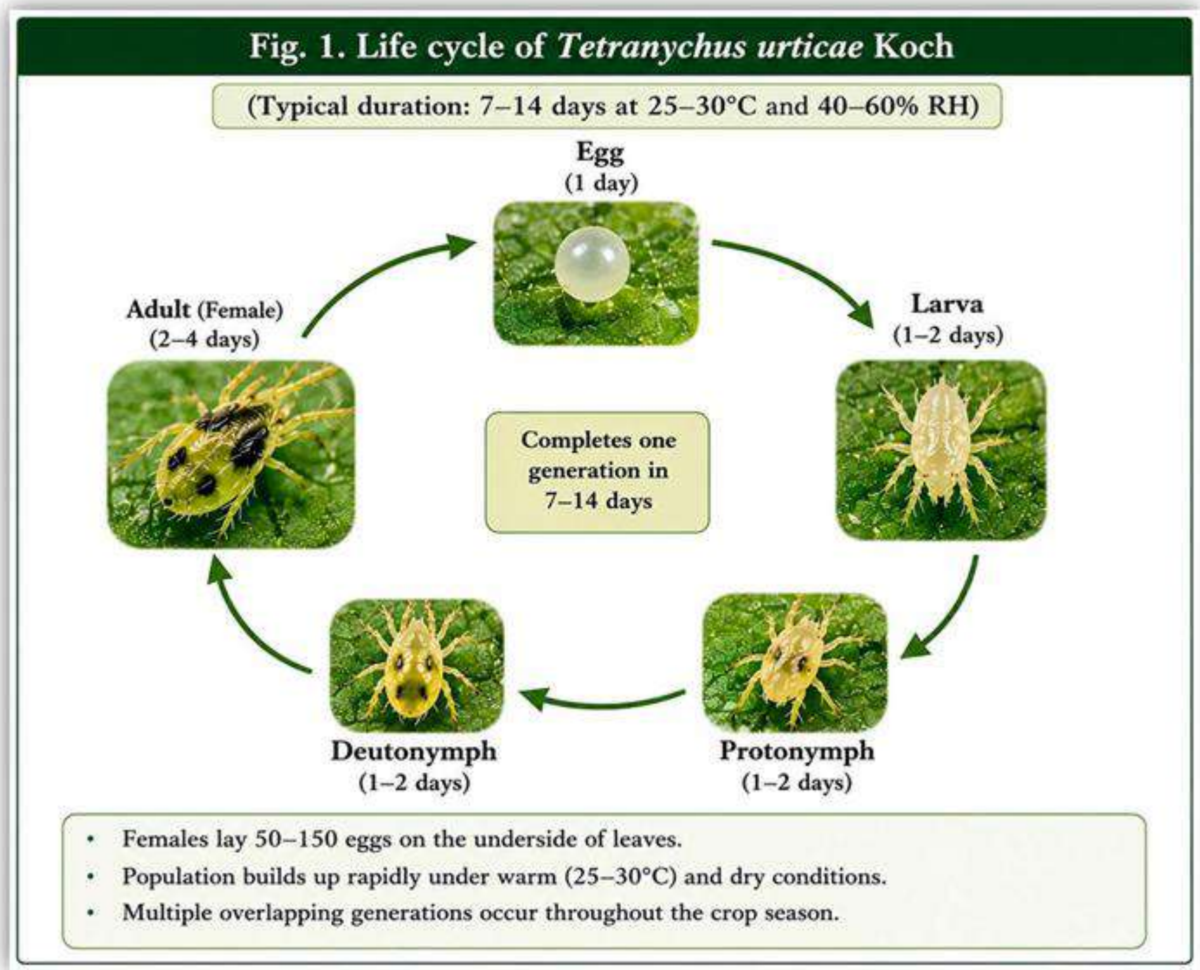

FIGURE 1: Life cycle of *Tetranychus urticae* Koch showing egg, larva, protonymph, deutonymph, and adult stages. The life cycle is completed in 7–14 days at 25–30°C and 40–60% RH.

III. DISTRIBUTION, HOST RANGE AND ECONOMIC DAMAGE

The two-spotted spider mite is among the most widely distributed mite pests in the world and has been reported from nearly all major agricultural regions, except Antarctica. Minhajul-Haque et al. (2011) recorded it on 20 vegetable and 24 ornamental plant species in Rajshahi, Bangladesh, including okra, cucumber, brinjal, tomato, and cowpea, with peak populations in August correlating directly with rising temperatures. Hoque et al. (2010) documented the highest *T. urticae* populations on lady's finger (174.35 per leaf) in August, compared to bean and eggplant, in Bangladesh.

Feeding injury results from the mite puncturing leaf tissues and extracting cellular contents, leading to progressive deterioration of leaf health and physiological activity. Park and Lee (2002) quantified that at 1,000 mite-days per 6 cm^2 leaf area, net photosynthesis was reduced by ~50–95% and total chlorophyll by ~55–80%. Findings from the doctoral investigations of Singh at Banaras Hindu University indicated that spider mite infestation significantly altered the biochemical composition of okra leaves, resulting in reductions in nitrogen, phosphorus, potassium, and micronutrient contents across susceptible genotypes. In Panjab-7, phosphorus loss of 0.23% in Punjab Padmini, potassium loss up to 0.72% in Azad Bhindi-2, and zinc content decrease of 39.51% in Azad Bhindi-1, among the 16 varieties evaluated. Documented yield losses of 7–48 percent in okra make *T. urticae* one of the most yield-limiting biotic stresses in warm-season okra cultivation.

TABLE 1
SELECTED HOST PLANTS OF *TETRANYCHUS URTICAE* KOCH

Host (Common Name)	Scientific Name	Reference
Okra / Lady's finger	*Abelmoschus esculentus*	Kumar et al. (2014); Geroh (2007)
Brinjal / Eggplant	*Solanum melongena*	Abou-Zaid et al. (2012); Siddiqui & Singh (2006)
Cucumber	*Cucumis sativus*	Park & Lee (2002); El-Adawy & El-Esnawy (2005)
Bean	*Phaseolus vulgaris*	Hoque et al. (2010); Gatarayiha et al. (2012)
Tomato	*Solanum lycopersicum*	Knapp et al. (2003); Makundi & Kashenge (2002)
Rose	*Rosa* spp.	Kumar & Shelke (2009); Singh et al. (2006)
Cotton	*Gossypium hirsutum*	Muhammad et al. (2012)
Strawberry	*Fragaria × ananassa*	Serce & Hancock (2002); Bernardi et al. (2013)
Grapevine	*Vitis vinifera*	Sivritepe et al. (2009)
Cowpea, Spinach	*Vigna unguiculata*, *Spinacia oleracea*	Minhajul-Haque et al. (2011)

IV. ECOLOGY AND POPULATION DYNAMICS

Abiotic factors exercise a decisive influence on *T. urticae* population dynamics. Kumar et al. (2014) monitored populations on okra at Varanasi during 2010–2011 and found peak populations at the 21st standard week (47.75 mites/2.5 cm² leaf) in 2010 and the 18th standard week (45.99) in 2011. Mean temperature and sunshine hours were positively correlated, while relative humidity and rainfall showed negative correlation with mite density. Geroh and Gulati (2007) documented bimodal population peaks on okra at Hisar during June (25.69 mites/cm² leaf) and August (22.50 mites/cm² leaf) in summer–Kharif 2006–07, with *T. urticae* positively correlated with temperature ($r = 0.60–0.78$) and negatively with humidity ($r = –0.39$).

Rising global temperatures driven by climate change are expected to accelerate mite development cycles, expand geographic ranges, and intensify outbreak frequency. Prolonged dry spells increasingly common in the Indo-Gangetic Plain create conditions particularly favourable for rapid population buildup, compounding the urgency of developing climate-resilient botanical acaricide-based IPM strategies.

V. SYNTHETIC ACARICIDES: EFFICACY AND LIMITATIONS

Synthetic acaricides have delivered effective short-term suppression of *T. urticae*. Rai and Singh (2008) recorded dicofol (92.55%), abamectin (88.44%), propargite (82.66%), and ethion (72.44%) as top performers on okra at Varanasi. Field investigations conducted during the doctoral research of Singh at Banaras Hindu University demonstrated that clofentazine and cyflumetofen were among the most effective acaricides against *T. urticae* under field conditions. However, these gains come at substantial ecological and toxicological costs.

Resistance development is the foremost concern: Kim et al. (1995) found 23-fold dicofol resistance in *T. urticae* maintained for one year without selection pressure. Sokeli et al. (2007) reported resistance ratios of 2.3–40.2-fold for chlorpyrifos in Turkish apple orchard populations. Resurgence is a related problem: Kumar and Singh (2002) confirmed that phosphamidon, fluvalinate, fenvalerate, dimethoate, and monocrotophos caused resurgence of spider mites on okra at BHU, whereas Clofentazine (–21.34%), Cyflumetofen (–15.94%), Fenpyroximate (–10.01%) and Propargite (–5.46%) did not induce resurgence in the doctoral investigations of Singh (2017). Singh and Singh (2005) demonstrated at Varanasi that dicofol and monocrotophos caused maximum mortality to the predatory mite *Amblyseius longispinosus*, whereas azadirachtin and sulfur recorded minimum predatory mite mortality, confirming differential selectivity.

VI. BOTANICAL ACARICIDES: CONCEPT AND MAJOR SOURCES

Botanical acaricides are plant-derived preparations comprising crude extracts, essential oils, or purified phytochemicals with acaricidal, repellent, antifeedant, growth-disruptive, or oviposition-deterrent properties. Ignacimuthu et al. (2008) emphasised that they are environment-friendly, economical, target-specific, and easily biodegradable. Ashok et al. (2010) noted that attention has shifted globally toward plant products as 'green pesticides' owing to their non-phytotoxicity, systemicity, easy biodegradability, and stimulatory potential for host plant metabolism. Several plant families, particularly Meliaceae, Fabaceae, Asteraceae, and Lamiaceae, are rich sources of acaricidally active secondary metabolites including terpenoids, alkaloids, phenolics, and volatile oils.

6.1 *Azadirachta indica* (Neem)

Neem remains the most researched and deployed botanical acaricide. Its primary active compound azadirachtin interferes with ecdysone-mediated moulting, inhibits feeding, and deters oviposition. Mironova and Khorkhordin (1997) confirmed that NeemAzal T/S at 0.5% caused 100% adult and nymph mortality of *T. urticae* on fig leaves, and all concentrations (0.1, 0.3, 0.5%) significantly reduced reproductive capacity. Knapp and Kashenge (2003) found that Neemroc EC achieved 78.3% adult mortality with an LC50 of 12.9 ml/l on tomato leaf discs, and all neem formulations caused repellence and oviposition deterrence. Mani et al. (2003) reported that 1,500 ppm azadirachtin caused 50% TSM mortality on okra (cv. Arka Anamika) at Varanasi, while neem oil and NSKE caused up to 30% mortality. The BHU multi-year field results (Singh, 2017) are the most comprehensive Indian okra data available: NSKE 5% achieved 50.84%, azadirachtin 0.03% achieved 49.53%, and neem oil 0.03% achieved 44.60% pooled reduction across two crop seasons. Martinez-Villar et al. (2005) demonstrated sublethal effects at 80 ppm—50% reduction in survival to adulthood and an almost eightfold reduction in fecundity.

6.2 *Pongamia pinnata* (Karanja)

Karanja oil from *Pongamia pinnata* (syn. *Millettia pinnata*) contains karanjin and pongamol as principal acaricidal furanoflavonoids. Mani et al. (2003) evaluated pungum (*Pongamia*) oil at recommended dose against TSM on okra at Varanasi, recording up to 30% mortality—comparable to neem oil. Kumar et al. (2002) observed some mite resurgence following pungum oil application on okra at BHU, suggesting the need for tank mixtures with complementary agents.

6.3 Garlic, Chilli, and Indigenous Organic Preparations

Chandrashekharaiah et al. (2011) evaluated six indigenous products used by organic farmers in Southern Karnataka against *T. urticae* in laboratory bioassays. Chilli plus garlic extract at 10% concentration produced the highest acaricidal activity of all indigenous materials tested—93.91% larval and 65.60% adult mortality—exceeding even the neem seed kernel plus *Calotropis* plus *Aloe vera* combination (87.23% larval, 71.70% adult). Cow urine at 10% caused 43.50% adult mortality, while all materials showed very low ovicidal activity. These results validate the traditional use of garlic-chilli preparations in organic okra cultivation.

6.4 *Ocimum tenuiflorum* (Tulsi)

Kumar et al. (2009) incorporated *O. tenuiflorum* leaf extract (10% aqueous) as a foliar spray in combination with FYM and entomopathogenic fungi on aubergine in Tamil Nadu. FYM at 25 t/ha + *O. tenuiflorum* at 10% achieved 71.66% mite reduction and 63.40% egg reduction over untreated control, with a cost-benefit ratio of 1:3.07 demonstrating economic viability for smallholder organic production systems.

6.5 Plant Extract Screening Studies

Yanar et al. (2011) evaluated crude methanol extracts of 12 plant species against *T. urticae* in controlled bioassays and found that *Lolium perenne* (flower/leaf), *Anthemis vulgaris* (flower), and *Chenopodium album* (flower/leaf) extracts exhibited significantly higher mortality than azadirachtin (10 g/L) and synthetic pesticides at 5% concentration. Ahn et al. (2008) screened 39 aquatic plant extracts and reported *Trapa japonica*, *Rotala* sp., and *Astragalus sinicus* caused 80–97% mortality of *T. urticae*. Dimetry et al. (1993) confirmed that neem seed kernel extracts showed biological activity against *T. urticae*, with pentane extraction producing more potent preparations than aqueous or cold-pressed oil extracts (Sanguanpong & Schmutterer, 1992). Abo-El-Ghar et al. (1986) were among the early workers to screen plant extracts against *T. urticae* in Egypt, reporting significant toxicity of several botanical extracts.

TABLE 2
MAJOR BOTANICAL ACARICIDES EVALUATED AGAINST *TETRANYCHUS URTICAE* KOCH ON OKRA

Botanical Source	Active Compound(s)	Dose / Conc.	Efficacy (%)	Reference
A. indica – NSKE	Azadirachtin, Nimbin	5% (field)	50.84 (mite reduction)	Singh (2017)
A. indica – Azadirachtin	Azadirachtin	0.03% (field)	49.53 (mite reduction)	Singh (2017)
A. indica – Neem oil	Azadirachtin, oils	0.03% (field)	44.60 (mite reduction)	Singh (2017)
NeemAzal T/S	Azadirachtin	0.50%	100% adult + nymph	Mironova & Khorkhordin (1997)
Neemroc EC	Azadirachtin + oil	Field rate	78.3% adult mortality	Knapp & Kashenge (2003)
Neem 1,500 ppm	Azadirachtin	1,500 ppm	50% TSM mortality	Mani et al. (2003)
Pongamia (Pungum oil)	Karanjin, Pongamol	Recommended	~30% mortality	Mani et al. (2003)
Garlic + Chilli 10%	Allicin, Capsaicin	10%	93.91% larval, 65.60% adult	Chandrashekharaiah et al. (2011)
NSKE + *Calotropis* mix	Mixed terpenoids	10%	87.23% larval, 71.70% adult	Chandrashekharaiah et al. (2011)
Ocimum tenuiflorum 10%	Eugenol	10% leaf extract	71.66% mite reduction	Kumar et al. (2009)
Capsicum annum 12%	Capsaicin	12% ethanolic	97% larval, 95% adult	Erdogan et al. (2010)
Lolium perenne/*Chenopodium*	Phenolics/Saponins	5% methanol	> Azadirachtin 10 g/L	Yanar et al. (2011)

VII. ESSENTIAL OILS AND ACARICIDAL ACTIVITY

Essential oils (EOs) are complex volatile mixtures predominantly monoterpenes, sesquiterpenes, and phenylpropanoids produced by aromatic plants as constitutive and induced defences. Their acaricidal mechanisms include acetylcholinesterase inhibition, octopamine receptor antagonism, spiracular blockage, and ovicidal penetration of the chorion (Isman, 2020). Key bioactive compounds include thymol, carvacrol, eugenol, 1,8-cineole, citral, limonene, and linalool.

Deka et al. (2011) demonstrated on cucumber that agricultural spray oil + azadirachtin (0.5–1%) caused the highest *T. urticae* mortality at 24, 48, and 72 hours post-spray in both laboratory and greenhouse trials, illustrating the synergistic value of oil-based botanical carrier systems. Yankova et al. (2009) confirmed that NeemAzal T/S 0.3% and Trilogy 1% (neem-based) showed very good efficacy against spider mites and greenhouse whitefly while maintaining low toxicity to the parasitoid *Encarsia formosa*, validating their suitability for biological vegetable production. Dimetry et al. (2008) reported laboratory evaluation of neem formulations with and without additive against *T. urticae*, confirming enhanced efficacy with oil-carrier combinations.

VIII. MODE OF ACTION OF BOTANICAL ACARICIDES

Unlike synthetic acaricides that typically have a single molecular target site, botanical acaricides deploy multiple overlapping mechanisms, which is their principal advantage in resistance management. The following modes have been documented against *T. urticae*:

- **Contact Toxicity** — Direct cuticle penetration by lipophilic terpenoids, oils, and alkaloids. NeemAzal T/S at 0.5% caused 100% adult contact mortality within 4 days on fig leaves (Mironova & Khorkhordin, 1997).
- **Growth Regulation** — Azadirachtin acts as an ecdysone antagonist disrupting the moulting hormone cascade. At 80 ppm, 50% of *T. urticae* failed to reach the adult stage (Martinez-Villar et al., 2005). The BHU laboratory study confirmed Clofentazine (ovicide) and Azadirachtin (growth regulator) as the top performers against egg and nymph stages respectively (Singh, 2017).
- **Reproductive Inhibition** — Azadirachtin at 64–128 ppm reduced *T. urticae* fecundity significantly, with mean fecundity reduced nearly eightfold in treated females (Martinez-Villar et al., 2005). Kumral and Susurluk (2007) demonstrated that azadirachtin reduced survival and fecundity of a pyrethroid-resistant *T. urticae* population.

- **Repellency and Antifeedancy** — Volatile compounds in garlic, chilli, and essential oils disrupt olfactory and contact chemosensory receptors. Knapp and Kashenge (2003) confirmed that all neem formulations caused repellence in *T. urticae* on tomato leaf discs.
- **Oviposition Deterrence** — Makundi and Kashenge (2002) demonstrated that neem formulations (except Neemros WP) showed strong ovipositional deterrence and suppressed nymph emergence on treated leaf discs. Sundaram (1996) reported AZ-A at sublethal concentrations reduced oviposition and caused growth disruption in *T. urticae* on aspen.

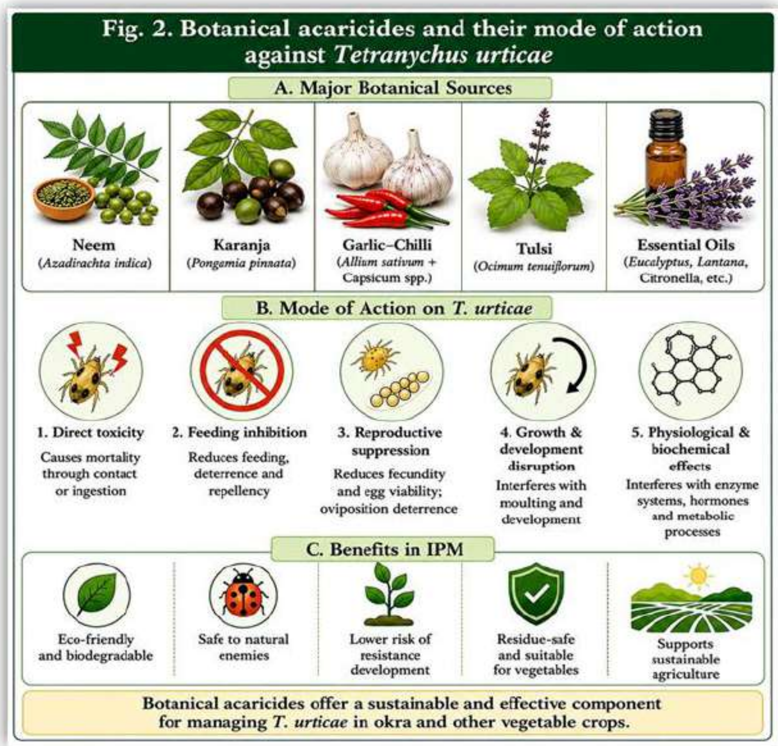

FIGURE 2: Schematic diagram illustrating the multiple modes of action of botanical acaricides against *Tetranychus urticae* Koch, including contact toxicity, growth regulation, reproductive inhibition, repellency, antifeedancy, and oviposition deterrence.

IX. COMPARATIVE EFFICACY: FIELD DATA FROM DOCTORAL INVESTIGATIONS (2013–2017)

The most comprehensive Indian field data on botanical acaricides for *T. urticae* management on okra comes from the multi-year doctoral investigations of Singh (2017) at BHU, Varanasi. Table 3 presents the pooled data from two years of field trials.

TABLE 3
POOLED EFFICACY OF ACARICIDES AGAINST *T. URTICAE* KOCH ON OKRA — BHU, 2013–15 (SINGH, 2017)

Treatment	Category	Pooled % Reduction	Category Rank
Clofentazine 50SC	Synthetic	91.62	1st (synthetic)
Cyflumetofen 20SC	Synthetic	82.52	2nd (synthetic)
Fenpyroximate 5EC	Synthetic	77.48	3rd (synthetic)
Propargite 57EC	Synthetic	72.05	4th (synthetic)
Dicofol 18.5EC	Synthetic	66.92	5th (synthetic)
NSKE 5%	Botanical	50.84	1st (botanical)
Azadirachtin 0.03%	Botanical	49.53	2nd (botanical)
Neem oil 0.03%	Botanical	44.6	3rd (botanical)
P. fumosoroseus (Dust)	Microbial	29.32	1st (microbial)
P. fumosoroseus (EC)	Microbial	22.37	2nd (microbial)
Water spray (control)	Control	11.63	—

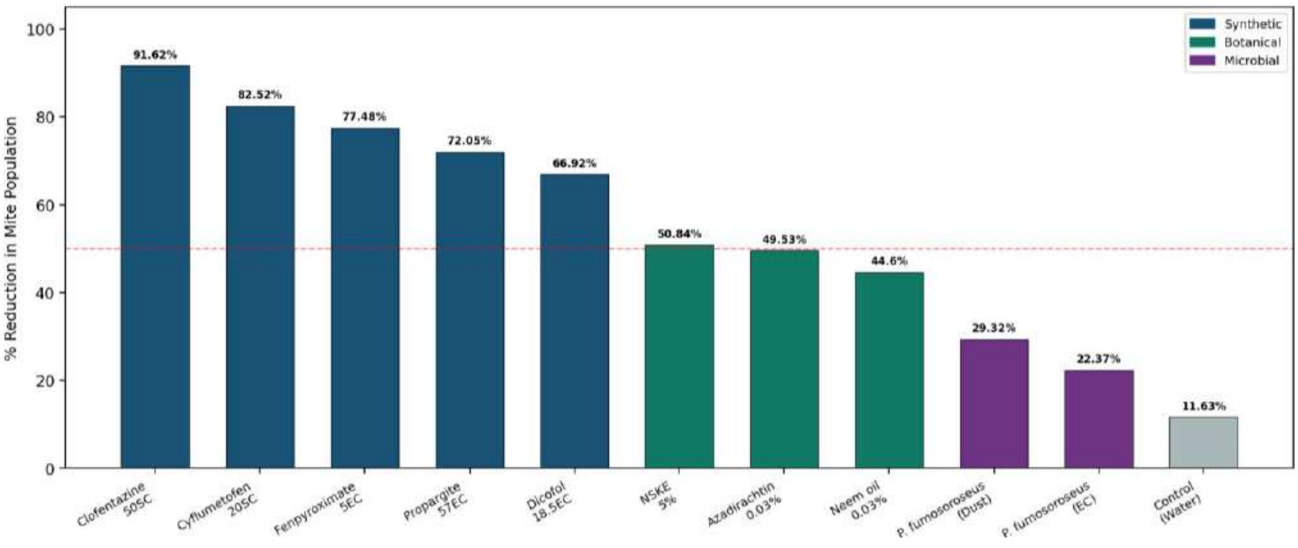

FIGURE 3: Comparative efficacy (% mite reduction) of synthetic, botanical and microbial acaricides against *T. urticae* Koch on okra

X. COMPATIBILITY WITH NATURAL ENEMIES

A decisive advantage of botanical acaricides within IPM is their comparatively low toxicity to natural enemies. Singh and Singh (2005) at Varanasi explicitly demonstrated that azadirachtin and wettable sulfur caused the minimum mortality to the predatory mite *Amblyseius longispinosus* on okra, whereas dicofol and monocrotophos caused maximum predatory mite mortality. This differential selectivity underpins botanical-predator compatibility in IPM frameworks.

Bernardi et al. (2013) demonstrated in Brazilian strawberry that azadirachtin (Azamax® 12 g L^{-1}) did not cause significant mortality in adult *Neoseiulus californicus* or *Phytoseiulus macropilis*, though fecundity was reduced 50%; critically, egg viability exceeded 80%, consistent with control. Azadirachtin's biological persistence (7 days) versus abamectin (21 days) further reduces selection pressure on beneficial arthropods. Abou-Zaid et al. (2012) reported that *P. persimilis* at predator:prey ratios of 1:5 and 1:10 caused 68.60% and 88.20% mean reduction in *T. urticae* respectively—an effect potentially augmented by concurrent sub-lethal botanical treatment. Yankova et al. (2009) confirmed NeemAzal T/S and Trilogy maintained low toxicity to *Encarsia formosa*, qualifying them for biological vegetable production systems.

XI. INTEGRATION WITHIN IPM FRAMEWORKS

Effective botanical-based IPM for okra *T. urticae* should integrate four pillars: (a) host plant resistance—moderately resistant varieties HRB-231, Kashi Sathdhari, Pant-A-4, Kashi Lalima, and Hisar Naveen identified in BHU multi-year screening (Singh, 2017); (b) biological control through conservation of phytoseiid mites and *Stethorus punctillum*; (c) strategic botanical acaricide applications during early or moderate infestations; and (d) judicious use of selective synthetic acaricides (clofentazine, cyflumetofen) only at economic threshold.

For organic okra production, NSKE 5% and azadirachtin 0.03% represent the most field-validated Indian options, achieving around 50% mite suppression with minimum natural enemy disruption (Singh, 2017). Kumar et al. (2009) confirmed CBR values of 1:3.07 for *O. tenuiflorum*-based treatments—economic viability comparable to chemical management. Singh and Singh (1999) demonstrated at Varanasi that azadirachtin 0.03% combined with dicofol at 3+2 ml/litre resulted in 100% mite mortality after 14 days, illustrating the potential of botanical-synthetic mixtures for transitional IPM programmes.

XII. NANOTECHNOLOGY AND FUTURE BOTANICAL FORMULATIONS

Conventional limitations of botanical acaricides—photodegradation, volatility, and inconsistent field performance—can be substantially addressed through nano-encapsulation. Chitosan-based nanoparticles loaded with azadirachtin have shown extended field half-life from 1–2 days to 5–7 days under UV exposure, critical for intense-sun summer okra production in northern India (Bhattacharyya et al., 2016). Nano-emulsions of essential oils in the 20–200 nm size range demonstrate enhanced cuticle penetration, improved rainfastness, and 3–5-fold reduction in effective concentrations compared to bulk formulations

(Isman, 2020). These advances open realistic pathways to botanical acaricides with field persistence and efficacy levels approaching synthetic standards.

XIII. CHALLENGES IN COMMERCIALISATION

Several barriers limit widespread adoption of botanical acaricides for Indian okra *T. urticae* management. The most critical is standardisation: commercial neem formulations vary widely in azadirachtin content (300–10,000 ppm), making dosage recommendations unreliable across brands (Knapp & Kashenge, 2003). Short shelf life due to UV and thermal instability, the regulatory burden of Central Insecticides Board and Registration Committee (CIBRC) registration, and farmer perception that botanicals are 'less effective' than synthetics all constrain market penetration. The moderate efficacy gap—44–51% for botanicals versus 67–92% for synthetics in BHU field trials (Singh, 2017)—must be contextualised: within IPM, botanicals are one component of a multi-tactic system, not standalone chemical substitutes. Extension communication has a vital role in reframing this perception.

XIV. KNOWLEDGE GAPS AND FUTURE RESEARCH PRIORITIES

- Absence of multi-location, multi-year field efficacy data for botanical acaricides across diverse Indian agro-climatic zones (semi-arid Deccan, humid eastern India, and hot arid northwestern plains).
- No standardised bioassay protocol for botanical acaricide evaluation against *T. urticae* comparable to IRAC CM002 for chemical products.
- Synergistic or antagonistic interactions among phytochemical mixtures (neem + garlic; essential oil blends) remain largely uncharacterised using combination index analysis.
- Resistance monitoring in *T. urticae* populations exposed to long-term botanical acaricide use—particularly azadirachtin—has not been systematically carried out.
- Field-level nano-botanical formulation efficacy, phytotoxicity, and environmental fate under Indian conditions remain unvalidated.
- ICT-based and mobile-platform advisory tools for delivering botanical acaricide recommendations to smallholder okra farmers in real time are largely underdeveloped.

XV. CONCLUSION

The findings reviewed in this article indicate that *Tetranychus urticae* continues to be a major constraint to profitable okra cultivation in many production regions. The pest's rapid reproductive capacity, wide host range, and ability to develop resistance to pesticides make its management particularly challenging. Although synthetic acaricides remain effective in reducing mite populations, their long-term sustainability is limited by issues related to resistance, environmental contamination, and adverse effects on non-target organisms.

Evidence generated from laboratory and field studies demonstrates that several botanical products, particularly neem-based formulations, possess significant potential for suppressing spider mite populations. Results obtained from multi-year field investigations at BHU, Varanasi, further support the usefulness of NSKE, azadirachtin, and neem oil as practical management options. In addition to direct toxicity, these products influence mite behaviour, growth, reproduction, and feeding activity, thereby contributing to population suppression through multiple pathways.

Botanical acaricides should not be viewed as complete replacements for synthetic acaricides but rather as important components of an integrated pest management strategy. Their compatibility with biological control agents and lower environmental impact provide clear advantages in sustainable crop production systems. Future research should focus on improving formulation stability, enhancing field persistence, standardising quality parameters, and validating efficacy under different agro-climatic conditions. Strengthening extension efforts and increasing farmer awareness will also be important for promoting wider adoption. With continued scientific refinement and field validation, botanical acaricides can contribute substantially to environmentally responsible and climate-resilient management of spider mites in okra.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The authors alone are responsible for the content and writing of this article.

REFERENCES

[1] Abo-El-Ghar, G. E., El-Sheikh, A. E., & Osman, A. A. (1986). Toxicity of some plant extracts on the two-spotted spider mite, *Tetranychus urticae* Koch (Acarina: Tetranychidae) in Egypt. *Menofia Journal of Agricultural Research*, *11*, 1003-1010.

[2] Abou-Zaid, A. M. M., Bakr, E. M., Yassin, S. A., & Hameed, N. A. A. (2012). Abundance of three sap sucking pests on three eggplant cultivars with utilization of *Phytoseiulus persimilis* against *Tetranychus urticae* Koch. *Acarines*, *6*, 49-53.

[3] Ahn, J. K., Park, H. Y., Hwang, S. J., Kong, D. S., Chun, S. C., & Khanh, T. D. (2008). Screening of aquatic plant extracts for herbicidal, fungicidal and insecticidal activity. *Allelopathy Journal*, *21*(2), 361-372.

[4] Bernardi, D., Botton, M., da Silva Cunha, U., Bernardi, O., Malausa, T., Garcia, M. S., & Nava, D. E. (2013). Effects of azadirachtin on *Tetranychus urticae* and its compatibility with predatory mites on strawberry. *Pest Management Science*, *69*(1), 75-80.

[5] Bhattacharyya, A., Bhaumik, A., Rani, P. U., Patra, S., & Mohapatra, T. (2016). Nanoparticles: A recent approach to insect pest control. *African Journal of Biotechnology*, *9*(24), 3489-3493.

[6] Chandrashekharaiah, M., Mohite, P. B., & Manjunatha, M. (2011). Acaricidal properties of indigenous products used by organic farmers in Southern Karnataka against *Tetranychus urticae* Koch. *Mysore Journal of Agricultural Sciences*, *45*(2), 415-420.

[7] Deka, S., Tanwar, R. K., Sumitha, R., Sabir, N., Bambawale, O. M., & Singh, B. (2011). Relative efficacy of agricultural spray oil and azadirachtin against two-spotted spider mite on cucumber under greenhouse and laboratory conditions. *Indian Journal of Agricultural Sciences*, *81*(2), 158-162.

[8] Dimetry, N. Z., Amer, S. A. A., & Reda, A. S. (1993). Biological activity of two neem seed kernel extracts against the two-spotted spider mite. *Journal of Applied Entomology*, *116*(3), 308-312.

[9] Dimetry, N. Z., Amer, S. A. A., & Saber, S. A. (2008). Laboratory evaluation of neem formulations with and without additive against *Tetranychus urticae* Koch. *Acarologia*, *48*(3/4), 171-176.

[10] FAO. (2022). *FAOSTAT: Crops and livestock products*. Food and Agriculture Organization of the United Nations.

[11] Geroh, M. (2007). *Ecology and management of Tetranychus urticae Koch on okra, Abelmoschus esculentus L.* [Ph.D. thesis, CCS Haryana Agricultural University].

[12] Hoque, M. F., Khalequzzaman, M., & Islam, W. (2010). Population dynamics of *Tetranychus urticae* Koch and *Phytoseiulus persimilis* on three host plants. *Pakistan Entomologist*, *32*(1), 6-11.

[13] Ignacimuthu, S., Vendan, S. E., & Goel, S. C. (2008). Botanical pesticides in insect pest management. In *Emerging trends of researches in insect pest management and environmental safety* (pp. 141-154).

[14] Isman, M. B. (2020). Botanical insecticides in the twenty-first century: Fulfilling their promise? *Annual Review of Entomology*, *65*, 233-249. https://doi.org/10.1146/annurev-ento-011019-025010

[15] Kim, G. H., Song, C., Chang, B. Y., Park, N. J., & Cho, K. Y. (1995). Stability of dicofol resistance in the two-spotted spider mite, *Tetranychus urticae* Koch. *Korean Journal of Applied Entomology*, *34*(1), 61-64.

[16] Knapp, M., & Kashenge, S. S. (2003). Effects of different neem formulations on the two-spotted spider mite, *Tetranychus urticae* Koch on tomato. *Insect Science and its Application*, *23*(1), 1-7.

[17] Kumar, D., Raghuraman, M., Singh, R. N., Santeswari, & Singh, J. (2014). Effect of environmental factors on the population of spider mite *Tetranychus urticae* Koch on okra in Varanasi region. *The Ecoscan*, *6*(S), 231-235.

[18] Kumar, S., & Singh, R. N. (2002). Effect of different insecticides/acaricides on the spider mite *Tetranychus urticae* on okra and resurgence. *Indian Journal of Entomology*, *64*(4), 434-439.

[19] Kumar, S. V., Chinniah, C., Muthiah, C., & Sadasakthi, A. (2009). Biorationals in the management of two-spotted spider mite *Tetranychus urticae* Koch in brinjal. *Karnataka Journal of Agricultural Sciences*, *22*(3), 682-684.

[20] Mani, C., Kumar, S., & Singh, R. N. (2003). Efficacy of acaricides and botanicals against two-spotted spider mite *Tetranychus urticae* Koch on okra. *Annals of Plant Protection Sciences*, *11*(1), 153-154.

[21] Martinez-Villar, E., Saenz-De-Cabezon, F. J., Moreno-Grijalba, F., Marco, V., & Perez-Moreno, I. (2005). Effects of azadirachtin on the two-spotted spider mite, *Tetranychus urticae*. *Experimental and Applied Acarology*, *35*, 215-222.

[22] Minhajul-Haque, M., Tamanna-Islam, N., Naher, N., & Haque, M. M. (2011). Seasonal abundance of spider mite *Tetranychus urticae* Koch on vegetable and ornamental plants in Rajshahi. *University Journal of Zoology*, *30*, 37-40.

[23] Navajas, M., de Moraes, G. J., & Auger, P. (2013). New invasive *Tetranychus urticae* Koch: Risks and opportunities of genomic data. *Experimental and Applied Acarology*, *59*, 1-14.

[24] Park, Y. L., & Lee, J. H. (2002). Leaf damage and tissue damage of cucumber caused by two-spotted spider mite. *Journal of Economic Entomology*, *95*(5), 952-957.

[25] Pavela, R., Benelli, G., & Maggi, F. (2021). *Petroselinum crispum* essential oil and its main compounds: A sustainable tool for pest management. *Industrial Crops and Products*, *161*, Article 113194. https://doi.org/10.1016/j.indcrop.2020.113194

[26] Rai, S. N., & Singh, J. (2008). Efficacy of some acaricides/insecticides against *Tetranychus urticae* Koch on okra. *Indian Journal of Entomology*, *70*(2), 169-171.

[27] Singh, R. N., & Singh, J. (1999). Effect of azadirachtin and some conventional acaricides against two-spotted spider mite, *Tetranychus urticae* Koch. *Shashpa*, *6*(1), 85-88.

[28] Singh, S. K. (2017). *Screening of okra varieties against two spotted spider mite, Tetranychus urticae Koch and its management* [Ph.D. thesis, Banaras Hindu University]. Shodhganga. http://hdl.handle.net/10603/275615

[29] Singh, S. P., & Singh, R. N. (2005). Efficacy of some pesticides against spider mite, *Tetranychus urticae* Koch and its predatory mite *Amblyseius longispinosus*. *Resistant Pest Management Newsletter*, *14*(2), 7-10.

[30] Sparks, T. C., Nauen, R., & IRAC. (2022). Insecticide resistance management and industry perspectives. *Pesticide Biochemistry and Physiology*, *186*, Article 105138. https://doi.org/10.1016/j.pestbp.2022.105138

[31] Yanar, D., Kadoglu, I., & Gokce, A. (2011). Acaricidal effects of different plant extracts on two-spotted spider mite. *African Journal of Biotechnology*, *10*(55), 11745-11750.

[32] Yankova, V., Masheva, S., Mateeva, A., Palagacheva, N., & Loginova, E. (2009). Biological activities of phytopesticides of *Azadirachta indica* towards some harmful and useful species. *Ecology and Future*, *8*(4), 26-29.

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African Natural and Man-Made Disasters: The Management of the Continent's Nemesis

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***Abstract*— *Disasters have been occurring since time immemorial and have significant economic and social impacts, causing direct damages and long-term economic losses requiring large fiscal outlays for reconstruction and recovery in Africa. This paper reviews the state of disaster management in Africa and how African countries can best strengthen their disaster preparedness and response capabilities. The review examines disasters that have occurred over the past five decades (1970–2023), including natural disasters (droughts, floods, cyclones, earthquakes, volcanoes, heatwaves, wildfires), man-made disasters (conflicts, insurgencies), and health emergencies (epidemics, pandemics, drug abuse). The research is based primarily on a qualitative literature review of secondary data sources, including journals, handbooks, working papers, government documents, and conference proceedings. The findings reveal that Africa faces a convergence of environmental, economic, and social vulnerabilities that reduce the capacity of individuals and communities to secure and protect their livelihoods. About 1,700 natural disasters have been reported in Africa over the past five decades, causing economic losses of approximately US$38.5 billion and over 750,000 deaths. The paper concludes that while disasters cannot be prevented, disaster management can be reinforced to reduce mortality and suffering. Strengthening early warning systems, enhancing institutional frameworks, promoting regional cooperation, and addressing underlying vulnerabilities are essential for building resilience and reducing disaster losses in Africa.*

Keywords*— *Africa, Climate change, Disaster occurrences, Disaster management, Pandemics, Conflicts, Drug abuse, Vulnerability, Resilience, Emergency management.

I. INTRODUCTION

This paper discusses the state of disaster management and how African countries can best strengthen their disaster preparedness and response capabilities. The paper reviews disasters that have taken place over the past five decades, covering the period from 1970 to 2023. Disasters have been occurring since time immemorial, but their impacts are being felt more acutely now than ever before [1]. Globally, the incidence of disasters appears to be increasing, and the number of vulnerable persons in disaster-prone areas, particularly in Africa, is also rising at alarming levels [2].

Disasters have significant economic and social impacts, causing direct damages to public and private property, resulting in short-term and long-term economic losses requiring large fiscal outlays for reconstruction and recovery, and further fueling the disaster risk and poverty nexus [3]. As societies have become more complex, it is evident that people are increasingly responsible, directly or indirectly, for the consequences of events previously ascribed to forces beyond their control [4].

Natural disasters include weather phenomena such as tropical storms, extreme heat or cold, winds, floods, earthquakes, and volcanic eruptions [4]. Disasters caused by humans include transportation accidents, industrial accidents, conflicts, and the collapse of poorly constructed buildings [4]. Reports state that the annual cost of natural disasters from 1980 to 2023 was approximately US$60.81 trillion annually [5]. According to reports in 2023, man-made disasters have caused economic damages worth approximately US$9 billion per annum [6].

II. BACKGROUND

The vulnerability of African countries to disasters is caused by a combination of environmental, economic, and social factors that negatively reduce the capacity of individuals to secure and protect their livelihoods [7]. Government assistance in such situations is often limited by already severe financial burdens, and recovery planning is often difficult. Consequently, only some national governments can assist all poor communities [2]. In 2022, the Emergency Event Database (EM-DAT) recorded 387 natural hazards and disasters worldwide, slightly higher than the average from 2002 to 2021, which was 370 [8]. The 2022 disasters resulted in the loss of 30,704 lives and affected 185 million individuals worldwide, and economic losses totaled approximately US$223.8 billion [8]. Heatwaves caused over 16,000 excess deaths in Europe, while droughts affected 88.9 million African people [8].

Disasters cause significant losses to crops by directly damaging or destroying them and indirectly disrupting markets, infrastructure, and supply chains, ultimately affecting livelihoods and food security [17]. Extreme weather events such as droughts and floods reduce crop yields and shrink harvested areas. Similarly, disasters pose significant threats to animals, resulting in death, injury, and habitat loss [2]. However, many species have developed adaptive strategies to survive, such as sensing impending danger or seeking shelter in safer areas [2]. The prevalence of disasters in African countries, especially droughts and famines, is attributed to poor planning compared to the European Union (EU) countries, where there is no risk of food shortages due to the well-established EU agricultural sector supported by the EU Common Agriculture Policy [9].

It is anticipated that between 1990 and 2019, Africa alone suffered at least 1,107 floods and droughts, leading to US$14 billion in damage to crops, livestock, and property [10]. In East Africa, the number of internally displaced populations is on the rise, with South Sudan leading with 281,000, Kenya 40,000, Tanzania 38,000, and Uganda 23,000 [11]. Terrorism is a new phenomenon on the continent currently fueled by the globalization of arms and trade and has contributed significantly to the escalation of conflicts in Africa [12].

III. PROBLEM STATEMENT

Disasters in Africa often take a significant toll on vulnerable populations consisting of more than 761.39 million people (the majority of whom live in makeshift accommodation), and the loss of life and livelihoods in the face of already existing challenges sets communities back, leaving them at risk when disasters occur [13]. African countries need more information to enable risk-informed decisions. While the magnitude and intensity of disasters are increasing in the region, the national capacity to systematically record disaster losses and damage is low [11].

About 1,700 natural disasters in Africa have been reported between 1970 and 2019, causing economic losses of around US$38.5 billion and causing over 750,000 deaths [14]. Africa's droughts significantly affect human health, destroy crops, and hurt other economic sectors like mining and electricity generation [15]. Human Immunodeficiency Virus/Acquired Immune Deficiency Syndrome (HIV/AIDS) in Africa is also one of the most significant humanitarian catastrophes and has killed millions of people and led to serious social problems, which include the growing number of orphans (for example, in South Africa 1.7 million, Mozambique 1.2 million, and 670,000 in Malawi) and economic consequences [16].

Outbreaks of diseases such as Ebola, yellow fever, anthrax, measles, malaria, and cholera have also been on the increase since 2000 [17]. Large-scale natural and human-made disasters cause severe destruction of lives and livelihoods by creating serious disorders and affecting people's social and economic well-being [18].

IV. METHODOLOGY

This research review seeks to highlight the management, or lack of management, of disasters (natural or man-made) in Africa. It examines various forms of disasters and their environmental, economic, and social impacts on the continent's population. This qualitative research review is based primarily on literature review from secondary data sources. Since the review is qualitative in nature, the research methods have been used to gather primarily non-numerical data and find meaning, opinions, and underlying reasons from various sources. It is based mainly on, concerned with, and verifiable by observation and experience. Theories on natural and man-made disasters and disaster management are scrutinized to confirm and understand statements and comments attributed to natural and man-made disasters.

The literature is drawn from journals, handbooks, working papers, published and unpublished theses, and publications from global scenarios of disaster occurrences and their manifestations, including conferences, seminars, and government documents drawn from Africa and the world. The paper defines perceptions of global disaster management, examines epidemics and pandemics (focusing on ways to manage them), and covers conflicts, cyclones, floods, droughts (including the El Niño phenomenon), wildfires, and drug abuse, leading to recommendations and conclusions.

V. LITERATURE REVIEW

5.1 Disasters

Disasters are defined as severe and aggressive damage to property, loss of lives, and disruptions that affect the functioning of a community and exceed its capacity to cope using its resources [19]. Disasters are caused by man-made, natural, and technological hazards, as well as various factors that influence the exposure and vulnerability of a community [19].

5.2 Emergency Management Theory

Emergency Management Theory is a disaster and risk management theory propounded by David McEntire, an American expert in emergency administration [20]. The theory was created to provide a realistic, proactive, and reactive paradigm for the management of disruptive and hazardous phenomena, especially after the insurgent attacks on the Pentagon and World Trade Centre in September 2001 [20]. The Emergency Management Theory suggests that disastrous emergencies are inevitable in society and tend to cause unrecoverable effects unless responsible, immediate, and urgent actions are taken to prevent, respond to, recover from, and mitigate these emergencies [20].

The Emergency Management Theory further states that unless these measures and the strategies for carrying them out are put in place, society is doomed to be marred by unrecoverable emergencies that will threaten its existence [20]. The theory also holds that if the human species and society do not want to be likened to extinct animal species, they should evolve proactive, reactive, and post-emergency measures and plans to prevent disastrous emergencies and their effects head-on [20]. Adopting measures should align with the nature of the disaster and conform to the essential principles of preparedness, response, recovery, and mitigation [20].

The measures to curb emergencies and their effects from destroying and ruining society should be taken before a disaster occurs in preparation for any eventuality of disastrous nature, and measures should be taken to eliminate, suppress, and minimize the effects of an already occurring disaster [20]. The measures should also be able to help disaster victims at the time of disaster occurrence in terms of disaster rescue and measures taken to normalize the area affected by the disaster and disaster-affected victims [20].

5.3 Disaster Management Cycle

Disaster management encompasses measures, programs, and activities that can be taken up before, during, and after a disaster to circumvent it, minimize its impact, or recover from its losses [21]. The three critical stages of activities taken up within disaster risk management include:

Pre-disaster: Activities taken during this stage are meant to minimize human and property losses caused by a potential hazard, and some of the initiatives include carrying out awareness campaigns, strengthening the existing weak structures, and preparing disaster management plans at household and community levels [21]. The measures taken under this stage are typically considered mitigation and preparedness activities.

Mitigation activities eradicate or diminish the chance of disaster occurrence or lessen the effects of inevitable disasters [22]. Mitigation largely depends on the integration of appropriate measures in regional and national development planning, and it largely depends on the readiness of information on emergency risks, hazards, and countermeasures to be taken [23].

In terms of preparedness, a well-prepared response is very effective, and preparedness addresses the strategy already in place that allows the implementation of a successful operational response [22]. The principle objective of emergency preparedness programs is to achieve an acceptable level of readiness to react to any emergency through programs that strengthen the managerial and technical capacity of governments, communities, and organizations [24].

During a disaster: During this stage, the plans taken are meant to ensure that the needs and provisions of the victims are met and that suffering is minimized. These activities are known as emergency response activities [21]. Emergency response mainly focuses on providing immediate assistance to improve health, maintain life, and support the confidence of the affected population [23]. The type of assistance under response initiatives includes the provision of temporary shelter, transport, and food to establish semi-permanent settlements in camps and other locations [25].

Post-disaster: These are activities taken as responses to a disaster. They are meant to ensure early recovery and rehabilitation of the affected communities just after a disaster strikes, and these activities are known as recovery activities [26]. Recovery activities continue until all systems become better or return to normal, and both short-term and long-term measures include temporary housing, returning vital life support systems to minimum operating standards, health and safety education, counseling programs, reconstruction, public information, and economic impact studies [23].

5.4 An Overview of Disasters in Africa

5.4.1 Epidemics and Pandemics

HIV/AIDS (Pandemic): HIV/AIDS is one of the biggest humanitarian disasters of our time. It has devastating social and economic implications and is still one of the most important societal challenges [16]. It is estimated that at least 25.5 million people living with the infection reside in Sub-Saharan Africa, and in 2016, there were 730,000 HIV/AIDS-related deaths in the region. The countries most affected by the epidemic include Botswana, Kenya, Lesotho, Malawi, Namibia, Nigeria, South Africa, Swaziland, and Zimbabwe [16]. South Africa is the hardest-hit country, with at least over 7 million people living with the virus.

It has been established that there are at least 1.7 million AIDS orphans in South Africa, 1.2 million children in Mozambique, and 670,000 children in Malawi, all of whom have lost one or both parents to the virus [16]. HIV/AIDS has resulted in the average life expectancy of many African countries decreasing, the number of people living below the poverty datum line increasing, loss of labor, reduction of production (especially in agriculture), rising health spending which weighs on public budgets, a decrease in tax revenues, and a reduction in economic growth [16].

COVID-19 (Pandemic): Another notable pandemic in Africa is COVID-19, which spread rapidly in March 2020 and claimed over 250,000 lives, with over 14 million cases recorded as of November 2022 in the region [27]. COVID-19 was a significant threat to many societies and economies, and this pandemic exposed inequality in health, economy, security, and social protection and intensified gender inequality in Africa [28]. Some health system challenges that COVID-19 intensified include the disruption of routine immunizations, diagnosis and treatment of other diseases, and maternal and child healthcare [29]. COVID-19 also intensified food insecurity in areas with conflicts or natural disasters, and tens of millions of people in African countries were pushed into extreme poverty by this pandemic [28].

Cholera (Epidemic): Cholera is also one of the epidemics ravaging African countries. It is an acute, extremely virulent infection that spreads rapidly and causes dehydration, which then results in high mortality and morbidity [30]. It is estimated that 26,000 cases and 660 deaths were reported as of 29 January 2023 in ten African countries facing the outbreak since the beginning of the year [31]. In 2022, nearly 80,000 cases and 1,863 deaths were recorded in 15 affected countries [31]. It is anticipated that if the fast current trend prevails, it could surpass the number of cases recorded in 2021, which was the worst year for cholera in Africa in nearly a decade [31]. Most cases were recorded in Malawi, Mozambique, and Zambia, and in East Africa, Ethiopia, Kenya, and Somalia were also affected [30].

Ebola (Epidemic): Ebola, a hemorrhagic fever caused by a virus, has affected African countries since its first appearance in 1976 in South Sudan and the Democratic Republic of Congo [32]. West African countries that were seriously affected by Ebola between 2014 and 2016 include Guinea, Liberia, and Sierra Leone. More than 28,000 cases were recorded, and more than 10,000 deaths and 10,000 survivors with after-effects [33]. It is estimated that the economic burden of the Ebola epidemic in West Africa ranges from US$2.8 billion to US$32.6 billion in GDP loss, and the overall economic and social burden of the 2014 Ebola epidemic has been estimated at US$53.19 billion [34].

5.4.2 Conflicts

According to [35], a conflict is best described in four ways, including antecedent conditions of conflictual behavior (such as scarcity of resources or policy differences), the affective states of individuals involved (such as tension and hostility), the cognitive state of individuals (referring to their perception or awareness of the conflictual situations), and lastly, the conflictual behavior ranging from passive resistance to over-aggression [35].

Conflicts in Africa are caused by several factors, such as arbitrary borders created by the colonial powers, corruption, poverty, climate change, and the heterogeneous ethnic composition of African states [36]. Conflicts primarily result in the displacement of people. It has been noted that the number of documented persons of concern from Africa, inclusive of internally displaced persons, asylum seekers, and refugees, has more than tripled, rising from 5 million in the 1980s to 18 million in 2017, with more intense conflicts generally implying larger displaced populations [37]. In 1994, over 1 million Tutsis were killed by the Rwandan government during the Rwandan genocide [37]. This disaster recorded the highest number of fatalities in Africa from any one-sided event recorded since 1989, as well as the most significant number of fatalities from any conflict event, regardless of the nature of the conflict [38].

Insurgency in Africa has been on the rise, and it is an evolving global problem and is one of the most intricate and demanding security challenges for the international community [39]. According to the Global Terrorism Index 2023 report, the Sahel region is now the epicenter of insurgency [40]. The report brings to light that at least 22,074 people have died in 6,408 insurgent attacks between 2007 and 2022 in Africa [40]. Most of the insurgent attacks, particularly in Burkina Faso, have been attributed to unknown insurgents. However, Daesh and Al Qaeda and Daesh/ISIS, which is linked to a group of Muslims, are also active [39]. Burkina Faso, Mali, and Niger, in particular, have experienced continued attacks from insurgents, and the Liptako-Gourma border area among the three countries remains highly volatile to insurgent threats [41].

One of the most prominent insurgent organizations in Africa is Boko Haram, which was established in Borno State, northern Nigeria, in 2002 as a domestic Islamic religious group [40]. The Boko Haram insurgency resorted to deadly violence due to differing religious ideologies in northern Nigeria as a tactic to counter non-Islamic ideology and influence the introduction of Sharia law [42]. Boko Haram has carried out more than 3,416 insurgent events since 2009, leading to more than 36,000 fatalities [43]. Boko Haram has been involved in sophisticated and diverse methods of warfare, and this has led to the mass forced displacement of over 2 million people who have crossed borders to other countries [43].

The Al-Shabaab insurgency has also considerably contributed to instability on the African continent and further polarized Somali society, which is already divided [40]. The Al-Shabaab insurgent group has remained a notorious group and creates severe security threats in Africa. The Al-Shabaab insurgent group is in charge of most rural parts of south and central Somalia, and the presence of this group has been felt in the country through intimidation and fear tactics [40]. Over 68 million civilians were displaced at the end of 2017 due to armed conflict between Al-Shabaab and the Somali army [40].

In Mozambique, the Cabo Delgado extremist insurgency known as Ansar Al-Sunna WaJamma (ASWJ) has been ongoing since October 2017 [44]. The alleged Jihadists targeted the Mozambican coastline and have carried out indiscriminate attacks in the Northern Province of Cabo Delgado, with the capture of coastal towns Mocimboa Da Praia in 2020 and Palma in 2021 being essential markers for the insurgents [44]. The intensive conflict, which has spanned more than five years, has resulted in 4,000 deaths and 800,000 internally displaced persons [45].

5.4.3 Cyclones and Floods

Climate change in Africa has led to increased rainfall associated with tropical cyclones [46]. Storm Daniel ravaged Libya in September 2023 and left more than 5,300 people dead as of 14 September 2023, and the death toll was expected to rise to 20,000 after heavy downpours hit eastern Libya [47]. The heavy rains accompanying Storm Daniel affected areas including Derna, Benghazi, and Tobruk, resulting in the collapse of two dams and sending waves more than 6 meters through the heart of Derna, leaving 10,000 missing and more than 7,000 wounded [48]. Most deaths could have been avoided if better warning systems had been in place [47].

The most damaging cyclones in Africa in the past few years include Cyclone Idai and Cyclone Kenneth, which hit Mozambique hard in March and April 2019 [46]. Cyclone Idai had more than 1,500 fatalities in Malawi, Mozambique, and Zimbabwe, and many more were missing [46]. In 2023, Cyclone Freddy hit Southern Africa and killed more than 500 people, mainly in Madagascar, Malawi, and Mozambique [49]. Cyclone Freddy lasted for more than a month, and it was recorded as the longest storm in history for its accumulated energy and cycles of intensification [49].

Flash flooding from heavy rains in Ethiopia and Somalia in 2023 killed dozens of people and affected more than 300,000 people [50]. The damaging flooding came after the East African region experienced almost three subsequent years of extreme drought [50]. In the Ethiopian Highlands, heavy rains overtopped the banks of the Shabelle and Juba rivers, and homes, schools, and health facilities were destroyed along the banks of the two rivers in Southern Somalia and Eastern Ethiopia, with more than 1,000 hectares of cropland destroyed [50].

Severe cyclones struck Madagascar, Malawi, and Mozambique in January and February 2022; these were Cyclone Ana and Cyclone Batsirai [51]. Cyclone Ana was characterized by strong winds and heavy rains and caused much damage and destruction to parts of Madagascar, Malawi, Mozambique, and Zimbabwe [51]. At least 21,000 people were affected by the cyclone, destroying schools and health centres in Mozambique [52]. Cyclone Batsirai followed, striking the south coast of

Madagascar, resulting in 94 deaths and affecting 116,000 people [53]. Mananjari was one of the towns in Madagascar that was severely affected by Cyclone Batsirai, where five health centres were destroyed, and rescue operations were complex to conduct since most roads were blocked [53].

In 2019, Cyclone Idai ravaged Madagascar, Malawi, Mozambique, and Zimbabwe; it brought strong winds and widespread flooding, which ripped apart roads, bridges, houses, schools, and health facilities and submerged large agricultural land [55]. In Zimbabwe, Cyclone Idai was characterized by flooding and landslides, which affected 270,000 people and left many people dead and others missing [54]. Chimanimani and Chipinge districts were the most affected, and roads and bridges collapsed, making the areas inaccessible. Cyclone Idai affected 840,000 people in Mozambique and 740,000 in Malawi [55].

5.4.4 El Niño Phenomenon and Droughts

El Niño phenomena cause unpredictable weather patterns to escalate in Southern and East Africa, which causes droughts [56]. El Niño refers to warming of the ocean surface or average sea surface temperatures in the central and eastern tropical Pacific Ocean [57]. The low-level surface winds, which generally blow from east to west along the equator (easterly winds), instead weaken or, in some cases, start blowing in the other direction from west to east (westerly winds) [57]. The El Niño phenomenon will mostly lead to reduced planted areas and delayed planting, resulting in depressed yields [58].

The most significant impact of El Niño events is mainly prevalent in Southern Africa, and its secondary impacts include a slowdown in agricultural and industrial activities, food insecurity, food price inflation (which will impact low-income households), limited water availability, and poor pasture conditions (which in turn affect livestock) [58]. Ethiopia is in the grips of its worst drought over the past five decades due to poor rainy seasons heightened by the effects of El Niño. As a result, crop failure and lack of rainfall directly impact 80% of the population who depend on agriculture for food and income [56]. In 2016, it was reported that 10.2 million people in Ethiopia required food aid, and 2.2 million cases of moderate acute malnutrition were predicted [56].

An estimated 5.8 million people needed emergency water supplies, and young children bore the cost of the crisis too, as schools were closing down, and most of them were missing school days to help their families fetch water [56]. In Malawi in 2016, a national disaster was declared because of drought and failed harvests, and it was estimated that at least 4 million people needed assistance to take them through to the following year [56]. Most families in Malawi were faced with severe food insecurity, and at least half of the children in Malawi were stunted due to malnutrition [56].

Mozambique recorded that over 1.5 million lives were threatened by hunger due to the drought experienced in 2016, and the government declared a state of national disaster [56]. This resulted from poor rainfall, which led to widespread crop failure and rising prices of staple food, thereby limiting access to food and leading to food insecurity. In Somalia, seasons of failed rains were exacerbated by the El Niño phenomenon, resulting in several droughts, and the situation reached emergency levels. Food security issues are a cause of concern in Somalia, and the prolonged dryness in Somaliland has resulted in livestock deaths and depleted water sources [56].

Harvey [59] perceives that at least 50 million people in the Horn of Africa are affected directly by drought, and another 100 million in the wider area. As families face acute food insecurity, many have left their homes in search of food, water, and pasture for animals [60]. At least 44 million people require assistance, and 180,000 refugees have fled Ethiopia, Kenya, Somalia, and South Sudan, which have been affected by drought; this has primarily been attributed to global heating, which has made the soil and pastures of the region much drier than they would usually be [61]. The more people are food insecure, the more they have limited choices between food and healthcare. Most of the time, nutritional deficiencies make them increasingly vulnerable to diseases [60]. A super El Niño is predicted in 2026/27.

5.4.5 Earthquakes

In Africa, seismicity is considered to be modest by world standards, and seismic activities tend to vary from region to region. That is, some regions are still considered to be aseismic, while others have witnessed disastrous seismic events [62]. Seismic events in seismic-prone regions are connected to tectonic activities, which affect the structure of the earth's crust, resulting in disturbances on the earth's surface [62]. The most outstanding tectonic feature on the continent is the East African rift system, one of the world's typical examples of continental rifts on land [63]. The rift system in Eastern Africa extends from the distant triangle of the Red Sea and Gulf of Eden through North Africa to Southern Africa. It is the bedrock of most seismic activities in the continent's northern, eastern, and southern parts [64].

A powerful earthquake struck Morocco's High Atlas Mountains on 9 September 2023, and it was recorded as the deadliest quake to hit the North African country in decades [65]. The earthquake measured 6.8 magnitudes on the Richter scale, and more than 2,000 people lost their lives, mainly in Marrakech and five provinces near the epicenter [66]. At least 2,059 people were injured, 1,404 critically, and the total toll was on the increase as rescuers struggled to bypass boulder-strewn roads to the remote mountain villages that were hit hardest [66].

In 1992, an earthquake occurred in Cairo (Egypt) and resulted in more than 500 human casualties, and there was massive damage to structures, including domestic settlements and historical monuments [67]. Algeria is also another country in Africa that experiences seismic activities [68]. In 2003, an earthquake of 6.8 magnitude on the Richter scale was recorded in the Bourmedes region, Central Algeria, and the impact was felt in Algiers, Tizi-Ouzou, Bouira, and Blida and as far as the Mediterranean Spanish Coast [68]. The earthquake was considered the worst in the history of the country, and there were over 2,280 fatalities recorded, more than 10,000 people were injured, and hundreds of people went missing [68].

5.4.6 Volcanoes

Volcanoes happen when tectonic plates come together or separate, but they also occur in the middle of plates due to volcanic hotspots [19]. Over 100 young volcanoes that have had activity in the past 10,000 years dot the landscape of the East African rift. This area runs over 3,000 kilometers from Djibouti and Eritrea through the Democratic Republic of Congo, Ethiopia, Kenya, Rwanda, Tanzania, and Uganda [69]. Volcanoes in East Africa are inactive but believed to erupt in the future, though 25% of Africa's volcanoes have erupted in the last 100 years [69].

One of the most active volcanoes in Africa and one of the most dangerous in the world erupted in May 2021 [70]. The lava flow from the Nyiragongo volcano flowed to the northeast of Goma in the Democratic Republic of Congo. The lava destroyed houses, schools, and the city's main water reservoir in its path [70]. Reports state that more than 3,500 houses, seven schools, and four health centres were destroyed, nearly 200,000 people were left without access to drinking water, and around 234,000 people were displaced in the days following the eruption in Minova, Sake, Rutshuru East, and Goma [70]. The volcanic eruption also separated many children from their parents in the areas affected.

In 2002, the Nyiragongo volcano erupted, and its lava flowed into the city of Goma, killing 250 people [71]. The volcano displaced over 400,000 and destroyed 20% of the city [72]. The eruption surprised everyone, and the confusion and lack of preparedness made disaster management complicated in the early hours of the crisis [73]. The lava flow devastated a densely populated area, and the intense seismic activity lasted several days [72]. Nabro, a volcano near the Eritrean–Ethiopian border, erupted in 2011, leaving seven people dead, and more than 12,000 people were left homeless. Regional air traffic was also disrupted for several days [69].

5.4.7 Heatwaves and Wildfires

Heatwaves are extended periods of unusually high temperatures and often high humidity, often resulting in fires [19]. Wildfires are causing damage to ecology and people as they ravage forests after being triggered by climate change and human factors [74]. The number and extent of forest fires are increasing, as are the greenhouse gas emissions and the overall temperatures of the planet [74].

More than 30 people were killed, and 1,500 were evacuated in July 2023 in wildfires that blazed across Algeria. Among those killed were ten soldiers who were trying to get the fire under control in the face of high winds and sweltering summer temperatures [75]. The wildfires were spread by strong winds and moved across forests and agricultural areas in 16 regions, causing 97 blazes in the North African country [75]. In July 2023, the fires also ravaged pine forests in Tunisia near its border with Algeria and forced at least 300 people to be evacuated by sea and land with temperatures nearing 50°C [76]. There was extensive damage near Nefza, west of the country's capital, Tunis. Around mid-July, wildfires occurred, and a border crossing had to be temporarily closed after 470 hectares of forests were burned [76].

Two large villages located 15 kilometers from Bakala, which is 458 kilometers from Bangui in the Central African Republic, experienced fires on the night of 24-25 February 2022, which caused considerable material and human damages [77]. The area experiences severe drought and very high temperatures at the end of the dry season between February and March, and this is the period during which fields go up in flames, spreading through the fields and vegetation to the buildings around [77]. The fire quickly spread to other nearby houses and was aggravated by the strength of the dry winds specific to the season and the savannah area. The fire continued until 26 February, and after a few hours, it started again on 28 February, affecting other villages [77]. An assessment done by IFRC 2022 highlighted that 503 households were affected in the areas affected, with 28 partially destroyed houses and 17 people injured [78].

Fires broke out in large parts of Algeria, killing almost 40 people, including 12 people who died in a bus trapped by the flames [79]. Some residents lost homes to the flames, and authorities have been accused of being ill-prepared with few firefighting aircraft available. The people affected were in the El Tarf region near Algeria's border with Tunisia, an area sweltering in 48°C [79]. This incident resulted in 200 people suffering from burns or respiratory problems [79]. Tunisia in North Africa endured one of the worst heatwaves and fires in Africa in July 2022, where Tunis recorded temperatures above 48°C, breaking a forty-year record [80]. The heatwave and fires severely damaged Tunisia's grain harvest, leading to the farmers union predicting that output would fall well short of government hopes [80]. In Morocco during the same period, 1,000 hectares of forests burned in Larache and Ouezzane, and the country is struggling under intense droughts and temperatures have risen to 45°C [80].

5.4.8 Drug Abuse

The number of drug users in Sub-Saharan Africa is anticipated to increase drastically, and the region is likely to experience the most significant growth of drug users [81]. The progression of the multifaceted global illicit drug problem is currently determined by a range of factors driven by socio-demographic trends, which include populations' gender, age, and the rate of urbanization [82]. The drug menace in Africa has been attributed to high unemployment levels in Africa, and the rate at which drugs are being consumed is intriguing [83].

The other force behind the rapid use of drugs is the fact that Africa is still young, increasingly affluent, and rapidly urbanizing; hence, all these factors elevate the probability that a person will decide to use illicit substances [81]. Cannabis remains the most widely abused drug in Africa, while in other countries such as Sierra Leone, children and youth use substances like benzodiazepines, which include diazepam, chlorpromazine, different inhalants, and other drugs that are injected [82].

Zimbabwe is one of the African countries experiencing an increase in problematic drug use among its population, along with the related public health issues that accompany specific drug type uses [84]. The substances that are used in Zimbabwe include alcohol, cannabis, heroin, glue, and cough mixtures such as histalix and bronclear, but cannabis (mbanje) remains the most used drug mainly because it is grown locally or smuggled in from neighbouring countries like Mozambique and Malawi [84]. Moonshine, locally known as tumbwa or kozoda, and prescription drugs such as Diazepam, Ketamine, Pethidine, Morphine, and Fentanyl are also being used by drug addicts in Zimbabwe [83].

Methamphetamine, better known on the streets as (crystal meth or mutoriro), is also a powerful addictive stimulant being used in Zimbabwe. It affects the central nervous system and is being heavily abused by young adults, and a massive rise in demand was recorded during the COVID-19 period [85]. Apart from the imported drugs in Zimbabwe, locals are also flooding the market with cheap, highly intoxicating substitutes. There is also musombodiya, a colourless drink made from ethanol and emblematic powders [83]. Some drug addicts even go to the extent of dipping diapers and bleach products in boiling water and inhaling the vapours as intoxicants [83]. Drug abusers in Zimbabwe are taking anything they think will keep them euphoric or sedated, and cases of organic psychosis are on the rise [83].

In Kenya, residents in the various suburbs of Nairobi have complained about the increasing number of teenagers who have been chewing what is called locally khat whilst others smoke cigarettes and bhang, consume alcohol, and use other substances like jet fuel [85]. The abuse of drugs such as marijuana, methamphetamines, and opioids is also rampant in South Africa in recent years, and this has resulted in the rise of criminal activities, poverty, and health-related issues [86]. Many drug addicts in South Africa have resorted to criminal activities to finance their addiction, and this has led to an increase in theft and violent crimes. Drug addiction has also contributed to poverty in South Africa, as many individuals who are addicted to drugs find it difficult to take care of themselves and their families [86].

5.4.9 Boat Disasters

The most disastrous boat disaster that took place in Nigeria in June 2023 was when more than 100 people drowned after a boat carrying them down the river Niger capsized in southwestern Nigeria [87]. The boat was ferrying more than 300 people travelling from Kwara State to Niger State after attending a wedding, and the boat capsized after part of the vessel collapsed, causing water to flood the boat [87].

A boat carrying 200 passengers capsized in the northwestern Congo's Equateur province, and the boat was headed to Lilanga in the neighbouring Republic of Congo when it sank in the Lulonga River near the town of Basankusu, leaving 145 people unaccounted for [88]. It has been reported that a lot of boat sinking has caused fatalities in the remote parts of the Democratic Republic of Congo, where travel by road is at times impossible [89].

At least 29 migrants from Sub-Saharan Africa died when their two boats sank off the coast of Tunisia as they tried to cross the Mediterranean to Italy in March 2023 [90]. It is also believed that in the same month of March 2023, 5 migrant boats sunk off the coast of the Southern city of Sfax in Tunisia, leaving 67 missing and nine dead after a significant increase in boats heading towards Italy [90]. Tunisia has taken over from Libya as a main departure point for people fleeing poverty and conflict in Africa, hoping for greener European pastures [90]. In October 2022, an estimated 75 people were killed in a boat when flooding of the Niger River caused it to tip over in Anambra State in Nigeria [91]. Boat accidents frequently occur in Nigeria because of overloading, speeding, poor maintenance, and disregarding navigation rules [91].

A rubber boat carrying dozens of migrants heading to Europe sank off the coast of Libya in April 2023, resulting in 55 people drowning, including women and children [92]. The boat was ferrying 60 migrants and had set off from the coastal town of Garabouli, East of Libya's capital, and the five migrants who survived the disaster were brought back to shore by the Libyan coast guard [92]. Another boat accident that occurred in Djibouti in 2021 killed 43 people after a migrant ship controlled by smugglers capsized off the coast of Djibouti [93]. The ship was packed with at least 60 migrants trying to return home to the horn of Africa, having fled from war-torn Yemen [93]. In March 2021, at least 80 migrants, including minors, were thrown overboard by people smugglers in the same waters, and more than five people were killed [93].

5.5 Challenges that Hinder Disaster Management in Africa

There are several areas of vulnerability to disaster management in Africa, and these include:

- **Limited fiscal resources and the scope to invest in disaster risk reduction measures.** Public spending on ex-ante investments in disaster risk reduction competes with other demands such as infrastructure development, health, defense, and debt service [3].
- **Lack of a collective regional approach when addressing disasters** [94]. This is evidenced by the response from Southern African Development Community (SADC) member states when Cyclone Idai hit the region in 2021. The regional body was unprepared, and member states have yet to learn much from earlier disasters [94]. During Cyclone Idai, out of the sixteen-member states, only Angola, Botswana, South Africa, Tanzania, and Zambia contributed to the relief efforts [94].
- **Weak and incomplete institutional frameworks** make it challenging to manage disasters, and there need to be more nationally developed, agreed-upon, and harmonized disaster management strategies, policies, and legal frameworks [94].
- **Africa's infrastructure to buffer against hydrometeorological events is limited** compared to other continents [3]. Transport infrastructure is poor, and schools and hospitals must be better built and maintained according to minimum standards to resist disasters such as earthquakes, cyclones, or floods [3]. Building standards in Africa should be enforced, which may result in higher costs for construction. The costs of reconstructing extensive infrastructure networks can significantly burden these economies [3].
- **Weak knowledge and information base to support disaster management** mainly due to a lack of awareness of disaster management among the public and some national authorities, lack of data and information, weak communication, inadequate inventory and exchange of best practices, unavailability of information about risks to support decision making, and inadequate research [94].
- **Providing health and other services in the African region is challenging** due to protracted humanitarian emergencies, poverty, lack of political commitment, and fragile health systems. Disease outbreaks are not detected early due to a lack of real-time surveillance, an optimal functional laboratory network, inadequate diagnostic testing capacity at national and peripheral healthcare levels, and inadequate human resources and technical and managerial capacities [95].

5.6 How Human Beings Can Improve Disaster Preparedness through Animal Behaviour in Determining the Occurrence of Disasters

Animal behaviour before disasters has prompted some researchers to devote severe scientific attention to the theory that animals may have built-in systems that alert them to impending natural disasters [96]. Some animals have empathetic senses of hearing or smell, while others can detect changes in atmospheric pressure or electromagnetic fields [97]. Many studies have shown that some animals can sense significant changes in the weather. For instance, birds are sensitive to air pressure changes and often hunker down before a big storm, and worms are known to flee rising groundwater [98].

In 2004, when the devastating Asian Tsunami occurred, local artificial early warning systems failed to raise any clear alerts, and a few hours before the Tsunami, some animals seemed to sense imminent danger and made efforts to flee [96]. Elephants ran for higher ground, flamingos abandoned low-lying nesting areas, and dogs refused to go outdoors in the coastal village of Bang Koey in Thailand [96]. Animals, which included cattle, birds, cats, and goats, deliberately moved inland shortly before the Tsunami struck and survived the disaster [99].

The research on how animals could predict disasters was conducted in Germany between October 2016 and April 2017. The study involved recording movement patterns of different animals, including sheep, dogs, and cattle, a process known as biologging on a farm [96]. This research was conducted in the earthquake-prone area of the Marches in central Italy, and collars with chips were attached to each animal, which sent movement data to a central computer every few minutes between October 2016 and April 2017 [96]. More than 18,000 earthquakes were recorded in the region, and the researchers found evidence that the farm animals began to change their behaviour up to twenty hours before an earthquake [96]. It was also highlighted that whenever the monitored farm animals were collectively 50% more active for more than 45 minutes at a stretch, the researchers predicted an earthquake above 4.7 on the Richter scale [96].

People have described unusual animal behaviour over the past centuries before seismic events whereby dogs tend to bark relentlessly, cow's milk let down is affected, and toads leap from ponds [100]. Some researchers have tried to establish a link between animal behaviour and seismic events. In a 2013 study, German scientists videotaped red wood ants that nested along a fault line and found that they had changed their usual routine before a quake, becoming more active in the evening and less active during the day [100].

VI. RECOMMENDATIONS

- **One of Africa's most crucial fundamentals of disaster management is the need to commit to early warning systems.** The investments are enormous as they have to focus on adaptation and resilience and information that allow countries to predict events such as droughts, heat waves, floods, and storms.
- **Investments in hydrometeorological services are another alternative for African countries to minimize disasters** since this helps people predict, understand, and warn citizens about hazards and disasters. The use of early warning systems helps communities deal with everything from volcanic eruptions to floods.
- **There is a need for Regional Economic Communities in Africa to work collectively to pool resources and mobilize disaster management efforts.** Secretariats for these regional economic communities must oversee these activities and ensure that funds for immediate humanitarian assistance and the reconstruction of infrastructure are available in a pre-existing disaster risk fund.
- **African countries must develop hazard risk maps and models identifying vulnerabilities** to help governments prioritize physical interventions. Strategic, innovative interventions must be built to reduce underlying risks and vulnerabilities.
- **African countries must enhance their capacity and capabilities to prepare for and respond to any public health event** that may threaten public health security by implementing international health regulations.
- **African countries must deal with the root causes of terrorism in the long run** by ensuring commitment to socio-economic progress and shared prosperity for all citizens. This can be done when governance reforms are included to strengthen public financial management, promote accountability and transparency in public service delivery, and combat corruption.

- **When it comes to the increasing number of drug users on the continent, there is a need to address the underlying causes,** which in most cases include poverty and unemployment, by providing education and job training programs so that individuals are empowered to break the cycle of addiction and poverty.
- **Early warning systems and heat action plans need to be put in place,** and these can be based on information from other countries with similar climates. Collaboration between local researchers, hospitals, and epidemiologists can identify direct health impacts of extreme heat. Simple procedures such as opening public buildings to provide cool rooms, distributing free drinking water, informing people about the dangers of heat, and early warning can reduce the damage considerably.

VII. CONCLUSION

Disasters cannot be stopped, but disaster management can be reinforced, aiming to reduce people's death rates and suffering. Disasters are amongst the main challenges facing Africa and not only lead to the loss of lives but also hinder the stabilization of local economies and prevent development. The economic costs of disasters have increased in Africa, where remediation funds are either lacking or limited. The high costs of dealing with the damages caused by disasters reflect the need to encourage disaster risk reduction, which lies in the strength of efficient disaster management and adaptation planning. The management of disaster risks largely depends on the strength of disaster management policies and strategies to prevent new disaster risks, reduce existing disaster risks, and manage residual risks, contributing to the strengthening of resilience and reduction of disaster losses.

The African Union can be tasked to set up a department to make Africa disaster prepared.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Rae, S., & Hendry, L. (2016). *What killed the dinosaurs*. Natural History Museum. https://www.nhm.ac.uk/discover/dinosaur-extinction.html
[2] United Nations Inter-Agency Secretariat UNISDR. (2004). *A global review of disaster reduction initiatives*.
[3] World Bank. (2010). *The challenges faced by the countries in Africa are mostly related to their level of development*.
[4] International Federation of Red Cross, IFRC. (2011). *Disasters in Africa*. https://oldmedia.ifrc.org/ifrc/wp-content/uploads/2020/10/Disasters-in-Africa_2011.pdf
[5] National Centre for Environmental Information. (2023). *Billion dollar weather and climate disasters*. https://www.ncei.noaa.gov/access/billions/
[6] Atlas Magazine. (2023). *Cost of natural and manmade catastrophes in 2022*. https://www.atlas-mag.net/en/natural-disasters/cost-of-natural-and-man-made-catastrophes-in-2022
[7] Bashir, F., Milena, P., & Wim, G. (2023). Hospital disaster preparedness in Sub-Saharan Africa: A systematic review of English Literature.
[8] Centre for Research on the Epidemiology of Disasters CRED. (2023). *2022 disasters in numbers*. https://www.preventionweb.net/publication/cred-crunch-newsletter-issue-no-70-april-2023-disasters-year-review-2022
[9] European Council of the European Union. (2023). *Food security and availability*. https://www.consilium.europa.eu/en/policies/food-security-and-affordability/
[10] Mounir, B. (2023). International Financial Corporation, adapting to natural disasters in Africa: What's in it for the private sector.
[11] East African Community EAC. (2017). *Floods and conflicts the major cause of disasters in East Africa*. https://www.eac.int/press-releases/144-environment-natural-resources/863-floods-and-conflicts-the-major-cause-of-disasters-in-east-africa
[12] Alyu, A. (2015). Management of disasters and complex emergencies in Africa: The challenges and constraints.
[13] Loretto, A., & Tegegn, Y. (1996). Disasters in Africa: Old and new hazards and growing vulnerability.
[14] Kamer, L. (2022). Reported economic losses due to natural disasters in Africa 1970-2019 by type.
[15] World Bank. (2021). *Climate change knowledge portal for development practitioners and policy makers*. https://climateknowledgeportal.worldbank.org/country/south-africa/vulnerability
[16] SOS. (2016). *AIDS in Africa: Facts, figures and background information on the epidemic*. https://www.sos-usa.org/about-us/where-we-work/africa/aids-in-africa
[17] WHO. (2022). *The greater horn of Africa's climate-related health crisis worsens as disease outbreaks surge*. https://www.afro.who.int/news/greater-horn-africas-climate-related-health-crisis-worsens-disease-outbreaks-surge
[18] Deryugina, T. (2022). *Economic effects of natural disasters*. https://wol.iza.org/articles/economic-effects-of-natural-disasters

[19] IFRC. (2022). *World Disasters Report 2022*. https://www.ifrc.org/document/world-disasters-report-2022

[20] McEntire, D. (2004). The status of emergency management theory: Issues, barriers and recommendations for improved scholarship. *Paper presented at the annual Emergency Management Higher Education Conference, National Emergency Training Center, Emmetsburg, Maryland*.

[21] Khan, H. (2008). *Disaster management cycle: A theoretical approach*. https://econpapers.repec.org/RePEc:aio:manmar:v:6:y:2008:i:1:p:43-50

[22] Tomasani, R., & Van Wassenhove, L. N. (2009). *Humanitarian logistics*. Palgrave.

[23] Baidoo, J. (2018). Challenges of strategies for rapid response in disaster relief operations in Ghana. *Textile International Journal of Management*, *4*(4).

[24] Nisha de Silva, F. (2001). Providing special decision support for evacuation planning: A challenge in integrating technologies. *Disaster Prevention and Management*, *10*(1).

[25] Long, D., & Wood, D. (1995). The logistics of famine relief. *The Journal of Business Logistics*, *16*(1).

[26] Lamont, J. (2005). KM: Role in the aftermath of disasters. *KM World*, *14*(10).

[27] Galal, S. (2022). *Coronavirus deaths in Africa, 2022 by country*. https://www.statista.com/statistics/1170530/coronavirus-deaths-in-africa/

[28] U.N. (2020). *Explainer: How the COVID-19 pandemic has increased the care burden of women and families*.

[29] Congressional Research Service. (2022). *Coronavirus Disease 2019 (COVID 19): Impact in Africa*. https://crsreports.congress.gov/product/pdf/IF/IF11532/15

[30] UNICEF. (2023). *The cholera outbreak in Eastern and Southern Africa is not just an outbreak; it's an emergency for children*.

[31] WHO. (2023). *New cholera cases in Africa surging fast reach a ⅓ of 2022 total in a month*. https://www.afro.who.int/news/new-cholera-cases-africa-surging-fast-reach-third-2022-total-month

[32] Huber, C., Finelli, L., & Stevens, W. (2018). The economic and social burden of the 2014 Ebola outbreak in West Africa.

[33] Centre for Disease Control and Prevention. (2014). *Ebola outbreak in West Africa*. https://www.cdc.gov/vhf/ebola/history/2014-2016-outbreak/index.html

[34] Elmahdawy, M., Elsisi, G. H., Carapinha, J., Lamorde, M. M., & Habib, A. (2017). Ebola virus epidemic in West Africa: Global health economic challenges, lessons learnt and policy recommendations.

[35] Pondy, L. R. (1967). *Pondy's model of organizational conflict – explained*. https://www.scirp.org/%28S%28351jmbntvnsjt1aadkozje%29%29/reference/referencespapers.aspx?referenceid=1736076

[36] Aremu, J. O. (2010). Conflicts in Africa: Meaning, causes, impact and solutions. *Africa Research Review: An International Multi-Disciplinary Journal*, *4*(4).

[37] Fang, X., Siddharth, K., McLoughlin, C., & Yenice, M. (2020). The economic consequences of conflict in Sub-Saharan Africa.

[38] Palik, J., Obermeier, A. M., & Rustad, S. A. (2022). Conflict trends in Africa 1989-2021.

[39] ACCORD. (2019). *Terrorism in Africa*. Conflict Trends 2019/1. https://www.accord.org.za/conflict-trends-issue/2019-1/

[40] Tasamba, J. (2023). *Burkina Faso most affected African country by terrorism: Report*. https://www.aa.com.tr/en/africa/burkina-faso-most-affected-african-country-by-terrorism-report/2857969

[41] Institute of Security Studies - PSC Report. (2022). *African conflicts to watch in 2022*.

[42] Azama, S. (2015). *A critical analysis of Boko Haram Insurgency*. https://apps.dtic.mil/sti/pdfs/AD1038853.pdf

[43] ACLED. (2018). *Profile crisis: Boko Haram*. https://acleddata.com/crisis-profiles/

[44] Van Rentergem, T. (2022). Al-Shabaab in Mozambique: Taking stock of an insurgency undercover.

[45] Bartlet, K. (2022). Mozambique's displaced recount brutality of Cabo Delgado insurgents.

[46] Joseph, N. (2023). *Cyclones in Southern Africa: Five essential reads*. https://theconversation.com/cyclones-in-southern-africa-five-essential-reads-200371

[47] Smith, P. (2023). 20000 people feared dead in Libyan city destroyed by floods.

[48] IFRC. (2023). *Libya: Storm Daniel*. https://www.ifrc.org/emergency/libya-storm-daniel

[49] Reuters. (2023). *Factbox: Cyclone Freddy among Africa's deadliest storms*. https://www.reuters.com/news/picture/factbox-cyclone-freddy-among-africas-dea-idUSKBN2VH11Z

[50] NASA Earth Observatory. (2023). *Heavy rains hit the drought-stricken horn of Africa*. https://earthobservatory.nasa.gov/images/151208/heavy-rains-hit-drought-stricken-horn-of-africa

[51] UNDRR. (2022). *Climate change increased rainfall associated with tropical cyclones hitting highly vulnerable communities in Madagascar, Mozambique and Malawi*.

[52] UNICEF. (2022). *Tropical Storm Ana wreaks havoc for children in Madagascar, Malawi and Zimbabwe*.

[53] Reliefweb. (2022). *Cyclone Batsirai leaves people vulnerable to food shortages and malaria*. https://reliefweb.int/report/madagascar/cyclone-batsirai-leaves-people-vulnerable-food-shortages-and-malaria

[54] Oxfam. (2019). *Cyclone Idai in Zimbabwe: An analysis of policy implications for post-disaster risk management*.

[55] Reliefweb. (2019). *Tropical Cyclone Idai-March 2019*. https://reliefweb.int/disaster/tc-2019-000021-moz

[56] Maedhbh, M. (2016). *El Niño drives crisis in Southern and Eastern Africa*. https://www.concern.net/news/el-nino-drives-crisis-in-south-and-east-africa
[57] National Oceanic & Atmospheric Administration (NOAA). (2023). *What are El Niño & La Nina*.
[58] WFP. (2016). *Implications of El Nino in Southern Africa from a food and nutrition security perspective*.
[59] Harvey, F. (2023). *Human-driven climate crisis fuelling Horn of Africa drought study*. https://www.theguardian.com/environment/2023/apr/27/human-driven-climate-crisis-fuelling-horn-of-africa-drought-study
[60] WHO. (2023). *Drought and food insecurity in the Greater Horn of Africa*. https://www.who.int/emergencies/situations/drought-food-insecurity-greater-horn-of-africa
[61] The Guardian. (2023). *Human-driven climate crisis fuelling the Horn of Africa*. https://www.theguardian.com/environment/2023/apr/27/human-driven-climate-crisis-fuelling-horn-of-africa-drought-study
[62] Brandt, M. (2011). *Seismic hazard in South Africa*. Council for a Geo Science report.
[63] Kebede, F., & Kulhaneck. (1991). Recent seismicity of East African rift system and its implications. *Physics of the Earth and Planetary Interiors*.
[64] Wafula, D. M. (2011). Impacts of the tectonic earthquake in the western rift valley of Africa on the volcanic activity of Nyiragongo. *Asian Journal of Scientific Research*.
[65] Lau, C., O'Murchu, S. F., Raine, A., Vogt, A., & Meyer, M. (2023). 9 September, 2023 Earthquake hits Morocco.
[66] The Guardian. (2023). Morocco earthquake: At least 2000 dead and thousands more injured.
[67] Khalil, A. E., Deif, A., & Abdel, H. E. (2015). Seismic hazard assessments at Islamic Cairo, Egypt. *Journal of Earth Sciences*.
[68] Samai, S., Idres, M., Boughacha, M. S., Bezzeghoud, M., & Borges, J. F. (2017). A structural scheme, proposal derived from geophysical data in the epicentre area of the Boumerdes, Algeria.
[69] Fontijn, K. (2018). *Tracking the hazards and benefits of volcanoes in East Africa*. https://theconversation.com/tracking-the-hazards-and-benefits-of-volcanoes-in-east-africa-106322
[70] UNICEF. (2021). *Nyiragongo volcano eruption: The aftermath*. https://www.unicef.org/drcongo/en/stories/nyiragongo-volcano-eruption-the-aftermath
[71] Pease, R. (2020). *Lava lake rises at dangerous African volcano*. https://pubmed.ncbi.nlm.nih.gov/33060337/
[72] NASA Earth Observatory. (2004). *Congo volcanoes erupt. Mt Nyamulagira is Africa's most active volcano*.
[73] Royal Belgian Institute for Space Aeronomy. (2022). *Africa's most dangerous volcano, may erupt without clear precursory signs*.
[74] De Souza, A., Tumuhimbise, A., Mensaque, B. L., & Ogunyale, K. (2023). Wildfire hotspots in Africa and Latin America are facing challenges.
[75] Al Jazeera. (2023). *Deadly wildfires raging across Algeria*. https://www.aljazeera.com/gallery/2023/7/25/deadly-wildfires-raging-across-algeria
[76] Harper, D. (2023). North Africa heatwave: Wildfires kill dozens and force over 1,500 people to evacuate.
[77] Reliefweb. (2022). *Central African Republic: Fires: February 2022*. https://reliefweb.int/disaster/fr-2022-000179-caf
[78] IFRC. (2022). *Central African Republic: Fires and strong winds in Bakala emergency plan of action*.
[79] France 24. (2022). *Scenes of devastation as deadly wildfires ravage Algeria*. https://www.france24.com/en/africa/20220818-scenes-of-devastation-as-deadly-wildfires-ravage-algeria
[80] Jones, S. (2022). Thousands evacuated as heat caused wildfires in Europe and North Africa.
[81] Donnefield, Z. (2019). What is driving Sub-Saharan Africa's rapid rise in drug use?
[82] WHO. (2021). *Substance abuse*. https://www.afro.who.int/health-topics/substance-abuse
[83] Mandura, T. (2023). *Zimbabwe battling growing drug addiction among youths*. https://www.trtafrika.com/africa/zimbabwe-battling-growing-drug-addiction-among-youth-12079529
[84] Swansea University. (2014). *Global drug policy observatory, country snapshots: Drugs in Zimbabwe*. Gdpo.swan.ac.uk
[85] Koigi, B. (2021). *Induced drug abuse rise in Africa*. https://www.fairplanet.org/story/cases-of-covid-19-induced-drug-abuse-rise-in-africa/
[86] Rehab helper. (2023). *How does drug abuse and addiction affect society in South Africa*. https://rehabhelper.co.za/blog/how-does-drug-abuse-and-addiction-affect-society-in-south-africa/
[87] Ambali, A., Ewokor, C., & Davies, A. (2023). Kwara boat accident: 100 dead and more missing in Nigeria.
[88] Muslim Network T.V. (2023). *145 people feared dead after Congo boat accident*. https://www.muslimnetwork.tv/145-people-feared-dead-after-congo-boat-accident/
[89] TRT World. (2023). *At least 145 people feared dead in the Democratic Republic of Congo boat tragedy*. https://www.trtworld.com/africa/at-least-145-people-feared-dead-in-drc-boat-tragedy-64691
[90] France 24. (2023). *Dozens of migrants killed in latest boat disaster off Tunisia*. https://www.france24.com/en/africa/20230326-at-least-19-african-migrants-killed-in-latest-migrant-boast-disaster-off-tunisia
[91] News 24. (2022). *76 people were killed in a Nigeria boat accident*. https://www.news24.com/news24/africa/news/76-people-killed-in-nigeria-boat-accident-20221010
[92] Magdy, S. (2023). United Nations says at least 55 migrants drowned in a shipwreck off Libya.
[93] UNICEF. (2021). *16 children and 27 adults dead off the coast of Djibouti after migrant boat capsizes*.

[94] Nshimbi, C. C. (2021). Southern African countries will only manage disasters if they work together.
[95] African Union. (2023). *Building testing capacity for epidemic-prone diseases*.
[96] Miller, N. (2022). *The animals that detect disasters*. https://www.preventionweb.net/news/animals-detect-disasters
[97] Saul, T. (2023). *A wilder view: Can animals sense oncoming natural disasters*. https://www.kpax.com/news/a-wilder-view/a-wilder-view-can-animals-sense-oncoming-natural-disasters
[98] PBS. (2008). *Can animals predict disasters? Tall tales or true*. https://www.pbs.org/wnet/nature/can-animals-predict-disaster-tall-tales-or-true/131/
[99] Bailey, R. (2019). *Can animals sense natural disasters?* https://www.thoughtco.com/can-animals-sense-natural-disasters-373256
[100] Averett, N. (2020). *Do animals really anticipate earthquakes? Sensors hit; they do*. https://www.scientificamerican.com/article/do-animals-really-anticipate-earthquakes-sensors-hint-they-do/

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Management of Major Insect Pests of Ash Gourd, *Benincasa hispida* Thunb. with Traps, Biopesticides and Newer Insecticides

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***Abstract*— *Ash gourd, Benincasa hispida Thunb., is an important vegetable crop, cultivated globally for its medicinal values, and its production is hampered by many insect pests. Therefore, field experiments were conducted to study the efficacy of sticky traps, botanicals and organic pesticides, biopesticides, and newer insecticides against major pests of ash gourd in the farmer's holdings at Kaliyavur village of Thoothukudi district, Tamil Nadu, India during Rabi 2018. The results revealed that cylindrical white sticky traps attracted more number of alate forms of Myzus persicae Sulzer, and cylindrical yellow sticky traps attracted more number of adults of Liriomyza trifolii Burgess. Azadirachtin 3000 ppm at 2 mL/L was effective in reducing the insect pests. Beauveria bassiana formulation at 2 g/L was effective against Myzus persicae Sulzer and* Aulacophora foveicollis *Lucas. Diaphania indica Saunders was controlled by the application of Bacillus thuringiensis at 2 g/L. Newer insecticide molecules were very prominent in managing the major insect pests of ash gourd. The findings of the study will be helpful for the effective management of insect pests of ash gourd.*

Keywords*— *Ash gourd, Insect pests, Sticky traps, Biopesticides, Newer molecules, Benincasa hispida, IPM, Botanicals, Myzus persicae, Aulacophora foveicollis, Diaphania indica.

I. INTRODUCTION

Ash gourd, *Benincasa hispida* Thunb., is one of the most important vegetable crops, being cultivated throughout the humid tropical and subtropical regions. Ash gourd is mainly grown in India, China, Malaysia, Bangladesh, Indonesia, Philippines, Taiwan, and the Caribbean Islands for vegetable and medicinal purposes (Tindall, 1986). Ash gourd fruit constitutes volatile oils, flavonoids, glycosides, proteins, carotenes, vitamins, minerals, and uronic acid. It is a good source of Vitamin B1 (thiamine), Vitamin B3 (niacin), and Vitamin C (ascorbic acid), and is also rich in calcium and potassium.

In India, the production of ash gourd is hampered by many insect pests viz., aphids, *Aphis gossypii* Glover and *Myzus persicae* Sulzer (Aphididae: Hemiptera); whitefly, *Bemisia tabaci* Gennadius (Aleyrodidae: Hemiptera); leafhopper, *Amrasca devastans* Distant (Cicadellidae: Hemiptera); thrips, *Scirtothrips dorsalis* Hood (Thripidae: Thysanoptera); serpentine leaf miner, *Liriomyza trifolii* Burgess (Agromyzidae: Diptera); pumpkin caterpillar, *Diaphania indica* Saunders (Crambidae: Lepidoptera); red pumpkin beetle, *Aulacophora foveicollis* Lucas (Chrysomelidae: Coleoptera); and melon fruit fly, *Bactrocera cucurbitae* Coquillett (Tephritidae: Diptera) (Atwal, 1993; Dhillon et al., 2005; Tamilnayagan et al., 2017a; Tamilnayagan et al., 2017b).

In Tamil Nadu, ash gourd was cultivated in an area of 441 hectares with a production of 8901.28 tonnes and productivity of 20.18 tonnes per hectare during 2016-17 (DES, 2019). Ash gourd growers mainly rely on synthetic chemical pesticides for managing the pests, and indiscriminate usage of chemical insecticides disturbs the ecosystem and leaves harmful pesticide residues which cause health concerns in consumers (Azmi et al., 2006). Hence the present study was undertaken to study the efficacy of sticky traps, botanicals and organic pesticides, biopesticides, and newer insecticides against major pests of ash gourd.

II. MATERIALS AND METHODS

The field experiments were carried out during the Rabi season (November 2018 - February 2019) in the farmer's holdings at Kaliyavur village of Thoothukudi district, Tamil Nadu, India to evaluate the efficacy of sticky traps, botanicals and organic pesticides, biopesticides, and newer insecticides against major pests of ash gourd.

2.1 Evaluation of Sticky Traps

Cylindrical shaped sticky traps of different colours were evaluated against the sucking pests viz., *B. tabaci* and *S. dorsalis*. Cylindrical shaped containers of 45.47 cm^2 dimension were taken and painted with yellow, blue, and white colours each. They were coated with castor oil as a sticking agent and kept in the field (1 foot above the canopy) at a distance of 5 m to avoid trap interactions. Weekly observations were made for trap catches and expressed as number of insects per trap.

2.2 Efficacy of Botanicals and Organic Pesticides, Biopesticides, and Newer Insecticides

The field experiments were laid out in a completely randomized block design (CRBD) with four replications separately for each set of treatments. Ash gourd F1 hybrid MAH 1 was sown on ridges and furrows (2 m × 60 cm) at a spacing of 45 cm between plants. The treatments were imposed when the pests reached the economic threshold level as a foliar spray. Pre-treatment and post-treatment counts on target pests were done on five randomly selected plants per replication. Post-treatment counts were recorded on 3, 7, 10, and 14 days after treatment (DAT). The incidence of insect pests is expressed as number of insects per five plants, and leaf damage by *L. trifolii* is expressed as per cent leaf damage per five plants.

2.3 Statistical Analysis

The data obtained from the field experiments were analyzed using SPSS (Statistical Package for Social Sciences) software Version 21. The data in numbers were subjected to square root transformation, and the data in percentage were subjected to arcsine transformation (Gomez and Gomez, 1984). Least significant difference (LSD) at $p < 0.05$ was used to evaluate the difference between treatments.

III. RESULTS

3.1 Evaluation of sticky traps

The trap catches of alate forms of *M. persicae* were recorded from 2 WAS (weeks after sowing) to 8 WAS. The trap catches were highest in white sticky traps as compared to blue and yellow sticky traps. The trap catches of *L. trifolii* adults were recorded from 2 WAS to 6 WAS, and yellow sticky traps recorded the highest catches as compared to blue and white sticky traps (Table 1).

TABLE 1
EFFICACY OF CYLINDRICAL STICKY TRAPS AGAINST MAJOR PESTS OF ASH GOURD

Treatments/ Weeks of observation	Number of insects/trap*					
	T1 - Yellow sticky trap		T2 - Blue sticky trap		T3 - White sticky trap	
	L. trifolii	*M. persicae*	*L. trifolii*	*M. persicae*	*L. trifolii*	*M. persicae*
2 WAS	2.5	0	2.3	1	1.9	1.2
3 WAS	3.1	1.9	2.9	2.2	2.5	3.5
4 WAS	2.4	5.1	1.8	6.5	1.6	6.7
5 WAS	2.2	5.9	1	7	0.8	7.2
6 WAS	1.2	3.7	0.6	4.5	0.2	4.7
7 WAS	0	2.1	0	3.4	0	4
8 WAS	0	1.2	0	1.9	0	2

***WAS = Weeks After Sowing;* Mean of seven replications**

3.2 Efficacy of Botanicals and Organic Pesticides

3.2.1 Aphid, *M. persicae*

The results of the field experiment conducted at farmer's holdings at Kaliyavur village of Thoothukudi district during Rabi 2018 revealed that among the five botanical and organic pesticides evaluated, Azadirachtin 3000 ppm at 2 mL/L was significantly effective against *M. persicae*, which reduced the population from 30.25 aphids per five plants before treatment to

0.25 per five plants at 14 days after treatment (DAT), followed by Neem Seed Kernel Extract at 5%. Fish ensilage oil at 10 mL/L recorded 1.50 aphids per five plants at 14 DAT (Table 2).

3.2.2 Serpentine Leaf Miner, *L. trifolii*

The per cent leaf damage caused by *L. trifolii* was lowest in the plots applied with Azadirachtin 3000 ppm at 2 mL/L. All other botanicals and organic insecticides also recorded reduction in leaf damage due to *L. trifolii* when compared to the untreated check (Table 2).

3.2.3 Red Pumpkin Beetle, *A. foveicollis*

Among the five botanical and organic pesticides, Azadirachtin 3000 ppm at 2 mL/L was effective against *A. foveicollis*, which reduced the population of beetles from 3.00 beetles per five plants before treatment to 1.75, 1.00, 0.25, and 0.00 beetles per five plants at 3, 7, 10, and 14 DAT, and was on par with Neem Seed Kernel Extract at 5% (Table 3).

3.2.4 Pumpkin Caterpillar, *D. indica*

The results showed that Azadirachtin 3000 ppm at 2 mL/L was effective against *D. indica* by reducing the population from 3.25 larvae per five plants before treatment to 2.00, 1.25, 0.25, and 0.00 larvae per five plants at 3, 7, 10, and 14 DAT, respectively, followed by Neem Seed Kernel Extract at 5% (Table 3).

3.2.5 Yield

The highest fruit yield was recorded in the plots treated with Azadirachtin 3000 ppm at 2 mL/L (37.48 t/ha), followed by Neem Seed Kernel Extract at 5% (37.17 t/ha) and Agni asthiram at 30 mL/L (36.92 t/ha) (Table 3).

TABLE 2
EFFICACY OF BOTANICALS AND ORGANIC PESTICIDES AGAINST *M. PERSICAE* AND *L. TRIFOLII* ON ASH GOURD DURING RABI 2018

S. No.	Treatments	Number of aphids/5 plants*					Per cent leaf damage by *L. trifolii*/5 plants#				
		PTC	3 DAT	7 DAT	10 DAT	14 DAT	PTC	3 DAT	7 DAT	10 DAT	14 DAT
T1	Agni asthiram @ 30 mL/L	30.00 (5.52)	10.50 (3.31)[a]	5.50 (2.44)[ab]	1.75 (1.44)[a]	0.75 (1.10)[ab]	12.78 (20.93)	3.99 (11.49)[ab]	3.89 (11.31)[b]	2.62 (9.22)[b]	1.38 (6.73)[b]
T2	Fish ensilage oil @ 10 mL/L	31.00 (5.61)	11.75 (3.50)[a]	6.75 (2.68)[b]	2.50 (1.72)[a]	1.50 (1.40)[b]	12.41 (20.60)	4.95 (12.84)[c]	4.51 (12.22)[b]	3.08 (9.98)[b]	1.87 (7.79)[b]
T3	Neem oil @ 20 mL/L	34.25 (5.89)	10.75 (3.34)[a]	5.75 (2.49)[ab]	2.00 (1.56)[a]	1.00 (1.18)[ab]	12.95 (21.07)	4.16 (11.74)[b]	3.95 (11.38)[b]	2.89 (9.75)[b]	1.45 (6.87)[b]
T4	Neem Seed Kernel Extract @ 5%	31.50 (5.65)	10.00 (3.23)[a]	5.25 (2.40)[ab]	1.75 (1.49)[a]	0.50 (0.97)[ab]	12.08 (20.31)	3.86 (11.33)[ab]	3.77 (11.14)[b]	2.40 (8.87)[ab]	1.28 (6.47)[b]
T5	Azadirachtin 3000 ppm @ 2 mL/L	30.25 (5.53)	9.50 (3.16)[a]	5.00 (2.34)[a]	1.50 (1.40)[a]	0.25 (0.84)[a]	12.50 (20.69)	3.32 (10.49)[a]	2.12 (8.33)[a]	1.49 (6.99)[a]	0.13 (1.01)[a]
T6	Untreated check	31.50 (5.65)	32.50 (5.74)[b]	33.50 (5.83)[c]	34.25 (5.89)b	35.00 (5.96)[c]	12.81 (20.96)	13.13 (21.23)[d]	13.23 (21.31)[c]	13.45 (21.52)[c]	13.82 (21.81)[c]
	CD (p=0.05)	NS	0.35	0.32	0.43	0.45	NS	1	1.46	1.89	1.75

PTC = Pre-treatment count; DAT = Days after treatment
Figures in parentheses are √(x+0.5) transformed values; #Figures in parentheses are arc-sine transformed values
In a column, means followed by common letters are not significantly different by LSD (P=0.05)

TABLE 3
EFFICACY OF BOTANICALS AND ORGANIC PESTICIDES AGAINST A. FOVEICOLLIS AND D. INDICA ON ASH GOURD DURING RABI 2018

S. No.	Treatments	Number of beetles/5 plants*					Number of larvae/5 plants*					Yield (t/ha)
		PTC	3 DAT	7 DAT	10 DAT	14 DAT	PTC	3 DAT	7 DAT	10 DAT	14 DAT	
T1	Agni asthiram @ 30 mL/L	3.25 (1.93)	2.25 (1.65)^{ab}	1.25 (1.31)^{b}	0.75 (1.10)^{b}	0.25 (0.84)^{b}	3.25 (1.93)	2.25 (1.65)^{ab}	1.75 (1.49)^{b}	1.00 (1.18)^{b}	0.25 (0.84)^{b}	36.92^{ab}
T2	Fish ensilage oil @ 10 mL/L	3.00 (1.87)	2.50 (1.73)^{b}	2.00 (1.58)^{c}	1.25 (1.27)^{b}	0.75 (1.10)^{b}	3.25 (1.93)	2.75 (1.80)^{ab}	2.00 (1.58)^{b}	1.50 (1.40)^{b}	0.75 (1.10)^{a}	35.11^{b}
T3	Neem oil @ 20 mL/L	3.25 (1.92)	2.25 (1.65)^{b}	1.75 (1.49)^{b}	1.00 (1.22)^{b}	0.50 (0.97)^{b}	3.75 (2.06)	2.50 (1.73)^{b}	1.75 (1.49)^{b}	1.25 (1.31)^{b}	0.25 (0.84)^{b}	36.56^{ab}
T4	Neem Seed Kernel Extract @ 5%	3.75 (2.06)	2.00 (1.58)^{ab}	1.25 (1.31)^{ab}	0.50 (0.97)^{ab}	0.00 (0.71)^{a}	3.50 (2.00)	2.25 (1.65)^{a}	1.50 (1.40)^{ab}	0.75 (1.10)^{ab}	0.00 (0.71)^{a}	37.17^{a}
T5	Azadirachtin 3000 ppm @ 2 mL/L	3.00 (1.86)	1.75 (1.49)^{a}	1.00 (1.22)^{a}	0.25 (0.84)^{a}	0.00 (0.71)^{a}	3.25 (1.93)	2.00 (1.58)^{a}	1.25 (1.31)^{a}	0.25 (0.84)^{a}	0.00 (0.71)^{a}	37.48^{a}
T6	Untreated check	3.00 (1.86)	3.25 (1.93)^{c}	3.50 (2.00)^{d}	3.50 (2.00)^{c}	3.75 (2.06)^{c}	3.50 (2.00)	3.50 (2.00)^{b}	3.75 (2.06)^{c}	4.00 (2.11)^{c}	3.75 (2.06)^{b}	23.25^{c}
	CD (p=0.05)	NS	0.19	0.21	0.33	0.31	NS	0.22	0.26	0.38	0.39	2.01

PTC = Pre-treatment count; DAT = Days after treatment
Figures in parentheses are $\sqrt{(x+0.5)}$ transformed values
In a column, means followed by common letters are not significantly different by LSD (P=0.05)

3.3 Efficacy of Biopesticides

3.3.1 Aphid, *M. persicae*

The results of the field experiment conducted at farmer's holdings at Kaliyavur village of Thoothukudi district during Rabi 2018 are presented in Table 4. Among the four biopesticides evaluated, *Beauveria bassiana* at 2 g/L was effective against *M. persicae*, which reduced the population before treatment (31.50 aphids per five plants) to 23.50, 12.00, 8.25, and 4.50 aphids per five plants at 3, 7, 10, and 14 DAT, respectively. *Lecanicillium lecanii* at 2 g/L reduced the aphid population from 31.50 aphids per five plants (before treatment) to 24.25, 12.75, 9.25, and 5.25 aphids per five plants at 3, 7, 10, and 14 DAT, respectively.

3.3.2 Serpentine leaf miner, *L. trifolii*

The per cent leaf damage due to infestation of *L. trifolii* was lowest in the plots treated with *Metarhizium anisopliae* at 2 g/L (11.96 per cent leaf damage per five plants before treatment and 1.87 per cent leaf damage per five plants at 14 DAT), followed by *B. bassiana* at 2 g/L (12.85 per cent leaf damage per five plants before treatment and 2.36 per cent leaf damage per five plants at 14 DAT) (Table 4).

3.3.3 Red Pumpkin beetle, *A. foveicollis*

The results of the experiment revealed that all the biopesticides significantly reduced the population of *A. foveicollis* in comparison with the untreated check. *B. bassiana* at 2 g/L was most effective against *A. foveicollis*, which reduced the population from 3.25 beetles per five plants (before treatment) to 1.00 beetles per five plants at 14 DAT and was on par with other biopesticides (Table 5).

3.3.4 Pumpkin caterpillar, *D. indica*

Among the biopesticides evaluated, *Bacillus thuringiensis* at 2 g/L applied plots recorded the lowest population of *D. indica*. The larval population was 0.50 per five plants at 3 days after treatment, and no larvae were recorded at 10 days after *B. thuringiensis* application (Table 5).

3.3.5 Yield

The highest yield was recorded in the plots applied with *B. bassiana* at 2 g/L (33.65 t/ha), followed by *M. anisopliae* at 2 g/L (32.55 t/ha). *L. lecanii* at 2 g/L (31.16 t/ha) and *B. thuringiensis* at 2 g/L (31.11 t/ha) also recorded the highest yield compared to untreated check (23.05 t/ha) and were on par with each other (Table 5).

TABLE 4
EFFICACY OF BIOPESTICIDES AGAINST *M. PERSICAE* AND *L. TRIFOLII* ON ASH GOURD DURING RABI 2018

S. No.	Treatments	Number of aphids/5 plants*					Per cent leaf damage by *L. trifolii*/5 plants#				
		PTC	3 DAT	7 DAT	10 DAT	14 DAT	PTC	3 DAT	7 DAT	10 DAT	14 DAT
T1	*Beauveria bassiana* @ 1×10⁸ CFU/g @ 2 g/L	31.50 (5.65)	23.50 (4.90)[a]	12.00 (3.53)[a]	8.25 (2.96)[a]	4.50 (2.22)[a]	12.85 (20.97)	5.30 (13.30)[a]	3.38 (10.58)[a]	2.84 (9.64)[ab]	2.36 (8.76)[ab]
T2	*Metarhizium anisopliae* @ 1×10⁸ CFU/g @ 2 g/L	32.00 (5.70)	25.00 (5.05)[a]	13.50 (3.74)[ab]	10.25 (3.27)[bc]	5.75 (2.49)[ab]	11.96 (20.19)	5.03 (12.96)[a]	3.06 (10.07)[a]	2.21 (8.54)[a]	1.87 (7.82)[a]
T3	*Lecanicillium lecanii* @ 1×10⁸ CFU/g @ 2 g/L	31.50 (5.65)	24.25 (4.97)[a]	12.75 (3.64)[a]	9.25 (3.12)[ab]	5.25 (2.39)[ab]	12.19 (20.41)	5.55 (13.63)[ab]	3.45 (10.69)[a]	3.22 (10.31)[bc]	2.52 (9.08)[ab]
T4	*Bacillus thuringiensis* @ 0.5% WP @ 2 g/L	34.75 (5.94)	25.75 (5.12)[a]	14.75 (3.90)[b]	11.75 (3.50)[c]	6.50 (2.64)[b]	12.89 (21.03)	6.01 (14.19)[b]	4.04 (11.60)[b]	3.87 (11.33)[c]	3.15 (10.19)[b]
T5	Untreated check	31.75 (5.66)	32.50 (5.74)[b]	33.25 (5.81)[c]	34.00 (5.87)[d]	35.50 (6.00)[c]	12.18 (20.41)	12.57 (20.75)[c]	12.92 (21.04)[c]	13.02 (21.14)[d]	13.03 (21.16)[c]
	CD (p=0.05)	NS	0.29	0.37	0.41	0.4	NS	1.29	1.9	2.32	2.06

PTC = Pre-treatment count; DAT = Days after treatment; WP = Wettable powder
Figures in parentheses are √(x+0.5) transformed values; #Figures in parentheses are arc-sine transformed values
In a column, means followed by common letters are not significantly different by LSD (P=0.05)

TABLE 5
EFFICACY OF BIOPESTICIDES AGAINST A. FOVEICOLLIS AND D. INDICA ON ASH GOURD DURING RABI 2018

S. No.	Treatments	Number of beetles/5 plants*					Number of larvae/5 plants*					Yield (t/ha)
		PTC	3 DAT	7 DAT	10 DAT	14 DAT	PTC	3 DAT	7 DAT	10 DAT	14 DAT	
T1	*Beauveria bassiana* @ 1×10⁸ CFU/g @ 2 g/L	3.25 (1.93)	2.00 (1.56)[a]	1.75 (1.49)[a]	1.25 (1.31)[a]	1.00 (1.22)[a]	3.25 (1.92)	2.75 (1.80)[b]	1.25 (1.31)[b]	0.50 (0.97)[b]	0.25 (0.84)[ab]	33.65[a]
T2	*Metarhizium anisopliae* @ 1×10⁸ CFU/g @ 2 g/L	3.50 (2.00)	2.25 (1.65)[a]	2.00 (1.58)[a]	1.50 (1.40)[a]	1.25 (1.31)[a]	3.50 (2.00)	3.00 (1.86)[b]	1.75 (1.49)[bc]	1.25 (1.31)[b]	0.75 (1.10)[b]	32.55[a]
T3	*Lecanicillium lecanii* @ 1×10⁸ CFU/g @ 2 g/L	3.25 (1.92)	2.25 (1.65)[a]	2.00 (1.58)[a]	1.75 (1.49)[a]	1.50 (1.40)[a]	3.50 (1.99)	2.75 (1.80)[b]	2.50 (1.73)[cd]	1.50 (1.40)[b]	0.75 (1.10)[b]	31.16[a]
T4	*Bacillus thuringiensis* @ 0.5% WP @ 2 g/L	3.50 (1.99)	2.50 (1.71)[a]	2.25 (1.65)[a]	1.75 (1.49)[a]	1.50 (1.40)[a]	3.75 (2.06)	0.50 (0.97)[a]	0.25 (0.84)[a]	0.00 (0.71)[a]	0.00 (0.71)[a]	31.11[a]
T5	Untreated check	3.50 (2.00)	3.75 (2.06)[b]	3.75 (2.06)[b]	3.50 (2.00)[b]	3.50 (2.00)[b]	3.25 (1.93)	3.50 (2.00)[b]	3.50 (2.00)[d]	3.75 (2.06)[c]	3.75 (2.06)[c]	23.05[b]
	CD (p=0.05)	NS	0.29	0.28	0.31	0.31	NS	0.28	0.23	0.34	0.32	3.93

PTC = Pre-treatment count; DAT = Days after treatment; WP = Wettable powder
Figures in parentheses are √(x+0.5) transformed values
In a column, means followed by common letters are not significantly different by LSD (P=0.05)

3.4 Efficacy of newer insecticides against major sucking pests

The results of the field experiment conducted during Rabi 2018 revealed that all the newer insecticides significantly reduced the population of *M. persicae*. The plots treated with Imidacloprid 17.8 SL (soluble liquid) at 0.2 mL/L recorded nil population of *M. persicae* from 3 DAT onwards till harvest, followed by Thiamethoxam 25 WG (water-dispersible granules) at 0.2 g/L, which recorded 0.25 aphids per five plants at 3 DAS and the population was nil after 7 DAT (Table 6). The plots treated with Imidacloprid 17.8 SL at 0.2 mL/L recorded the highest yield (37.25 t/ha), followed by Thiamethoxam 25 WG at 0.2 g/L (37.12 t/ha) and Acetamiprid 20 SP (soluble powder) at 0.2 g/L (36.82 t/ha) (Table 6).

TABLE 6
EFFICACY OF NEWER INSECTICIDES AGAINST APHID, *M. PERSICAE* ON ASH GOURD DURING RABI 2018

S. No.	Treatments	Number of aphids/5 plants*					Yield (t/ha)
		PTC	3 DAT	7 DAT	10 DAT	14 DAT	
T1	Imidacloprid 17.8 SL @ 0.2 mL/L	30.75 (5.59)	0.00 (0.71)[a]	0.00 (0.71)[a]	0.00 (0.71)[a]	0.00 (0.71)[a]	37.25[a]
T2	Thiamethoxam 25 WG @ 0.2 g/L	31.50 (5.65)	0.25 (0.84)[ab]	0.00 (0.71)[a]	0.00 (0.71)[a]	0.00 (0.71)[a]	37.12[a]
T3	Acetamiprid 20 SP @ 0.2 g/L	31.25 (5.63)	0.75 (1.10)[bc]	0.00 (0.71)[a]	0.00 (0.71)[a]	0.00 (0.71)[a]	36.82[a]
T4	Thiacloprid 240 SC @ 0.6 mL/L	33.50 (5.83)	1.00 (1.22)[cd]	0.00 (0.71)[a]	0.00 (0.71)[a]	0.00 (0.71)[a]	36.78[a]
T5	Dimethoate 30 EC @ 1.5 mL/L	32.25 (5.70)	1.50 (1.40)[d]	1.25 (1.31)[b]	1.00 (1.22)[b]	0.25 (0.84)[a]	36.11[a]
T6	Untreated check	33.50 (5.82)	34.00 (5.87)[e]	36.50 (6.08)[c]	37.75 (6.18)[c]	39.00 (6.28)[b]	21.98[b]
	CD (p=0.05)	NS	0.32	0.34	0.3	0.29	1.95

PTC = Pre-treatment count; DAT = Days after treatment; SL = Soluble liquid; WG = Water-dispersible granules; SP = Soluble powder; SC = Suspension concentrate; EC = Emulsifiable concentrate
Mean of four replications; Figures in parentheses are $\sqrt{(x+0.5)}$ transformed values
In a column, means followed by common letters are not significantly different by LSD (P=0.05)

3.5 Efficacy of newer insecticides against major defoliators and borers

3.5.1 Red Pumpkin beetle, *A. foveicollis*

The results of the field experiment conducted at farmer's holdings at Kaliyavur village of Thoothukudi district during Rabi 2018 revealed that all the insecticides applied had significantly reduced the population of *A. foveicollis* in comparison with the untreated check. Spinosad 45 SC (suspension concentrate) at 0.5 mL/L, Flubendiamide 480 SC at 0.1 mL/L, and Chlorantraniliprole 18.5 SC at 0.3 mL/L were most effective against *A. foveicollis* and recorded nil population from 3 DAT till harvest, and they were on par with Emamectin benzoate 5 SG at 0.4 g/L and Chlorpyriphos 20 EC at 2 mL/L (Table 7).

3.5.2 Pumpkin caterpillar, *D. indica*

The plots treated with Flubendiamide 480 SC at 0.1 mL/L and Chlorantraniliprole 18.5 SC at 0.3 mL/L recorded cent per cent control of *D. indica* from 3 DAT till harvest. Emamectin benzoate 5 SG at 0.4 g/L and Spinosad 45 SC at 0.5 mL/L were also effective and recorded nil population from 7 DAT till harvest (Table 7).

3.5.3 Yield

All the newer insecticides significantly recorded the highest fruit yield compared to untreated check. Chlorantraniliprole 18.5 SC at 0.3 mL/L treated plots recorded the highest yield of 37.65 t/ha, followed by Flubendiamide 480 SC at 0.1 mL/L (37.55 t/ha) and Spinosad 45 SC at 0.5 mL/L (37.51 t/ha) (Table 7).

TABLE 7
EFFICACY OF NEWER INSECTICIDES AGAINST *A. FOVEICOLLIS* AND *D. INDICA* ON ASH GOURD DURING RABI 2018

S. No.	Treatments	Number of beetles/5 plants*					Number of larvae/5 plants*					Yield (t/ha)
		PTC	3 DAT	7 DAT	10 DAT	14 DAT	PTC	3 DAT	7 DAT	10 DAT	14 DAT	
T1	Spinosad 45 SC @ 0.5 mL/L	3.00 (1.87)	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	3.00 (1.86)	0.25 (0.84)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	37.51^{a}
T2	Flubendiamide 480 SC @ 0.1 mL/L	3.25 (1.93)	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	3.25 (1.93)	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	37.55^{a}
T3	Chlorantraniliprole 18.5 SC @ 0.3 mL/L	3.25 (1.92)	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	3.00 (1.86)	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	37.65^{a}
T4	Emamectin benzoate 5 SG @ 0.4 g/L	3.25 (1.92)	0.25 (0.84)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	3.50 (2.00)	0.25 (0.84)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	37.35^{a}
T5	Chlorpyriphos 20 EC @ 2 mL/L	2.75 (1.80)	0.25 (0.84)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	3.25 (1.92)	0.50 (0.97)^{a}	0.25 (0.84)^{a}	0.00 (0.71)^{a}	0.00 (0.71)^{a}	37.11^{a}
T6	Untreated check	3.00 (1.87)	3.25 (1.93)^{b}	3.50 (2.00)^{b}	3.75 (2.06)^{b}	3.75 (2.06)^{b}	3.00 (1.86)	3.25 (1.93)^{b}	3.50 (2.00)^{b}	3.50 (2.00)^{b}	3.75 (2.06)^{b}	22.75^{b}
	CD (p=0.05)	NS	0.24	0.29	0.3	0.27	NS	0.3	0.39	0.35	0.26	2.06

PTC = Pre-treatment count; DAT = Days after treatment; SC = Suspension concentrate; SG = Soluble granule; EC = Emulsifiable concentrate
Mean of four replications; Figures in parentheses are √(x+0.5) transformed values
In a column, means followed by common letters are not significantly different by LSD (P=0.05)

IV. DISCUSSION

4.1 Evaluation of Sticky Traps

In the present investigation, cylindrical yellow sticky traps recorded the highest catches of *L. trifolii* adults, whereas white cylindrical sticky traps attracted the highest number of alate forms of *M. persicae*. The present findings are in confirmatory with Arida et al. (2013), who reported that yellow sticky traps are more attractive to *L. trifolii* adults than blue, purple, or white traps in onion. Sticky traps are efficient in attracting winged forms of aphids, which is in confirmation with earlier findings of Elango et al. (2017), Jasrotia et al. (2022), and Grupe et al. (2023).

4.2 Efficacy of Botanicals and Organic Pesticides

Among the botanical and organic pesticides tested against major pests of ash gourd, Azadirachtin 3000 ppm at 2 mL/L was most effective against pests viz., *M. persicae*, *L. trifolii*, *A. foveicollis*, and *D. indica* in Rabi 2018. This is in line with the findings of Tandon and Sirohi (2009) and Patel et al. (2021), who reported that Azadirachtin was effective in repelling *A. foveicollis*. Christopher et al. (2009) found that the survival of *M. persicae* nymphs was affected by azadirachtin.

4.3 Efficacy of Biopesticides

Biopesticides are good alternatives to synthetic chemical pesticides, and in the present study, *Beauveria bassiana* at 1×10^{8} CFU/g at 2 g/L was effective against *M. persicae* and *A. foveicollis*. Khan et al. (2012) stated that *L. lecanii* and *B. bassiana* strains were effective against *M. persicae*. Earlier, Joseph and Sudharma (2016) and Gahlot et al. (2024) reported that *B. bassiana* was highly effective in bringing mortality of *A. foveicollis*. *Metarhizium anisopliae* at 1×10^{8} CFU/g at 2 g/L was effective against *L. trifolii* on ash gourd. El-Salam et al. (2013) also reported that *M. anisopliae* was effective against *L. trifolii* on fababean. *Bacillus thuringiensis* at 0.5% WP at 2 g/L recorded the lowest population of pumpkin caterpillar, *D. indica*, which is confirmatory with Jacob et al. (2019). Soumya et al. (2017) also reported that *B. thuringiensis* was very effective against *D. indica*.

4.4 Efficacy of Newer Insecticides

Newer insecticide molecules with novel modes of action at lower rates than the conventional insecticides are being used against different insect pests in various crops. These chemicals are relatively safer to the non-target organisms and leave no harmful residues in the environment. Keeping this in mind, newer insecticide molecules were evaluated against the major sucking pests and defoliators of ash gourd. In the present course of study, Imidacloprid 17.8 SL at 0.2 mL/L, followed by Thiamethoxam 25 WG at 0.2 g/L and Acetamiprid 20 SP at 0.2 g/L, significantly reduced the population of *M. persicae* on ash gourd and recorded higher yield over the untreated check. Similar kinds of results were obtained by various scientific workers on different crops (Christopher et al., 2009; Halder et al., 2011; El-Sayed, 2013; Gavkare et al., 2013; Sretenovic et al., 2019), which shows the effectiveness of newer insecticides.

Similarly, Spinosad 45 SC at 0.5 mL/L, Flubendiamide 480 SC at 0.1 mL/L, and Chlorantraniliprole 18.5 SC at 0.3 mL/L were most effective against *A. foveicollis* and *D. indica*. The reduction of *D. indica* population might be due to the translaminar action of the newer molecules, and these results are in accordance with the findings of Nagaraju et al. (2018), who reported that chlorantraniliprole 18.5 SC at 0.2 mL/L followed by flubendiamide 48 SC at 0.15 mL/L were effective against *D. indica*.

V. CONCLUSION

The study tested the efficacy of sticky traps, botanicals and organic pesticides, biopesticides, and newer insecticides against major pests of ash gourd in field conditions. The findings of the study will be helpful in developing Biointensive Pest Management (BIPM) modules for the effective management of insect pests of ash gourd.

Key Recommendations:

1) **Sticky Traps:** White sticky traps for monitoring *M. persicae* (alate forms) and yellow sticky traps for monitoring *L. trifolii* can be effectively used in IPM programmes.
2) **Botanicals:** Azadirachtin 3000 ppm at 2 mL/L was the most effective botanical, followed by Neem Seed Kernel Extract at 5%, for managing multiple pests and recording the highest yield (37.48 t/ha).
3) **Biopesticides:** *Beauveria bassiana* at 2 g/L was effective against *M. persicae* and *A. foveicollis*; *Metarhizium anisopliae* at 2 g/L against *L. trifolii*; and *Bacillus thuringiensis* at 2 g/L against *D. indica*. These can be integrated into organic pest management programmes.
4) **Newer Insecticides:** Imidacloprid 17.8 SL at 0.2 mL/L for sucking pests, and Spinosad 45 SC at 0.5 mL/L, Flubendiamide 480 SC at 0.1 mL/L, and Chlorantraniliprole 18.5 SC at 0.3 mL/L for defoliators and borers, were highly effective and should be recommended to farmers for effective pest management with minimal environmental impact.
5) **Future Research:** Long-term studies on the impact of these treatments on natural enemies, and their integration into a comprehensive IPM package, are recommended.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The authors alone are responsible for the content and writing of this article.

REFERENCES

[1] Arida, G. S., Punzal, B. S., Shepard, B. M., & Rajotte, E. G. (2013). Sticky board traps for managing leafminer, *Liriomyza trifolii* (Burgess) (Diptera: Agromyzidae), infestation in onion (*Allium cepa* Linn.). *Philippine Entomologist*, *27*(2), 109-119.

[2] Atwal, A. S. (1993). *Agriculture pests of India and South East Asia*. Kalyani Publishers.

[3] Azmi, M. A., Naqvi, S. N., Azmi, M. A., & Aslam, M. (2006). Effect of pesticide residues on health and different enzyme levels in the blood of farm workers from Gadap (rural area) Karachi-Pakistan. *Chemosphere*, *64*(10), 1739-1744.

[4] Christopher Cutler, G., Ramanaidu, K., Astatkie, T., & Isman, M. B. (2009). Green peach aphid, *Myzus persicae* (Hemiptera: Aphididae), reproduction during exposure to sublethal concentrations of imidacloprid and azadirachtin. *Pest Management Science*, *65*(2), 205-209.

[5] DES. (2019). *Area, production and productivity of Ash gourd (vegetables) by district-wise in Tamil Nadu for year 2016-17*. Directorate of Economics and Statistics, Government of India.

[6] Dhillon, M. K., Singh, R., Naresh, J. S., & Sharma, H. C. (2005). The melon fruit fly, *Bactrocera cucurbitae*: A review of its biology and management. *Journal of Insect Science*, *5*(1), 40.

[7] Elango, K., Sridharan, S., Saravanan, P. A., & Balakrishnan, S. (2017). Relative performance of different colour laden sticky traps on the attraction of sucking pests in pomegranate. *International Journal of Current Microbiology and Applied Sciences*, *6*(11), 2997-3004. https://doi.org/10.20546/ijcmas.2017.611.350

[8] El-Salam, A. M. E., Salem, H. A., & Salem, S. A. (2013). Biocontrol agents against the leafminer, *Liriomyza trifolii* in fababean fields. *Archives of Phytopathology and Plant Protection*, *46*(9), 1054-1060.

[9] El-sayed, W. (2013). Field evaluation of plant extracts and certain insecticides against *Bemisia tabaci* (Gennadius) on tomato plants and *Myzus persicae* (Sulzer) on pepper plants. *Journal of Applied Sciences Research*, *9*(3), 2372-2377.

[10] Gahlot, N., Kumar, P., Choudhary, A. K., & Gangwar, B. (2024). Performance of management of the red pumpkin beetle (*Aulacophora foveicollis*) Lucas on bottle gourd by different bio-pesticides. *Uttar Pradesh Journal of Zoology*, *45*(17), 332-336. https://doi.org/10.56557/upjoz/2024/v45i174376

[11] Gavkare, O., Kumar, S., Sharma, N., & Sharma, P. L. (2013). Evaluation of some novel insecticides against *Myzus persicae* (Sulzer). *The Bioscan*, *8*(3), 1119-1121.

[12] Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research* (2nd ed.). John Wiley & Sons.

[13] Grupe, B., Dieckhoff, C., & Meyhöfer, R. (2023). Keep an eye on natural enemies: What *Aphidius* on sticky traps tells us about aphid pest population dynamics. *Entomologia Experimentalis et Applicata*, *171*(10), 722-731. https://doi.org/10.1111/eea.13360

[14] Halder, J., Kodandaram, M. H., & Rai, A. B. (2011). Differential responses of major vegetable aphids to newer insecticide molecules. *Vegetable Sciences*, *38*(2), 191-193.

[15] Jacob, J. R., Girija, D., Mathew, M. P., & Gopal, K. S. (2019). Evaluation of *Bacillus thuringiensis* isolates against *Diaphania indica* (Saund.) (Lepidoptera: Crambidae). *Journal of Tropical Agriculture*, *57*(1), 1-9.

[16] Jasrotia, P., Yadav, J., Singh, B., Patil, S. D., Kumar, S., & Singh, G. P. (2022). Efficiency of sticky traps for monitoring aphids in wheat under North-Western Plains and Peninsular zones of India. *Journal of Environmental Biology*, *43*(6), 794-800. https://doi.org/10.22438/jeb/43/6/MRN-1952

[17] Joseph, A., & Sudharma, K. (2016). Evaluation of bioassay of entomopathogenic fungi, *Beauveria bassiana* (Bals.) Vuill and *Metarhizium anisopliae* (Metchnikoff) Sorokin on red pumpkin beetle, *Aulacophora foveicollis* Lucas. *International Journal of Agriculture Innovations and Research*, *4*(5), 917-920.

[18] Khan, S., Guo, L., Shi, H., Mijit, M., & Qiu, D. (2012). Bioassay and enzymatic comparison of six entomopathogenic fungal isolates for virulence or toxicity against green peach aphids *Myzus persicae*. *African Journal of Biotechnology*, *11*(77), 14193-14203.

[19] Nagaraju, M. C., Nadagouda, S., Hosamani, A. C., & Hurali, S. (2018). Field evaluation of insecticides for the management of cucumber moth, *Diaphania indica* (Saunders) (Lepidoptera: Crambidae) on bitter gourd. *Journal of Entomology and Zoology Studies*, *6*(2), 79-82.

[20] Patel, D. R., Patel, R. M., Patel, P. H., & Dabhi, M. V. (2021). Evaluation of different botanicals against red pumpkin beetle, *Aulacophora foveicollis* Lucas infesting cucumber. *International Journal of Current Microbiology and Applied Sciences*, *10*(2), 3133-3140. https://doi.org/10.20546/ijcmas.2021.1002.343

[21] Soumya, K., Visalakshy, P. G., Swathi, C., Krishnamoorthy, A., & Gopalakrishna Pillai, K. (2017). Integrated pest management of melon borer, *Diaphania indica* (Lepidoptera: Pyralidae) in bittergourd. *Journal of Biological Control*, *31*(4), 240-244.

[22] Sretenovic, M., Miletic, N., & Tamas, N. (2019). Efficacy of different insecticides for the control of green peach aphid (*Myzus persicae* Sulzer) in nectarine orchards. *Pakistan Journal of Agricultural Sciences*, *56*(3), 661-668. https://doi.org/10.21162/PAKJAS/19.8690

[23] Tamilnayagan, T., Suganthy, M., Ganapathy, N., Renukadevi, P., & Malathi, V. G. (2017a). Population dynamics of defoliator pests and two spotted spider mite of ash gourd. *International Journal of Entomology and Zoology Studies*, *5*(3), 293-296.

[24] Tamilnayagan, T., Suganthy, M., Ganapathy, N., Renukadevi, P., & Malathi, V. G. (2017b). Seasonal abundance of sucking pests of ash gourd (*Benincasa hispida*) (Thunb.) Cogn.) in Tamil Nadu. *International Journal of Entomology and Zoology Studies*, *5*(3), 430-433.

[25] Tandon, P., & Sirohi, A. (2009). Laboratory assessment of the repellent properties of ethanolic extracts of four plants against *Raphidopalpa foveicollis* Lucas (Coleoptera: Chrysomelidae). *International Journal of Sustainable Crop Production*, *4*(2), 1-5.

[26] Tindall, H. D. (1986). *Vegetables in the tropics*. Macmillan Education Ltd.

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Nanotechnology: Current Applications, Safety Issues and Future Prospects in Veterinary Pharmacology and Toxicology

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Abstract— *Nanotechnology has emerged as one of the most promising advancements in modern pharmaceutical sciences due to its ability to manipulate materials at the nanoscale and enhance their interaction with biological systems. In veterinary pharmacology and toxicology, nanotechnology offers innovative solutions to overcome the limitations associated with conventional drug delivery systems, such as poor bioavailability, lack of target specificity, rapid elimination, systemic toxicity, and drug residue concerns in food-producing animals. Nanotechnology-based drug delivery systems improve therapeutic efficacy by enhancing drug solubility, stability, controlled release, and targeted delivery.*

Various nanocarriers, including liposomes, polymeric nanoparticles, solid lipid nanoparticles, nanoemulsions, dendrimers, quantum dots, magnetic nanoparticles, nanoshells, and nanopores, have shown significant applications in veterinary therapeutics, diagnostics, oncology, vaccine delivery, and infectious disease management. These nanosystems improve the pharmacokinetic and pharmacodynamic properties of drugs while minimizing adverse effects.

Despite their advantages, nanotechnology-based products raise important safety and toxicological concerns. The unique physicochemical properties of nanoparticles may result in organ toxicity, immunotoxicity, reproductive toxicity, oxidative stress, and environmental hazards. Species-specific responses and long-term exposure effects further complicate safety evaluation in veterinary applications. Therefore, comprehensive nanotoxicological assessment and regulatory oversight are essential before widespread adoption.

The future prospects of nanotechnology in veterinary pharmacology and toxicology include the development of smart nanocarriers, nano-theranostics, nano-phytogenics, precision veterinary medicine, and environmentally safer nanomaterials. This review consolidates findings from multiple scientific studies to present a comprehensive overview of the current applications, safety issues, and future prospects of nanotechnology in veterinary pharmacology and toxicology (Alivisatos, 2004; McNeil, 2009; Patra et al., 2018).

Keywords— Nanotechnology; Veterinary pharmacology; Veterinary toxicology; Nanocarriers; Drug delivery systems; Nanotoxicology; Nanomedicine; Targeted drug delivery; Veterinary therapeutics; Nanosafety; Environmental toxicity.

I. INTRODUCTION

Veterinary pharmacology and toxicology form the foundation of effective disease prevention, treatment, and control in animals. The rational use of drugs in veterinary practice is essential not only for animal health and welfare but also for ensuring food safety and public health. Conventional drug formulations often face several limitations, including poor aqueous solubility, low bioavailability, non-specific distribution, rapid metabolism, and short biological half-life. These drawbacks frequently necessitate higher doses or repeated administration, increasing the risk of toxicity and drug residues in milk, meat, and eggs (Patel et al., 2017).

In recent years, advancements in pharmaceutical sciences have focused on the development of novel drug delivery systems to overcome these challenges. Among these advancements, nanotechnology has gained significant attention due to its ability to modify drug behaviour at the molecular and cellular levels. Nanotechnology involves the design, synthesis, and application of materials with dimensions typically ranging from 1 to 100 nanometers. At this scale, materials exhibit unique physicochemical properties such as increased surface area, enhanced reactivity, altered optical behaviour, and improved interaction with biological membranes (Alivisatos, 2004).

In veterinary pharmacology, nanotechnology provides opportunities to enhance drug absorption, improve tissue targeting, prolong circulation time, and achieve controlled release. Nanocarriers protect drugs from premature degradation and facilitate site-specific delivery, thereby reducing systemic toxicity. In veterinary toxicology, nanotechnology offers tools to study toxicokinetics, minimize adverse drug reactions, and develop safer therapeutic formulations. Additionally, nanotechnology has expanded its applications beyond drug delivery to include diagnostics, imaging, vaccine development, and cancer therapy in animals (McNeil, 2009; Patra et al., 2018).

However, the increasing application of nanomaterials raises concerns regarding their safety. Due to their small size and high reactivity, nanoparticles may cross biological barriers and accumulate in vital organs. Understanding the toxicological implications of nanotechnology is therefore crucial for its safe and responsible application. This review aims to discuss the current applications of nanotechnology in veterinary pharmacology and toxicology, highlight associated safety issues, and explore future prospects in this rapidly evolving field.

II. DEFINITION AND CONCEPT OF NANOTECHNOLOGY

Nanotechnology is defined as the science and engineering of materials at the nanometer scale, typically between 1 and 100 nanometers, where unique physical, chemical, and biological properties emerge. At the nanoscale, materials exhibit increased surface-to-volume ratio, enhanced reactivity, and improved interaction with biological systems, making them suitable for pharmaceutical and biomedical applications (Alivisatos, 2004).

In the context of veterinary pharmacology and toxicology, nanotechnology refers to the application of nanoscale materials and systems for improving drug delivery, therapeutic efficacy, diagnostic accuracy, and safety evaluation in animals. Nanomaterials can be engineered to encapsulate drugs, vaccines, genes, or imaging agents and deliver them in a controlled and targeted manner. Surface modification of nanocarriers with polymers, ligands, or antibodies further enhances biocompatibility and specificity (Sapino et al., 2022).

III. HISTORY OF NANOTECHNOLOGY

TABLE 1
HISTORICAL DEVELOPMENT OF NANOTECHNOLOGY AND ITS RELEVANCE TO VETERINARY PHARMACOLOGY AND TOXICOLOGY

Year/Period	Major Development	Relevance to Veterinary Pharmacology & Toxicology
1959	Richard Feynman proposed manipulation of matter at atomic level	Laid conceptual foundation for nanoscale drug design and targeted therapy
1974	Term "nanotechnology" coined by Norio Taniguchi	Formal beginning of nanoscale precision relevant to drug formulation
1980-1985	Development of STM and AFM techniques	Enabled characterization of nanodrug carriers used in pharmacology
1985	Discovery of fullerenes	Sparked interest in nanoscale materials with biological relevance
1990-1995	Development of liposomes as drug carriers	First nanocarriers applied for controlled drug delivery and toxicity reduction
Late 1990s	Expansion of nanotechnology into biomedical research	Adoption of nano-drug delivery concepts in veterinary medicine
Early 2000s	Polymeric nanoparticles and nanoemulsions developed	Improved pharmacokinetics and bioavailability of veterinary drugs
2005-2010	Emergence of nanotoxicology	Evaluation of nanoparticle-induced organ toxicity and safety
2010-2015	Targeted nanocarriers (SLNs, magnetic NPs) explored	Reduced systemic toxicity and drug residues in food animals
2015-2020	Use in veterinary oncology and vaccines	Improved cancer therapy and immune response in animals
2020-Present	Focus on precision veterinary medicine and nano-theranostics	Integration of pharmacology with safety, diagnostics and regulation

IV. NEED FOR NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

The urgent need for nanotechnology in veterinary science arises from the severe limitations of conventional medicine (Trif et al., 2023). Despite significant advances in veterinary therapeutics, conventional drug delivery systems continue to present multiple challenges that limit therapeutic success. Many veterinary drugs suffer from poor aqueous solubility, instability in gastrointestinal fluids, rapid first-pass metabolism, and non-specific tissue distribution. These limitations often result in reduced bioavailability and unpredictable therapeutic responses, particularly when the same drug is administered across different animal species with varying physiological characteristics. Standard diagnostic methods can often take days or weeks to identify a disease, during which time an entire herd may become infected, necessitating mass culling (Hill & Li, 2017). Nanotechnology addresses these needs by providing tools for early, on-site pathogen detection and "smart" delivery systems that release medications directly to diseased cells without harming healthy tissue (Woldeamanuel et al., 2021). It also offers a way to "re-life" old or toxic drugs by using nanocarriers to improve their solubility, half-life, and safety profiles (Woldeamanuel et al., 2021).

In food-producing animals, the use of higher or repeated drug doses increases the likelihood of drug residues in edible tissues such as milk, meat, and eggs. Residue persistence poses a serious concern for public health and may lead to the development of antimicrobial resistance. In addition, frequent handling and repeated dosing cause stress to animals, negatively affecting productivity and welfare. These challenges highlight the need for advanced drug delivery approaches that improve therapeutic efficiency while minimizing toxicity and residue-related risks (Patel et al., 2017).

Nanotechnology-based systems offer a promising solution to these limitations by improving drug solubility, protecting active molecules from enzymatic degradation, and enabling sustained and targeted drug release. By modifying pharmacokinetic behaviour, nanotechnology allows the use of lower drug doses while maintaining or enhancing therapeutic efficacy. This approach is particularly valuable in veterinary pharmacology, where species-specific dosing and safety margins are critical considerations (Patra et al., 2018).

V. SCOPE OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

The scope of nanotechnology in veterinary pharmacology and toxicology extends beyond conventional drug delivery and encompasses multiple aspects of animal healthcare. Nanotechnology-based systems are increasingly used for targeted drug delivery, controlled release formulations, diagnostic imaging, vaccine development, cancer therapy, and toxicological assessment.

In veterinary pharmacology, nanocarriers improve drug absorption, enhance tissue targeting, and prolong circulation time, thereby optimizing pharmacokinetic and pharmacodynamic profiles. In veterinary toxicology, nanotechnology contributes to the development of safer drug formulations by reducing off-target toxicity and enabling detailed evaluation of toxicokinetic behaviour. Additionally, nanomaterials are used as tools to study cellular and molecular mechanisms of toxicity, providing insights into drug-tissue interactions and adverse effect pathways (McNeil, 2009).

The integration of nanotechnology supports the concept of precision veterinary therapeutics, where treatments are tailored based on disease condition, species, and physiological status of animals. This broad scope highlights the multidisciplinary nature of nanotechnology in veterinary pharmacology and toxicology.

VI. CLASSIFICATION OF NANOMATERIALS

Nanomaterials used in veterinary pharmacology and toxicology can be broadly classified into organic, inorganic, and hybrid nanomaterials based on their composition and functional properties.

6.1 Organic Nanomaterials

Organic nanomaterials include liposomes, polymeric nanoparticles, solid lipid nanoparticles, nanoemulsions, and dendrimers. These systems are generally biocompatible and biodegradable, making them suitable for drug delivery applications. Organic nanocarriers are widely explored for the delivery of antimicrobials, antiparasitic agents, anticancer drugs, and vaccines in veterinary practice.

6.2 Inorganic Nanomaterials

Inorganic nanomaterials include metallic nanoparticles, magnetic nanoparticles, quantum dots, and nanoshells. These materials possess unique optical, magnetic, and thermal properties that make them useful for diagnostic imaging, targeted therapy, and therapeutic monitoring. However, inorganic nanomaterials often raise greater safety concerns due to their persistence and potential for bioaccumulation.

6.3 Hybrid Nanomaterials

Hybrid nanomaterials combine the advantages of both organic and inorganic components to achieve improved functionality and safety. These systems are designed to enhance therapeutic efficacy while minimizing toxicity, thereby offering promising applications in veterinary pharmacology and toxicology (Sapino et al., 2022).

VII. TYPES OF NANOCARRIERS AND THEIR APPLICATIONS

7.1 Liposomes

Liposomes are spherical vesicular systems composed mainly of phospholipids and cholesterol, arranged as one or more concentric bilayers surrounding an aqueous core. Due to their structural similarity to biological membranes, liposomes exhibit excellent biocompatibility and are widely used as drug delivery systems in veterinary pharmacology. They are capable of encapsulating both hydrophilic drugs within their aqueous core and lipophilic drugs within the lipid bilayer, thereby increasing formulation flexibility.

In veterinary pharmacology, liposomes are extensively explored to improve drug stability, enhance bioavailability, and reduce systemic toxicity. Liposomal drug delivery modifies pharmacokinetic behaviour by prolonging circulation time and enabling passive targeting to organs such as the liver and spleen. This is particularly useful in the treatment of systemic infections and neoplastic conditions in animals. Liposomal formulations of amphotericin B have demonstrated reduced nephrotoxicity compared to conventional formulations, highlighting their importance in veterinary therapeutics (Patel et al., 2017).

Additionally, liposomes reduce drug exposure to non-target tissues, thereby minimizing adverse effects and improving safety margins. In food-producing animals, this contributes to reduced drug residues in edible tissues, supporting food safety regulations. Liposomes are also explored as vaccine adjuvants and carriers, enhancing antigen presentation and immune response in veterinary vaccines (Sapino et al., 2022).

7.2 Polymeric Nanoparticles

Polymeric nanoparticles are solid colloidal systems typically prepared from biodegradable and biocompatible polymers such as poly(lactic acid), poly(lactic-co-glycolic acid), and chitosan. Chitosan is valued for its mucoadhesive properties and ability to protect DNA or drug payloads from degradation (Mweetwa et al., 2022). These nanoparticles range in size from a few nanometers to several hundred nanometers and are designed to provide controlled and sustained drug release.

In veterinary pharmacology, polymeric nanoparticles play a crucial role in improving drug delivery efficiency by protecting drugs from enzymatic degradation and releasing them in a predictable manner. Sustained drug release reduces dosing frequency, which is advantageous in large animals and wildlife where repeated administration is difficult. Polymeric nanoparticles have been investigated for the delivery of antimicrobials, antiparasitic drugs, anti-inflammatory agents, and hormones in animals (Carvalho et al., 2020).

Surface modification of polymeric nanoparticles enables active targeting to specific tissues, thereby reducing off-target toxicity. This targeted approach is particularly relevant in veterinary toxicology, as it helps minimize systemic exposure and adverse effects. In food-producing animals, polymeric nanoparticles also aid in reducing drug residue levels by maintaining therapeutic efficacy at lower doses (Zhou et al., 2024).

7.3 Solid Lipid Nanoparticles

Solid lipid nanoparticles are lipid-based nanocarriers composed of physiologically compatible solid lipids stabilized by surfactants. Unlike liquid lipid systems, solid lipid nanoparticles remain solid at body temperature, providing better physical stability and controlled drug release.

In veterinary pharmacology, solid lipid nanoparticles are used to improve the delivery of poorly water-soluble drugs. They enhance oral bioavailability by increasing drug solubility and protecting the active ingredient from degradation in the gastrointestinal tract. Solid lipid nanoparticles have been explored for delivering antimicrobials, anticancer drugs, and nutraceuticals in poultry and livestock (Patra et al., 2018).

From a toxicological perspective, solid lipid nanoparticles are considered relatively safe due to their biodegradable lipid composition. Their ability to reduce peak plasma concentrations helps minimize dose-related toxicity. Additionally, these systems offer potential for reducing drug residues, making them suitable for use in food-producing animals.

7.4 Nanoemulsions

Nanoemulsions are kinetically stable colloidal dispersions consisting of oil and water phases stabilized by surfactants, with droplet sizes typically below 200 nm. Due to their small droplet size, nanoemulsions exhibit enhanced drug solubilization and improved absorption across biological membranes.

In veterinary pharmacology, nanoemulsions are widely studied for oral, topical, and parenteral drug delivery. They are particularly useful for delivering lipophilic drugs and phytogenic compounds. Nanoemulsions improve bioavailability and therapeutic efficacy while reducing variability in drug absorption. In poultry and livestock, nanoemulsions are explored for antimicrobial delivery, vaccine formulations, and feed additives (Youssef, 2019).

Nanoemulsions also contribute to reduced drug doses and lower systemic toxicity, making them relevant from a veterinary toxicology standpoint. However, surfactant selection and concentration must be carefully optimized to avoid irritation or toxicity.

7.5 Quantum Dots

Quantum dots are semiconductor nanocrystals that exhibit size-dependent optical and fluorescent properties. In veterinary pharmacology, quantum dots are mainly used as diagnostic and research tools rather than therapeutic carriers. Their strong fluorescence and photostability make them valuable for imaging, drug tracking, and studying pharmacokinetics in animal models. Quantum dots are semiconductor nanocrystals used as highly sensitive bio-imaging probes (Dhakad et al., 2017).

Quantum dots are used to visualize drug distribution, tissue targeting, and cellular uptake, thereby aiding in pharmacological and toxicological evaluation of new formulations. In veterinary oncology, quantum dots assist in tumour imaging and lymph node mapping, supporting early diagnosis and therapeutic monitoring (Alivisatos, 2004).

However, due to concerns related to heavy metal content and long-term toxicity, quantum dots are mainly restricted to experimental and diagnostic applications. Their safety profile remains an important area of research in veterinary toxicology.

7.6 Magnetic Nanoparticles

Magnetic nanoparticles, particularly superparamagnetic iron oxide nanoparticles, possess unique magnetic properties that allow them to be guided using external magnetic fields. In veterinary pharmacology, these nanoparticles are used for targeted drug delivery, diagnostic imaging, and hyperthermia-based cancer therapy.

Drug-loaded magnetic nanoparticles can be directed to specific tissues using an external magnetic field, resulting in localized drug accumulation and reduced systemic exposure. This targeted approach enhances therapeutic efficacy while minimizing adverse effects. In veterinary oncology, magnetic nanoparticles are explored for localized tumour treatment through magnetic hyperthermia (Ianiski et al., 2022).

From a toxicological perspective, superparamagnetic behaviour ensures that nanoparticles do not retain magnetization once the magnetic field is removed, reducing the risk of aggregation and vascular embolization. Nevertheless, long-term safety and iron overload concerns must be carefully evaluated.

7.7 Nanoshells

Nanoshells are nanostructures consisting of a dielectric core, usually silica, coated with a thin metallic layer. These systems are engineered to absorb near-infrared radiation and convert it into heat, enabling localized thermal destruction of diseased tissues.

In veterinary pharmacology, nanoshells are being investigated primarily for tumour therapy. Upon exposure to external infrared radiation, nanoshells produce localized heat, leading to selective tumour cell destruction without damaging surrounding healthy tissues. This photothermal therapy approach offers a minimally invasive alternative for cancer treatment in animals (Patra et al., 2018).

Although promising, nanoshell applications are still under experimental evaluation and their safety profile requires further investigation in veterinary toxicology.

7.8 Nanoparticles and Nanoporous Systems (Nanopores)

Nanopores are highly porous nanostructures that allow selective passage of small molecules such as oxygen, glucose, and insulin while preventing the movement of immune cells and antibodies. This selective permeability makes nanopores useful in immune-protected drug and cell delivery systems.

In veterinary pharmacology, nanopores are explored for controlled drug release and cell-based therapies. Encapsulation of pancreatic β-cells within nanoporous systems allows nutrient exchange while preventing immune rejection, offering a novel approach for managing insulin-dependent diabetes mellitus in animals.

Nanopore systems represent an advanced interface between pharmacology and biotechnology, with significant therapeutic potential. However, long-term biocompatibility and safety concerns remain areas of active research.

VIII. ADVANTAGES OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

Nanotechnology provides significant advantages in veterinary pharmacology by improving the bioavailability of drugs that otherwise show poor solubility and limited absorption. Nano-sized drug carriers enhance dissolution rate and protect active pharmaceutical ingredients from chemical and enzymatic degradation, thereby improving systemic availability and therapeutic efficacy (Patra et al., 2018).

Targeted drug delivery is another major advantage of nanotechnology. Nanocarriers can be designed to selectively accumulate in diseased tissues through passive or active targeting mechanisms, reducing drug exposure to healthy tissues. This targeted approach enhances pharmacological efficacy while minimizing adverse effects, where dose margins are often narrow (Ianiski et al., 2022).

Nanotechnology also enables controlled and sustained release of drugs. Sustained release formulations maintain therapeutic drug concentrations over prolonged periods, reducing dosing frequency. This is highly beneficial in veterinary practice, especially in livestock and poultry, where repeated handling and administration cause stress and economic loss (Carvalho et al., 2020).

From a veterinary toxicology perspective, nanotechnology contributes to reduced systemic toxicity. By lowering peak plasma concentrations and restricting off-target distribution, nanoformulations decrease dose-related adverse effects. Reduced toxicity also helps minimize drug residues in animal-derived food products, improving food safety and public health protection (Patel et al., 2017).

In addition, nanotechnology enhances diagnostic and therapeutic capabilities in the veterinary field. Nanomaterials such as quantum dots and magnetic nanoparticles facilitate advanced imaging, drug tracking, and cancer therapy. Nano-vaccines and nano-adjuvants improve antigen delivery and immune response, leading to better disease prevention strategies in animals (Sapino et al., 2022).

IX. DISADVANTAGES AND LIMITATIONS OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

Despite its advantages, nanotechnology presents several limitations and safety concerns in veterinary pharmacology and toxicology. One of the major disadvantages is nanotoxicity. Due to their small size and large surface area, nanoparticles may induce oxidative stress, inflammation, and cellular damage. Accumulation of nanoparticles in vital organs such as the liver, kidneys, lungs, and spleen has been reported, raising concerns about long-term toxicity (Singh, 2019).

Another important limitation is the lack of comprehensive safety and species-specific toxicity data. Most toxicological studies are conducted in laboratory animals, and extrapolation of these results to different veterinary species is challenging due to physiological and metabolic differences. This uncertainty complicates risk assessment and safe dose determination in veterinary toxicology (Chrishtop et al., 2021).

Environmental toxicity is also a growing concern associated with nanotechnology. Nanomaterials may enter the environment through animal excreta, pharmaceutical waste, or agricultural runoff. The persistence and accumulation of nanoparticles in soil and aquatic ecosystems may adversely affect microorganisms, plants, and non-target organisms. The long-term environmental impact of veterinary nanoproducts remains insufficiently understood (McNeil, 2009).

Economic and technical constraints further limit the widespread application of nanotechnology in veterinary practice. The development and manufacturing of nano-based formulations require specialized equipment, skilled personnel, and high production costs. These factors restrict large-scale commercialization and field-level application, particularly in developing countries (Carvalho et al., 2020).

Regulatory and ethical challenges also represent major disadvantages. Currently, standardized regulatory guidelines for approval, quality control, and post-marketing surveillance of nanotechnology-based veterinary products are limited. Ethical concerns related to animal welfare, environmental safety, and long-term exposure further emphasize the need for cautious implementation of nanotechnology in veterinary pharmacology and toxicology (Sapino et al., 2022).

X. EXPANDED CURRENT APPLICATIONS OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

Nanotechnology has revolutionized veterinary pharmacology by enabling precise control over drug delivery, improving therapeutic outcomes, and reducing toxicological risks. The application of nanotechnology is largely driven by the need to optimize pharmacokinetic behaviour of drugs, minimize adverse effects, and address issues such as antimicrobial resistance and drug residues in food-producing animals. Recent reviews have highlighted the broad applications of nanotechnology in the veterinary field, including drug delivery, diagnostics, oncology, vaccine development, and safety evaluation. These applications demonstrate the growing role of nanotechnology in improving therapeutic efficacy and reducing toxicological risks in veterinary practice (Bilgili & Uysal, 2019).

10.1 Advanced Drug Delivery Applications in Veterinary Pharmacology

Nanotechnology-based drug delivery systems play a crucial role in modifying absorption, distribution, metabolism, and excretion of veterinary drugs. Nanocarriers enhance drug dissolution rate and membrane permeability, thereby improving oral and parenteral bioavailability. This is particularly relevant for drugs with poor aqueous solubility, such as antiparasitic agents and anticancer drugs. Nanoparticles also protect drugs from degradation in the gastrointestinal tract and during first-pass metabolism, leading to more predictable therapeutic responses (Patra et al., 2018).

Targeted drug delivery represents a major advancement enabled by nanotechnology. Surface modification of nanocarriers with ligands or antibodies allows selective accumulation of drugs at disease sites such as tumours, inflamed tissues, or infected organs. This targeted approach reduces off-target exposure and systemic toxicity, which is a major concern in veterinary pharmacology. In companion animals undergoing long-term therapy, targeted nanocarriers improve treatment efficacy while reducing adverse drug reactions (Ianiski et al., 2022).

Sustained and controlled drug release achieved through nanotechnology reduces dosing frequency and improves animal compliance. This application is especially beneficial in livestock and poultry, where repeated handling causes stress and economic loss. Controlled-release nanoformulations maintain therapeutic drug concentrations over extended periods, improving disease management and productivity (Patel et al., 2017).

10.2 Applications in Antimicrobial and Antiparasitic Therapy

Nanotechnology has shown significant potential in improving antimicrobial and antiparasitic therapy. Nanoformulated antibiotics exhibit enhanced penetration into infected tissues and biofilms, increasing antimicrobial efficacy. This is particularly important in the treatment of chronic infections and intracellular pathogens, where conventional antibiotics show limited effectiveness.

Nanotechnology also plays a role in addressing antimicrobial resistance. By improving drug targeting and reducing required doses, nanocarriers minimize selective pressure on microorganisms. Nano-phytogenics and nano-antimicrobials are being explored as alternative therapeutic strategies to reduce reliance on conventional antibiotics, thereby contributing to antimicrobial stewardship in veterinary practice (Sapino et al., 2022).

10.3 Diagnostic and Imaging Applications in Veterinary Toxicology

Nanotechnology has enhanced diagnostic and imaging capabilities in the veterinary field. Quantum dots and magnetic nanoparticles are used as imaging probes due to their superior optical and magnetic properties. These nanomaterials facilitate early disease detection, tumour localization, and real-time monitoring of drug distribution in animal tissues (Alivisatos, 2004). In disease diagnostics, the use of genosensors and biochips allows for the simultaneous detection of thousands of disease biomarkers (Prasad et al., 2021).

In veterinary toxicology, imaging-based nanotechnology applications help in evaluating drug biodistribution, organ accumulation, and toxicokinetic behaviour. These tools provide valuable insights into mechanisms of drug-induced toxicity and support the development of safer formulations.

10.4 Applications in Veterinary Vaccines and Immunotherapy

Nanotechnology has significantly improved vaccine delivery and immunotherapy in the veterinary field. Nanocarriers act as antigen carriers and adjuvants, enhancing antigen stability and immune response. Nano-vaccines improve antigen uptake by antigen-presenting cells and prolong immune stimulation, resulting in enhanced protection against infectious diseases.

Nanotechnology-based vaccines are particularly useful in poultry and livestock, where effective mass vaccination strategies are required. Improved vaccine efficacy reduces disease incidence, antimicrobial usage, and economic losses in animal production systems (Sapino et al., 2022).

10.5 Applications in Feed Additives, Nutraceuticals, and Growth Promotion

Nanotechnology is increasingly applied in the formulation of feed additives and nutraceuticals in veterinary practice. Nanoformulated vitamins, minerals, and phytogenic compounds exhibit improved absorption and bioavailability compared to conventional formulations. These applications enhance growth performance, immune function, and disease resistance in animals.

From a veterinary toxicology perspective, nanoformulations allow precise dose control and reduce the risk of toxicity associated with overdosing of micronutrients. However, long-term exposure studies are essential to ensure safety and environmental compatibility (Youssef, 2019).

10.6 Role of Nanotechnology in Toxicological Research and Risk Assessment

In veterinary toxicology, nanotechnology serves both as a therapeutic tool and a subject of safety evaluation. Nanomaterials are used to study cellular and molecular mechanisms of toxicity, oxidative stress, and inflammatory responses. At the same time, the toxicological effects of nanomaterials themselves are evaluated under the discipline of nanotoxicology.

Nanotechnology-based tools enable detailed assessment of toxicokinetics, species-specific responses, and environmental impact. These studies support the development of regulatory guidelines and safer nanotechnology-based veterinary products (Singh, 2019).

XI. SAFETY ISSUES AND NANOTOXICOLOGICAL CONCERNS OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

Although nanotechnology offers numerous advantages in veterinary pharmacology, its application raises important safety and toxicological concerns. The unique physicochemical properties of nanomaterials, such as extremely small size, high surface area, surface charge, and increased reactivity, influence their interaction with biological systems in ways that differ significantly from conventional drugs. These properties may result in unintended biological effects, making safety evaluation a critical component of nanotechnology-based veterinary products. Extremely small particles can become highly reactive and hazardous by increasing the production of reactive oxygen species (ROS), which leads to oxidative stress and cellular damage (Alghuthaymi et al., 2021).

11.1 General Factors Influencing Nanotoxicity

The toxicological behaviour of nanomaterials depends on several factors, including particle size, shape, surface chemistry, dose, route of administration, and duration of exposure. Smaller nanoparticles are more likely to cross biological barriers such as the gastrointestinal epithelium, blood-brain barrier, and placental barrier. Surface charge and coating also influence cellular uptake, biodistribution, and clearance. In veterinary pharmacology, these factors complicate dose standardization across species with different physiological and metabolic characteristics (McNeil, 2009).

11.2 Organ-Specific Toxicity

One of the major safety concerns in veterinary toxicology is organ-specific accumulation of nanoparticles. Following systemic exposure, nanoparticles tend to accumulate in organs involved in detoxification and clearance, particularly the liver, kidneys, lungs, and spleen. Accumulation in the liver may cause hepatotoxicity through oxidative stress, inflammation, and disruption of normal metabolic processes. Renal accumulation may lead to nephrotoxicity, especially with prolonged exposure or repeated dosing (Singh, 2019).

Pulmonary toxicity is of concern when nanoparticles are inhaled or reach the lungs through systemic circulation. Nanoparticles deposited in the lungs may induce inflammation, fibrosis, and impaired respiratory function. In food-producing animals, organ accumulation raises additional concerns regarding the persistence of nanomaterials and their potential transfer into edible tissues.

11.3 Immunotoxicity

Nanomaterials may interact with the immune system and alter immune responses. Depending on their composition and surface properties, nanoparticles can either stimulate or suppress immune function. Immunostimulation may lead to unintended inflammatory responses, while immunosuppression can increase susceptibility to infections. Such effects are particularly important in the veterinary field, where immune competence directly influences disease resistance and vaccine efficacy (Chrishtop et al., 2021).

Nanoparticles used as vaccine carriers or adjuvants must be carefully evaluated to ensure that immune modulation is beneficial rather than harmful. Uncontrolled immune activation may lead to hypersensitivity reactions or autoimmune-like responses in animals.

11.4 Oxidative Stress and Cellular Toxicity

A common mechanism underlying nanotoxicity is the induction of oxidative stress. Nanoparticles can generate reactive oxygen species (ROS), leading to lipid peroxidation, protein denaturation, and DNA damage. Oxidative stress may result in cellular apoptosis or necrosis, contributing to tissue damage. In veterinary toxicology, oxidative stress-related toxicity is a major concern, particularly with inorganic nanomaterials such as metallic nanoparticles and quantum dots (Singh, 2019).

11.5 Reproductive and Developmental Toxicity

Reproductive and developmental toxicity is an emerging concern associated with nanotechnology. Certain nanoparticles have been reported to cross the placental barrier and reach fetal tissues, potentially affecting fetal development. In breeding animals, such effects may result in reduced fertility, embryonic loss, or developmental abnormalities. The long-term impact of nanoparticle exposure on reproductive performance in livestock and companion animals remains inadequately understood and requires further investigation (Patra et al., 2018).

11.6 Neurotoxicity

Due to their small size, some nanoparticles may cross the blood-brain barrier and interact with the central nervous system. Neurotoxicity may manifest as behavioural changes, altered neurotransmission, or neuronal damage. Although data on neurotoxicity in veterinary species are limited, this potential risk necessitates caution, particularly when nanotechnology-based drugs are intended for systemic use.

11.7 Environmental and Ecotoxicological Concerns

Environmental toxicity is a significant safety issue associated with nanotechnology. Nanomaterials may enter the environment through animal excreta, pharmaceutical waste, or agricultural runoff. Once released, nanoparticles may persist in soil and water, affecting microorganisms, plants, and aquatic organisms. Environmental accumulation of nanomaterials may disrupt ecosystems and indirectly affect animal and human health (McNeil, 2009).

In veterinary toxicology, environmental safety is closely linked to food safety. The potential for nanomaterials to bioaccumulate in the food chain raises concerns regarding long-term exposure of humans and animals to nanomaterial residues.

11.8 Species-Specific Toxicity

One of the major challenges in veterinary nanotoxicology is species-specific variability in toxic responses. Differences in anatomy, physiology, metabolism, and drug handling among species make it difficult to extrapolate safety data from laboratory animals to livestock, poultry, or companion animals. A nanomaterial considered safe in one species may exhibit toxic effects in another. Therefore, species-specific toxicity studies are essential for safe veterinary application (Ianiski et al., 2022).

11.9 Regulatory and Risk Assessment Challenges

Currently, regulatory frameworks for nanotechnology-based veterinary products are limited and not well standardized. Conventional toxicity testing methods may not adequately predict the safety of nanomaterials due to their unique properties. Risk assessment strategies must therefore be adapted to account for nanoparticle-specific behaviour, including long-term exposure and environmental impact. The lack of clear regulatory guidelines remains a major barrier to the clinical translation of nanotechnology in veterinary pharmacology and toxicology (Sapino et al., 2022).

XII. FUTURE PROSPECTS OF NANOTECHNOLOGY IN VETERINARY PHARMACOLOGY AND TOXICOLOGY

Nanotechnology is expected to play an increasingly important role in the future of veterinary pharmacology and toxicology by enabling safer, more effective, and precision-based therapeutic strategies. Continuous advancements in nanoscience, material engineering, and biological understanding are likely to expand the scope of nanotechnology beyond conventional drug delivery into integrated therapeutic, diagnostic, and safety-oriented applications.

12.1 Precision Veterinary Pharmacology

One of the most promising future prospects of nanotechnology is its contribution to precision veterinary pharmacology. Nanotechnology-based drug delivery systems can be tailored according to species, disease condition, age, and physiological status of animals. Such individualized treatment approaches improve therapeutic outcomes while minimizing adverse effects. Precision drug targeting using ligand-modified nanocarriers is expected to reduce systemic exposure and improve pharmacodynamic efficiency, especially in chronic diseases and cancer therapy in companion animals (Ianiski et al., 2022).

12.2 Nano-Theranostics

Nano-theranostics, which combine diagnostic and therapeutic functions within a single nanoplatform, represent a major advancement. The term "theranostics" refers to the integration of therapeutic and diagnostic capabilities within a single system. These systems allow simultaneous disease diagnosis, targeted drug delivery, and monitoring of therapeutic response. In veterinary oncology, nano-theranostic systems enable real-time tumour imaging along with localized treatment, improving treatment accuracy and prognosis. The integration of pharmacology and diagnostics is expected to transform disease management strategies in animals (Patra et al., 2018).

12.3 Development of Safer and Biodegradable Nanocarriers

Future research in veterinary pharmacology and toxicology is expected to focus on the development of safer, biodegradable, and environmentally friendly nanomaterials. Organic and polymer-based nanocarriers with minimal long-term accumulation and reduced toxicity are likely to replace persistent inorganic nanomaterials. Emphasis will be placed on surface modification and controlled degradation to improve clearance and minimize organ accumulation, addressing major concerns in veterinary toxicology (Sapino et al., 2022).

12.4 Nano-Phytogenics and Alternative Therapeutics

Nano-phytogenics represent an emerging and promising area in veterinary pharmacology. Nanoformulation of plant-derived bioactive compounds enhances their stability, bioavailability, and therapeutic efficacy. These nano-phytogenic compounds are expected to serve as safer alternatives to conventional antibiotics, growth promoters, and chemotherapeutic agents. Their use may significantly contribute to reducing antimicrobial resistance and drug residues in food-producing animals, which is a major goal of veterinary toxicology and public health (Youssef, 2019).

12.5 Future Role in Vaccine Development and Immunotherapy

Nanotechnology is expected to revolutionize veterinary vaccines and immunotherapy. Nano-vaccines with improved antigen delivery and immune stimulation can provide long-lasting immunity with fewer booster doses. Future vaccine formulations may incorporate nanocarriers that enhance mucosal immunity, which is particularly important in poultry and livestock. Improved vaccine safety and efficacy will reduce dependence on antimicrobial therapy and contribute to better disease control strategies (Sapino et al., 2022).

12.6 Advances in Nanotoxicology and Risk Assessment

The future of nanotechnology in veterinary toxicology will involve the development of advanced nanotoxicological evaluation methods. Improved *in vitro* and *in vivo* models, along with computational toxicology and predictive risk assessment tools, will enhance understanding of nanoparticle behaviour in biological systems. Species-specific toxicity data and long-term exposure studies will be prioritized to ensure safe veterinary application. Regulatory frameworks are expected to evolve to incorporate nanoparticle-specific safety testing and environmental impact assessment (Singh, 2019).

12.7 Environmental Safety and Sustainable Veterinary Practice

Environmental sustainability will be a key focus in the future application of nanotechnology. Research efforts will aim to minimize environmental release and persistence of nanomaterials. Development of eco-friendly nanomaterials and biodegradable formulations will reduce environmental contamination and food chain accumulation. These advancements will support sustainable veterinary practice and align with global food safety and environmental protection goals (McNeil, 2009).

12.8 Translation to Field-Level Veterinary Practice

In the future, efforts will be directed toward translating nanotechnology-based products from laboratory research to field-level veterinary practice. Cost-effective manufacturing, scalable production methods, and simplified delivery systems will be essential for widespread adoption, particularly in livestock and poultry sectors. Collaboration between researchers, regulatory agencies, and veterinary professionals will play a crucial role in the successful implementation of nanotechnology in routine veterinary care.

XIII. CONCLUSION

Nanotechnology has emerged as a transformative tool in veterinary pharmacology and toxicology by offering innovative solutions to the limitations of conventional drug delivery systems. The application of nanotechnology has significantly improved drug bioavailability, targeting efficiency, controlled release, and therapeutic efficacy across different veterinary species. Nanocarriers such as liposomes, polymeric nanoparticles, solid lipid nanoparticles, nanoemulsions, magnetic nanoparticles, nanoshells, and nanopores have demonstrated promising applications in drug delivery, diagnostics, oncology, vaccine development, and feed supplementation.

From a veterinary toxicology perspective, nanotechnology has contributed to a better understanding of drug-tissue interactions, toxicokinetics, and safety evaluation. However, the unique physicochemical properties of nanomaterials also raise concerns regarding organ toxicity, immunotoxicity, reproductive toxicity, neurotoxicity, and environmental impact. Species-specific responses and long-term exposure effects further emphasize the need for comprehensive safety evaluation and risk assessment before widespread veterinary application.

Future prospects of nanotechnology in veterinary pharmacology and toxicology are highly promising, particularly in the areas of precision veterinary medicine, nano-theranostics, nano-phytogenics, and environmentally safer nanomaterials. Advances in nanotoxicology, regulatory frameworks, and sustainable manufacturing are expected to facilitate safer and more effective use of nanotechnology in veterinary practice. With responsible application, appropriate regulation, and continued research, nanotechnology has the potential to significantly enhance animal health, productivity, food safety, and environmental sustainability.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript. The authors alone are responsible for the content and writing of this article.

REFERENCES

[1] Alghuthaymi, M. A., Hassan, A. A., Kalia, A., Sayed El Ahl, R. M., El Hamaky, A. A., Oleksak, P., ... & Abd-Elsalam, K. A. (2021). Antifungal nano-therapy in veterinary medicine: Current status and future prospects. *Journal of Fungi*, *7*(7), 494.

[2] Alivisatos, A. P. (2004). The use of nanocrystals in biological detection. *Nature Biotechnology*, *22*(1), 47-52.

[3] Bilgili, A., & Uysal, M. H. (2019). Use areas of nanotechnology in veterinary medicine. *Journal of Food Science and Engineering*, *9*, 201-216.

[4] Carvalho, S. G., Rodrigues, L. R., & Lima, E. (2020). Advances and challenges in nanocarriers for veterinary nanomedicines. *Journal of Controlled Release*, *327*, 555-568.

[5] Chrishtop, V. V., Mironov, V. A., Prilepskii, A. Y., Nikonorova, V. G., & Vinogradov, V. V. (2021). Nanosafety versus nanotoxicology: Adequate animal models for assessment. *Toxicology*, *462*, 152957.

[6] Dhakad, G., Aich, R., Kushwah, M. S., & Yadav, J. S. (2017). Nanotechnology: Trends and future prospective. *Global Journal of Bio-Science and Biotechnology*, *6*(3), 548-553.

[7] Feynman, R. P. (1960). There's plenty of room at the bottom. *Engineering and Science*, *23*(5), 22-36.

[8] Hill, E. K., & Li, J. (2017). Current and future prospects for nanotechnology in animal production. *Journal of Animal Science and Biotechnology*, *8*(1), 26.

[9] Ianiski, L. B., Faccin-Galhardi, L. C., & Gonçalves, J. L. (2022). Nanotechnology in veterinary medicine: Applications and perspectives. *Pesquisa Veterinária Brasileira*, *42*, e06944.

[10] McNeil, S. E. (2009). Nanotechnology for the biologist. *Journal of Leukocyte Biology*, *85*(4), 561-564.

[11] Mweetwa, L. (2022). Past, present and future perspective of application of nanobiotechnology in pharmacology and innovative therapeutics. *Medical Research Archives*.

[12] Patel, K., Patel, M., Patel, N., Patel, D., & Patel, B. (2017). Nanotechnology-based drug delivery systems in veterinary medicine. *Veterinary World*, *10*(9), 1051-1057.

[13] Patra, J. K., Das, G., Fraceto, L. F., Campos, E. V. R., Rodriguez-Torres, M. P., Acosta-Torres, L. S., ... & Shin, H. S. (2018). Nano based drug delivery systems: Recent developments and future prospects. *Journal of Nanobiotechnology*, *16*, 71.

[14] Prasad, R. D., Charmode, N., Shrivastav, O. P., Prasad, S. R., Moghe, A., Sarvalkar, P. D., & Prasad, N. R. (2021). A review on concept of nanotechnology in veterinary medicine. *ES Food & Agroforestry*, *4*(5), 28-60.

[15] Sapino, S., Chirio, D., Peira, E., & Gallarate, M. (2022). Nanocarriers in veterinary medicine: A challenge for translation. *Pharmaceutics*, *14*(1), 45.

[16] Singh, A. V. (2019). Review of emerging concepts in nanotoxicology. *Nanotoxicology*, *13*(1), 1-23.

[17] Taniguchi, N. (1974). On the basic concept of nanotechnology. In *Proceedings of the International Conference on Production Engineering* (pp. 18-23). Tokyo, Japan.

[18] Trif, E., Cerbu, C., Olah, D., Zăblău, S. D., Spînu, M., Potârniche, A. V., & Brudașcă, F. (2023). Old antibiotics can learn new ways: A systematic review of florfenicol use in veterinary medicine and future perspectives using nanotechnology. *Animals*, *13*(10), 1695.

[19] Woldeamanuel, K. M., Kurra, F. A., & Roba, Y. T. (2021). A review on nanotechnology and its application in modern veterinary science. *International Journal of Nanomaterials, Nanotechnology and Nanomedicine*, *7*(1), 026-031.

[20] Youssef, F. S., El-Banna, H. A., Elzorba, H. Y., & Galal, A. M. (2019). Application of some nanoparticles in the field of veterinary medicine. *International Journal of Veterinary Science and Medicine*, *7*(1), 78-93.

[21] Zhou, Y., Guo, L., Dai, G., Li, B., Bai, Y., Wang, W., & Zhang, J. (2024). An overview of polymeric nanoplatforms to deliver veterinary antimicrobials. *Nanomaterials*, *14*(4), 341.

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Evaluation of Natural Materials and Edible Coatings for Ripening Regulation and Shelf-Life Extension of Banana (*Musa* spp.) and Papaya (*Carica papaya* L.)

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***Abstract*—** *Fruit ripening is a vital physiological process that enhances the color, flavor, texture, and nutritional quality of climacteric fruits such as banana (*Musa *spp.) and papaya (*Carica papaya *L.). However, uncontrolled ripening accelerates senescence, leading to substantial postharvest losses. The present study aimed to evaluate simple, safe, and economical methods for accelerating (forward ripening) and delaying (reverse ripening) fruit ripening under ambient storage conditions. Mature, uniform, and defect-free banana and papaya fruits were subjected to different forward ripening treatments, including paper wrapping, banana leaf covering, plastic cover storage, and storage with ripened fruits to promote natural ethylene accumulation. Reverse ripening treatments consisted of coatings containing calcium chloride and sodium alginate at different concentrations, while potassium permanganate was evaluated as an ethylene scavenger. Fruits were stored at room temperature and monitored for seven days. Quality attributes, including total soluble solids (TSS), physiological weight loss, color development, and texture, were assessed using standard analytical procedures.*

The results demonstrated that forward ripening treatments accelerated uniform ripening and improved market readiness through enhanced ethylene accumulation. In contrast, calcium chloride–sodium alginate coatings effectively delayed ripening; the 3% calcium chloride–sodium alginate coating extended ripening to 9 days while reducing physiological weight loss to 7 g, maintained firmness, and preserved fruit quality during storage. Potassium permanganate further contributed to extending shelf life by reducing ethylene concentration.

The study concludes that natural ripening techniques and edible coating treatments provide effective, low-cost, and safe alternatives for ripening management. These approaches have practical applications for farmers, retailers, and fruit industries by reducing postharvest losses, extending shelf life, and improving the marketability and quality of climacteric fruits.

***Keywords*— Banana, Papaya, Edible coating, Calcium chloride, Sodium alginate, Shelf life, Postharvest, Ripening regulation, Ethylene management, Climacteric fruits, Tropical fruits.**

I. INTRODUCTION

Fruits are an essential component of a healthy diet because they provide vitamins, minerals, dietary fiber, antioxidants, and other bioactive compounds that contribute to human health and nutrition. Among tropical fruits, banana (*Musa* spp.) and papaya (*Carica papaya* L.) are widely cultivated and consumed due to their high nutritional value, year-round availability, affordability, and economic importance. Banana is an excellent source of carbohydrates, potassium, vitamin B6, and dietary fiber, whereas papaya is rich in vitamins A and C, folate, and the proteolytic enzyme papain, making both fruits valuable for improving nutritional security and supporting the fruit processing industry [1,2].

Banana and papaya are climacteric fruits that continue to ripen after harvest through a process characterized by increased respiration and ethylene production. Ripening enhances desirable quality attributes such as color, flavor, sweetness, aroma, and texture, thereby improving consumer acceptability. However, uncontrolled ripening accelerates senescence, resulting in excessive softening, moisture loss, microbial spoilage, and reduced marketability. Consequently, postharvest losses of climacteric fruits remain a significant challenge, particularly in developing countries where inadequate storage, transportation, and ripening management practices contribute to substantial economic losses [1,2].

Ethylene is the primary plant hormone regulating ripening in climacteric fruits. Even at low concentrations, it triggers biochemical and physiological changes that promote chlorophyll degradation, sugar accumulation, fruit softening, and aroma development. Proper management of ethylene is therefore essential to either accelerate ripening for immediate marketing or delay ripening during storage and transportation. Safe and economical techniques for controlling ethylene are particularly important for farmers, retailers, and exporters who require flexibility in fruit marketing and distribution [3,4].

Natural packaging materials are widely used as simple ripening methods because they create a semi-enclosed environment that promotes the accumulation of naturally produced ethylene around fruits. Traditional practices such as wrapping fruits in paper, covering them with banana leaves, storing them in plastic covers, or placing them with ripe fruits can accelerate uniform ripening without the use of hazardous chemicals. These methods are inexpensive, environmentally friendly, and suitable for small-scale farmers and local fruit markets [5].

Edible coatings have emerged as an effective postharvest technology for delaying ripening and extending shelf life. Coatings based on natural biopolymers act as semipermeable barriers that reduce moisture loss, respiration, and gas exchange while maintaining fruit firmness and overall quality. Sodium alginate is a biodegradable polysaccharide widely used for edible coating applications because of its excellent film-forming properties, whereas calcium chloride strengthens cell wall integrity and delays tissue softening. The combination of sodium alginate and calcium chloride forms a stable cross-linked coating that effectively preserves fruit quality during storage. In addition, potassium permanganate has been extensively used as an ethylene scavenger to reduce ethylene concentration and slow ripening [6,7,8].

Although numerous studies have investigated commercial ripening agents and individual edible coatings, limited information is available on the comparative effectiveness of low-cost natural packaging materials and calcium chloride–sodium alginate coatings for both accelerating and delaying ripening of banana and papaya under ambient storage conditions. Such information is particularly relevant for regions lacking cold-chain infrastructure and modern postharvest facilities [6,8].

Therefore, the present study was undertaken to evaluate simple and economical forward and reverse ripening techniques for banana and papaya under ambient conditions. The study aimed to compare natural packaging methods and edible coating treatments by assessing changes in total soluble solids, physiological weight loss, color, and texture. The findings are expected to contribute to the development of safe, sustainable, and affordable postharvest technologies for reducing fruit losses, maintaining quality, and improving the marketability of climacteric fruits.

II. MATERIALS AND METHODS

2.1 Experimental Location

The experiment was conducted under ambient laboratory conditions in the Department of Food Science and Technology. All treatments were carried out under hygienic conditions, and observations were recorded over a storage period of seven days.

2.2 Fruit Materials

Fresh, mature, and unripe banana (*Musa* spp.) and papaya (*Carica papaya* L.) fruits of uniform size, maturity, and color, free from physical damage and disease, were procured from a local market. The specific varieties used were [Please specify variety] for banana and [Please specify variety] for papaya. Fruits were washed with clean water, air-dried, and used immediately for the experiment.

2.3 Experimental Treatments

The study evaluated both forward and reverse ripening methods. The following treatments were evaluated:

Forward Ripening Treatments (to accelerate ripening):

1) Paper bag wrapping
2) Banana leaf covering
3) Plastic cover storage
4) Storage with naturally ripened fruits (apples) to promote ethylene accumulation
5) Storage with ripe bananas

Reverse Ripening Treatments (to delay ripening):

1) 1% calcium chloride + sodium alginate coating
2) 2% calcium chloride + sodium alginate coating
3) 3% calcium chloride + sodium alginate coating
4) Potassium permanganate (ethylene scavenger)
5) Untreated control

Additional treatment combinations tested:

- Banana leaf + Paper packaging
- Banana leaf + Plastic cover packaging
- Charcoal + Ash (as an ethylene adsorbent)

These treatments were applied to evaluate their effectiveness in regulating ripening and extending shelf life [9,10].

2.4 Experimental Design and Storage Conditions

The experiment was arranged in a Completely Randomized Design (CRD) with different ripening treatments applied to banana and papaya fruits. After treatment, fruits were stored separately in plastic trays under ambient conditions (27 ± 2°C) for seven days. Observations were recorded at regular intervals to evaluate ripening behavior and postharvest quality [11].

2.5 Quality Evaluation

The effectiveness of the different ripening treatments was assessed by monitoring ripening period, physiological weight loss, total soluble solids (TSS), fruit color, firmness, pH, titratable acidity, and sensory quality. Physiological weight loss, total soluble solids, pH, titratable acidity, and other quality parameters were determined according to the standard methods of the Association of Official Analytical Chemists (AOAC) where applicable [12]. Fruit color and firmness were evaluated visually and manually to monitor ripening progression.

2.6 Statistical Analysis

All experiments were conducted in triplicate, and the results were expressed as mean ± standard deviation. Data were analyzed using one-way analysis of variance (ANOVA), and significant differences among treatment means were determined at $p < 0.05$ according to the procedures described by Gomez and Gomez [11].

III. RESULTS AND DISCUSSION

The present study evaluated the influence of natural packaging materials and edible coating treatments on the ripening behavior and postharvest quality of banana and papaya stored under ambient conditions. Packaging materials significantly affected ripening rate, physiological weight loss, and fruit quality (Table 1). Paper packaging accelerated ripening, reducing the ripening period to six days while producing the highest physiological weight loss (132–147 g). The rapid ripening observed in paper-wrapped fruits is attributed to enhanced ethylene accumulation together with greater moisture loss and respiration. Similar observations have been reported by Paul et al. [13], who found that paper-based packaging promotes ethylene-mediated ripening but shortens storage life.

TABLE 1
EFFECT OF PACKAGING MATERIALS ON RIPENING PERIOD AND PHYSIOLOGICAL WEIGHT LOSS OF BANANA AND PAPAYA

Treatment	Fruit	Ripening period (days)	Weight loss (g)*	Remarks
Control	Banana/Papaya	8–13	44 ± 2.3	Normal ripening
Paper packaging	Papaya + Apple	6	132 ± 5.1	Rapid ripening, high moisture loss
Plastic cover packaging	Papaya + Apple	9	20 ± 1.8	Delayed ripening, fungal growth observed
Paper packaging	Papaya + Banana	6	147 ± 6.2	Rapid ripening
Plastic cover packaging	Papaya + Banana	11	95 ± 4.3	Delayed ripening
Banana leaf + Paper packaging	Papaya	7	8 ± 0.9	Moderate ripening
Banana leaf + Plastic cover	Papaya	9	42 ± 3.1	Delayed ripening, fungal growth

Mean ± standard deviation (n=3). Values with different superscripts within each column are significantly different (p < 0.05).
Note: "Papaya + Apple" and "Papaya + Banana" refer to storage of papaya with ripe apples or ripe bananas to promote ethylene accumulation.

Plastic cover packaging delayed ripening compared with paper packaging and considerably reduced physiological weight loss, indicating improved moisture retention. However, fungal growth developed during storage because of excessive humidity within the closed environment. Similar findings were reported by Dhall [7], who observed that high relative humidity in modified packaging suppresses moisture loss but may increase microbial spoilage if ventilation is inadequate.

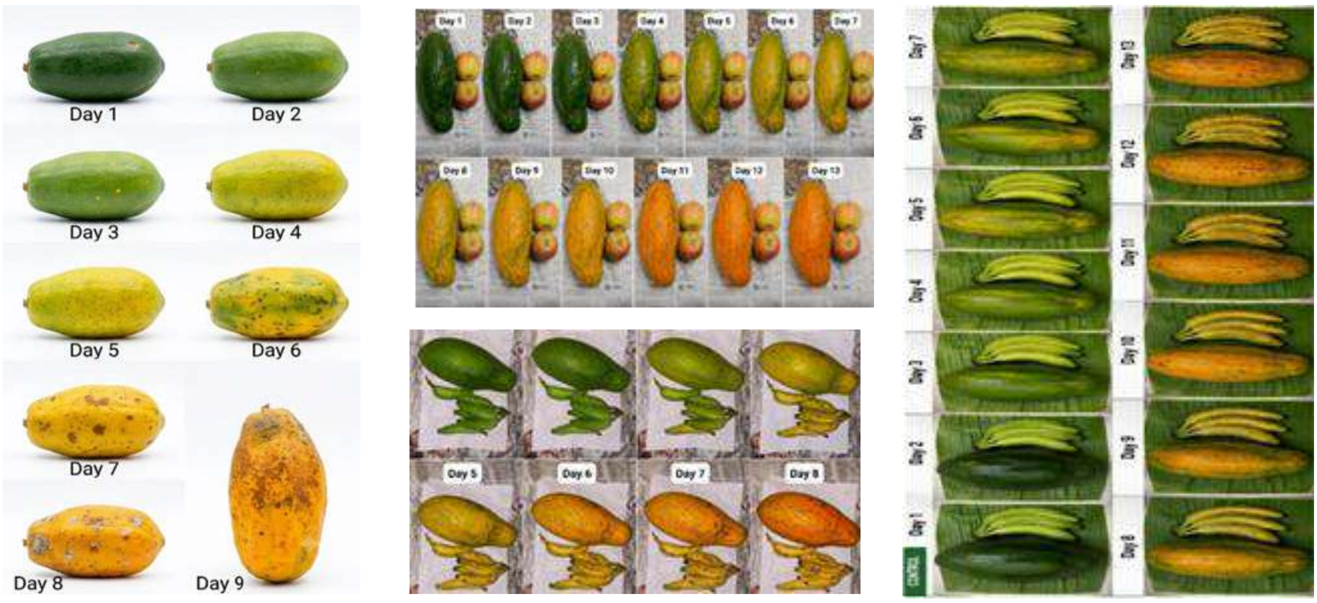

FIGURE 1: Effect of different packaging treatments (paper packaging, plastic cover packaging, banana leaf covering, and control) on the ripening of banana and papaya during seven days of ambient storage.

Banana leaf packaging moderately delayed ripening and reduced moisture loss compared with paper packaging. The semi-permeable nature of banana leaves likely maintained a favorable microenvironment around the fruit while permitting limited gas exchange. Similar observations have been reported for natural plant-based packaging materials used to improve postharvest quality and reduce environmental waste [14].

TABLE 2
EFFECT OF CALCIUM CHLORIDE–SODIUM ALGINATE COATINGS ON BANANA QUALITY

Treatment	TSS (°Brix)*	Weight loss (g)*	Ripening period (days)*	Quality response
Control	6.5 ± 0.4	10 ± 1.2	8 ± 0.5	Normal ripening
1% $CaCl_2$ + Sodium alginate	5.0 ± 0.3	17 ± 1.8	9 ± 0.6	Delayed ripening
2% $CaCl_2$ + Sodium alginate	7.0 ± 0.5	9 ± 0.8	7 ± 0.4	Moderate effect
3% $CaCl_2$ + Sodium alginate	4.5 ± 0.3	7 ± 0.6	9 ± 0.5	Best shelf-life extension

Mean ± standard deviation (n=3). Values with different superscripts within each column are significantly different ($p < 0.05$).

Note: The higher TSS value observed in the 2% $CaCl_2$ treatment may be attributed to variability in initial fruit maturity or measurement error and warrants further investigation.

Among the reverse ripening treatments, calcium chloride–sodium alginate coatings showed the greatest effectiveness in preserving fruit quality (Table 2). The 3% coating delayed ripening to nine days, recorded the lowest physiological weight loss (7 g), and maintained lower total soluble solids (4.5 °Brix), indicating reduced metabolic activity. Calcium chloride strengthens the cell wall through calcium–pectate interactions, whereas sodium alginate forms a semipermeable edible film that restricts respiration, transpiration, and ethylene diffusion. Comparable improvements in fruit firmness, moisture retention, and shelf-life extension have been reported for alginate-based edible coatings [15,16].

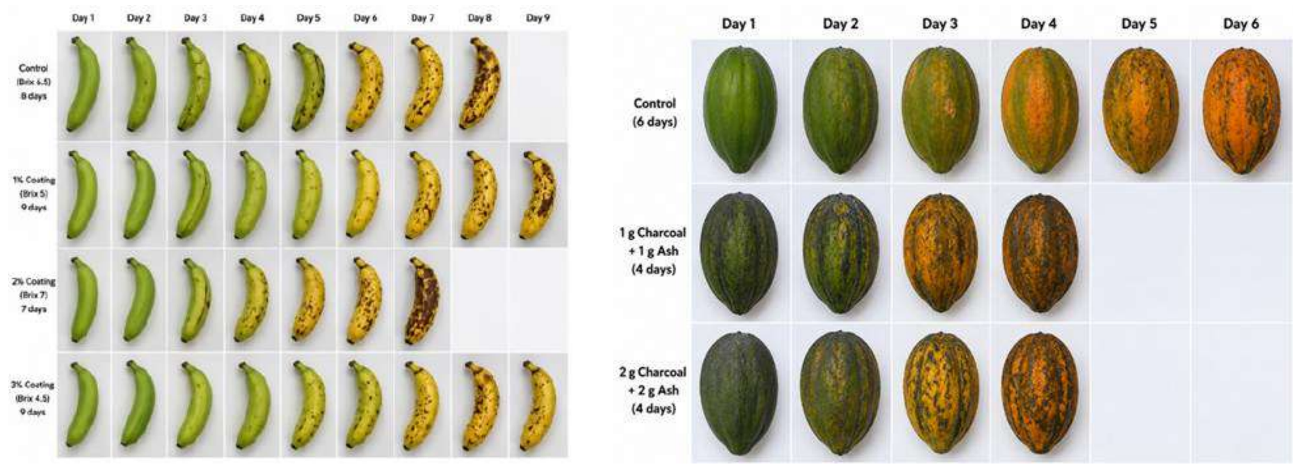

FIGURE 2: Effect of calcium chloride–sodium alginate coatings at different concentrations (1%, 2%, 3%) on the ripening period and shelf life of banana stored under ambient conditions.

Ethylene management plays a critical role in regulating ripening of climacteric fruits. Treatments that promoted natural ethylene accumulation, such as paper packaging and storage with ripe fruits, accelerated ripening and improved market readiness. In contrast, edible coatings and potassium permanganate reduced ethylene activity, slowed respiration, and delayed senescence. Similar responses have been reported in banana and papaya, where regulation of ethylene production effectively prolonged shelf life while maintaining acceptable fruit quality [13,17].

TABLE 3
OVERALL COMPARISON OF RIPENING TREATMENTS

Treatment	Ripening effect	Shelf-life	Moisture retention	Overall performance
Paper packaging	Accelerated	Low	Poor	Suitable for rapid marketing
Plastic cover packaging	Delayed	Moderate	Good	Risk of fungal growth
Banana leaf packaging	Moderate	Moderate	Good	Eco-friendly alternative
Charcoal + Ash	Accelerated	Low	Poor	Not recommended
3% Sodium alginate coating	Delayed	High	Excellent	Most effective treatment

Overall, the results indicate that the 3% calcium chloride–sodium alginate coating was the most effective treatment for extending shelf life and maintaining fruit quality under ambient conditions (Table 3). Although paper packaging is suitable where rapid ripening is required for immediate marketing, edible coatings provide a safer and more sustainable approach for postharvest preservation. These findings support the application of natural edible coatings as low-cost technologies for reducing postharvest losses and improving the storage quality of climacteric fruits, particularly in regions lacking cold-chain infrastructure [15–19].

IV. CONCLUSION

The present study demonstrated that natural packaging materials and edible coatings can effectively regulate the ripening and shelf life of banana (*Musa* spp.) and papaya (*Carica papaya* L.) under ambient storage conditions. Among the treatments evaluated, the 3% calcium chloride–sodium alginate coating was the most effective, significantly delaying ripening, minimizing physiological weight loss, and maintaining overall fruit quality compared with other treatments. In contrast, paper packaging accelerated ripening and is more suitable for situations requiring rapid market readiness.

These findings indicate that edible coatings offer a simple, safe, and cost-effective approach for postharvest management of climacteric fruits. The technology has considerable commercial potential for farmers, retailers, exporters, and the fruit processing industry by reducing postharvest losses, extending shelf life, and improving marketability without relying on expensive cold-chain infrastructure. Future research should focus on optimizing coating formulations, incorporating natural antimicrobial agents, evaluating consumer acceptance, and assessing large-scale commercial application under different storage and transportation conditions.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

REFERENCES

[1] Food and Agriculture Organization of the United Nations. (2023). *The state of food and agriculture 2023*. FAO.
[2] Yahia, E. M., García-Solís, P., & Celis, M. E. M. (2019). Contribution of fruits and vegetables to human nutrition and health. In E. M. Yahia (Ed.), *Postharvest physiology and biochemistry of fruits and vegetables* (pp. 19-45). Woodhead Publishing.
[3] Wills, R. B. H., & Golding, J. B. (2016). *Postharvest: An introduction to the physiology and handling of fruit and vegetables* (6th ed.). CABI.
[4] Paul, V., Pandey, R., & Srivastava, G. C. (2023). Role of ethylene in fruit ripening and postharvest management of climacteric fruits. *Journal of Food Science and Technology*, *60*(5), 1453-1467.
[5] Bisen, A., & Pandey, S. K. (2008). Natural methods of fruit ripening and postharvest handling of tropical fruits. *Indian Horticulture*, *53*(2), 18-22.
[6] Hasan, M. U., Riaz, R., Malik, A. U., Khan, A. S., Anwar, R., & Rehman, R. N. U. (2021). Recent advances in edible coatings for extending the postharvest shelf life of fresh fruits. *Food Reviews International*, *37*(5), 435-450.
[7] Dhall, R. K. (2020). Advances in edible coatings for fresh fruits and vegetables: A review. *Critical Reviews in Food Science and Nutrition*, *60*(3), 435-450.
[8] Baldwin, E. A., Hagenmaier, R., & Bai, J. (2022). *Edible coatings and films to improve food quality* (2nd ed.). CRC Press.
[9] Gomez, K. A., & Gomez, A. A. (1984). *Statistical procedures for agricultural research* (2nd ed.). John Wiley & Sons.
[10] AOAC International. (2019). *Official methods of analysis of AOAC International* (21st ed.). AOAC International.
[11] Ali, A., Maqbool, M., Ramachandran, S., & Alderson, P. G. (2022). Natural packaging materials and biodegradable films for postharvest preservation of fresh fruits and vegetables: A review. *Food Packaging and Shelf Life*, *31*, 100787.
[12] Kader, A. A. (2021). Postharvest technology of horticultural crops: Recent advances and future challenges. *Horticulturae*, *7*(8), 206.

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Analysis of the Dynamics of Forest Landscape Fragmentation in Western Madagascar under the Influence of Migration

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Abstract— *Economic activities by migrant populations lead to changes in landscape structure and land use in non-forested areas. This article aims to analyse the spatial and temporal dynamics of forest fragmentation and to examine the influence of migration on the configuration of the forest landscape within the Menabe Antimena protected area between 2017 and 2022. The methods used include a diachronic analysis of satellite imagery using remote sensing. Following canopy classification, land-use classes were categorised as forest or non-forest. The results reveal that forest fragmentation shows a generalised increase of 13.94% within the protected area and 25.05% at its periphery, with an overall peak observed in 2022. Furthermore, the configuration of forest fragments is significantly correlated with migration inflows. The landscape is dominated by micro-fragments covering an area of less than 20 ha, which account for between 98.86% (16,197 out of 16,383 fragments) and 99.18% (20,622 out of 20,792 fragments) of the total within the protected area; and 99.08% (11,607 out of 11,715 fragments) to 99.30% (12,226 out of 12,312 fragments) outside the protected area. At the same time, fragment density increased from 2.32 to 3.92 fragments/ha, resulting in a significant change in the fragmentation index (from 0.60 to 0.87) for the 20–50 ha class. These results make a major contribution to the overhaul of national conservation strategies by demonstrating the need to incorporate internal population flows into protected area management plans.*

Keywords— Menabe Antimena Protected Area, Migration, Anthropogenic pressure, Fragmentation, Conservation, Forest fragmentation, Deforestation, Remote sensing, Landscape ecology, Madagascar, Dry forest, Climate-induced migration, Protected area management.

I. INTRODUCTION

Population growth and agricultural expansion, particularly in developing countries, are the main causes of deforestation and forest degradation (Jallat et al., 2021; Ahmed et al., 2023). Forests are among the natural resources whose preservation is a key concern for sustainable development, particularly given the importance of their numerous ecosystem services to both current and future generations (Wainger et al., 2010). Covering a total area of 10 million km² (Senior et al., 2019), tropical forests constitute one of the world's most ecologically important habitat types (Hending et al., 2025). They harbour more than half of the world's forest carbon and more than 80% of terrestrial biodiversity; they play a fundamental role in regulating the climate at both regional and global levels and provide countless services and products to people (Sist, 2025). Unfortunately, tropical forests are among the most threatened habitats in the world (Edwards et al., 2019). Due to factors ranging from large-scale forest conversion to the overexploitation of resources for subsistence purposes, tropical forests have been massively affected by agricultural activities that drive deforestation and forest degradation (Achard et al., 2004; Asner et al., 2009). Currently, most of the remaining tropical forests are fragmented into more than 130 million patches, with an average area of around 29 ha (Taubert et al., 2018). Forest fragmentation manifests itself through typical changes in the spatial structure of the landscape and is characterised by an increase in the number of patches, a reduction in their size, greater complexity in their shape and increased isolation between them (Ma et al., 2023; Peptenatu et al., 2023; Rahman and Islam, 2021). However, the spatial configuration of landscapes, including plot shape and connectivity, plays a crucial role in the provision of ecosystem services (Lamy et al., 2016). This observation highlights the significant impact of forest fragmentation, particularly in areas with high population density, on the continuity and effectiveness of these services (Hisham and Hua, 2026).

Climate-related events are forcing thousands of people to move within their own countries (Veron, 2020). This climate-induced migration directly alters population growth rates and demographic characteristics, both through the migration itself and by interacting with and amplifying other demographic processes (Hauer et al., 2024). As such, the issue of demographic pressures remains a major and pervasive concern in documents examining deforestation, land degradation, the loss and degradation of biodiversity, threats to peace, future stability, and global warming (Agrawal, 2018). In recent years, the forests of sub-Saharan Africa have been under increasing pressure, mainly due to demographic pressure and migration caused by climate change (Nicoletti et al., 2023; Vinke et al., 2022). In these countries, access to land is considered important for improving the incomes and food security of rural households (Holden and Otsuka, 2014; Muraoka et al., 2018). However, migrants often adopt unsustainable agricultural practices (Sunderlin and Pokam, 2002), including itinerant slash-and-burn agriculture. Changes in land use linked to human development are the main drivers of forest fragmentation. With population growth and economic expansion, forests are cleared for agriculture, urbanisation and infrastructure development (Perea, 2024).

The establishment of protected areas is the cornerstone of conservation policies aimed at reducing biodiversity loss and ensuring the long-term conservation of nature, ecosystem services and the associated cultural values (Vimal et al., 2021). However, protected areas in Africa are generally highly vulnerable, due to their proximity to settlements and the impacts of human activities (Triplet, 2009). Furthermore, human migration to resource-rich border regions can be a significant driver of forest change and biodiversity loss (Jones et al., 2018), thereby threatening the integrity of protected areas (Scholte and De Groot, 2010).

As for Madagascar, although it is recognised as one of the world's most biodiverse countries and is classified as a biodiversity hotspot, with a very high rate of endemism, its biodiversity is under severe threat from human activities (Myers et al., 2000; Tovondrazane et al., 2020). As a result, the level of forest fragmentation has been steadily increasing since 1953 (Vieilledent et al., 2018) and, by 2024, forest cover will account for only 20.7% of the island's total land area (Rakotoarisoa et al., 2025).

Although the link between human migration and the degradation of natural resources has been recognised for some time, the role of migration in environmental change continues to attract growing interest in its many facets (Bechard, 2018). In recent years, the link between climate-induced human mobility and environmental health has attracted increasing attention. Deforestation, land loss and forest fragmentation are among the most significant environmental issues threatening forest ecosystems worldwide (Ravonjimalala, 2019). Nowadays, the fragmentation of natural forests, largely linked to human activities, agricultural practices and the expansion of road networks, is a recurring phenomenon faced by tropical countries (Hending et al., 2025; Mahapatra et al., 2025). Consequently, the fragmentation of these tropical forests and protected areas leads to a loss of habitat and biodiversity, as well as an increase in carbon emissions (Hansen et al., 2020).

The Central Menabe region is still home to the largest remnant of dry forest in western Madagascar. These forests harbour a rich biodiversity, including several local and regional endemic species (Zinner et al., 2014), the most famous of which are *Hypogeomys antimena*, the largest endemic rodent in Madagascar; *Microcebus berthae*, the world's smallest lemur (Wilmet et al., 2022; Markolf et al., 2019). Central Menabe has a long history of forest conversion to agricultural land, for both plantations and subsistence farming (Scales, 2011). The expansion of agricultural land and plantations, together with forest fires, is currently intensifying forest fragmentation, posing a profound and irreversible threat to forest ecosystems (Caron et al., 2023; Fischer et al., 2021).

Well known for its dense dry forests and mangroves, the Menabe region is renowned for having welcomed and integrated groups of migrants from all over Madagascar, particularly from the south, and is considered a prime destination for internal migration (IOM, 2024). Furthermore, this human mobility affects forest management in several regions of Madagascar

(Rabemananjara, 2014), including Menabe Antimena, but there is no evidence of spatial overlap or correlation with deforestation (Rakotonarivo et al., 2026). Within this protected area, migrants from the south settle and cultivate land cleared through slash-and-burn practices, or 'Hatsake', leading to significant deforestation and land grabbing, in defiance of conservation efforts and participatory ecosystem management with local communities (MEDD, 2022). The protected area recorded an annual deforestation rate of 0.85% (2000–2010) rising to 2.35% (2010–2014) (Salvaterra & INDRI, 2017), and is estimated at 4.27% per year (2018–2022); 2.50% (2022–2023) (Andrianambinina et al., 2025) due to the illegal cultivation of maize (*Zea mays*) and peanuts (*Arachis hypogaea*) (MEDD, 2022). Consequently, forest cover in Menabe Antimena decreased by 22.1% between 2017 and 2022 (Andrianandrasana et al., 2025).

This reduction in forest area is accompanied by fragmentation, whereby forest plots are divided into several smaller plots (Taubert et al., 2018), and forests fragmented by human activities are at greater risk of further fragmentation or loss than those fragmented by natural causes (Wade et al., 2003). There is good evidence that forest fragmentation has a significant impact in maintaining ecosystem services and is generally recognised as a stressor for ecosystem stability (Fu et al., 2025; Li et al., 2022). In this regard, there is a significant lack of scientific analysis, particularly concerning the causal relationships between landscape spatial configurations and the ecosystem services provided by protected areas.

However, previous studies carried out within the Menabe Antimena protected area have not highlighted the heterogeneity, the degree of temporal and spatial fragmentation, the evolution and their correlation with migration patterns within and around their green belts. Many questions therefore remain unanswered, notably to what extent the migratory influx that occurred between 2017 and 2022 has altered the degree of fragmentation and the spatial configuration of the Menabe Antimena forest landscape. If this migration were to lead to an expansion of subsistence farmland, then the number of forest fragments would increase, as new arrivals clear the denser forest blocks to practise agriculture. Thus, the primary scientific aim of this research is to characterise and quantify the changes occurring in the forest landscape, and to examine the spatial and temporal dynamics of fragmentation in a dry forest in the western ecoregion of Madagascar between 2017 and 2022, whilst assessing its impact on ecosystem resilience. Secondly, to provide a scientific analysis of human migration flows as an independent predictor of vegetation dynamics within the protected area. The results of this study contribute to a better understanding of the relationship between forest fragmentation and agricultural expansion by migrant and indigenous populations, and will serve as a warning and a catalyst for mobilising all stakeholders to develop realistic development policies in the regions from which migrants originate and to devise effective strategies for forest sustainability.

II. MATERIALS AND METHODS

2.1 Study Areas

The ecoregion of western Madagascar is characterised by dry tropical forests and mangrove forests. The Menabe region (Figure 1), situated in western Madagascar, covers an area of 4,612,100 ha, with Morondava as its capital. It is a region rich in biodiversity, with various categories of protected areas, including: the Menabe Antimena Protected Area, the Ambondrombe Lake-Forest Complex, the Ambohijanahary Special Reserve, the Ambararata Londa Forest Station, the Andranomena Special Reserve, the Kirindy Mite National Park, the Mangoky Ihotry Wetland Complex, and, of course, the famous Alley of the Baobabs harmonious landscape.

The Menabe Antimena Protected Area (Figure 1), classified as a Category V Protected Harmonious Landscape according to the IUCN classification, is situated in the districts of Morondava and Belo sur Tsiribihina, at the geographical coordinates 19°56'37"S 44°40'46"E. It comprises three Ramsar sites: the Bedo wetlands (1,962 ha), the Ambondrombe wetlands (13,000 ha) and the Belo sur Tsiribihina mangroves (47,218 ha). Managed by the Fanamby Association, Menabe Antimena covers a total area of 216,011 ha, comprising a core area of 68,874 ha and a buffer zone of 141,126 ha (Goodman et al., 2018), with 57,689 ha of forest (27.47% of its total area) (Andrianambinina et al., 2025).

In recent years, the Menabe Antimena Protected Area has been facing rapid deforestation, resulting in the loss of around 30% of its dry forests (Markolf et al., 2019). Furthermore, it has seen a massive influx of survival migrants, particularly in the rural communes of Marofandilia, Beroboka Nord, Tsimafana, Tsarahotana and Antsoha, coming from the Androy region, the driest region in Madagascar. The Androy region has a Standard Precipitation Index (SPI) of up to (SPI $\leq$ -2), classifying it as an extremely dry region in the south of the country according to the table by McKee et al. (Panigrahi and Vidyarthi, 2024).

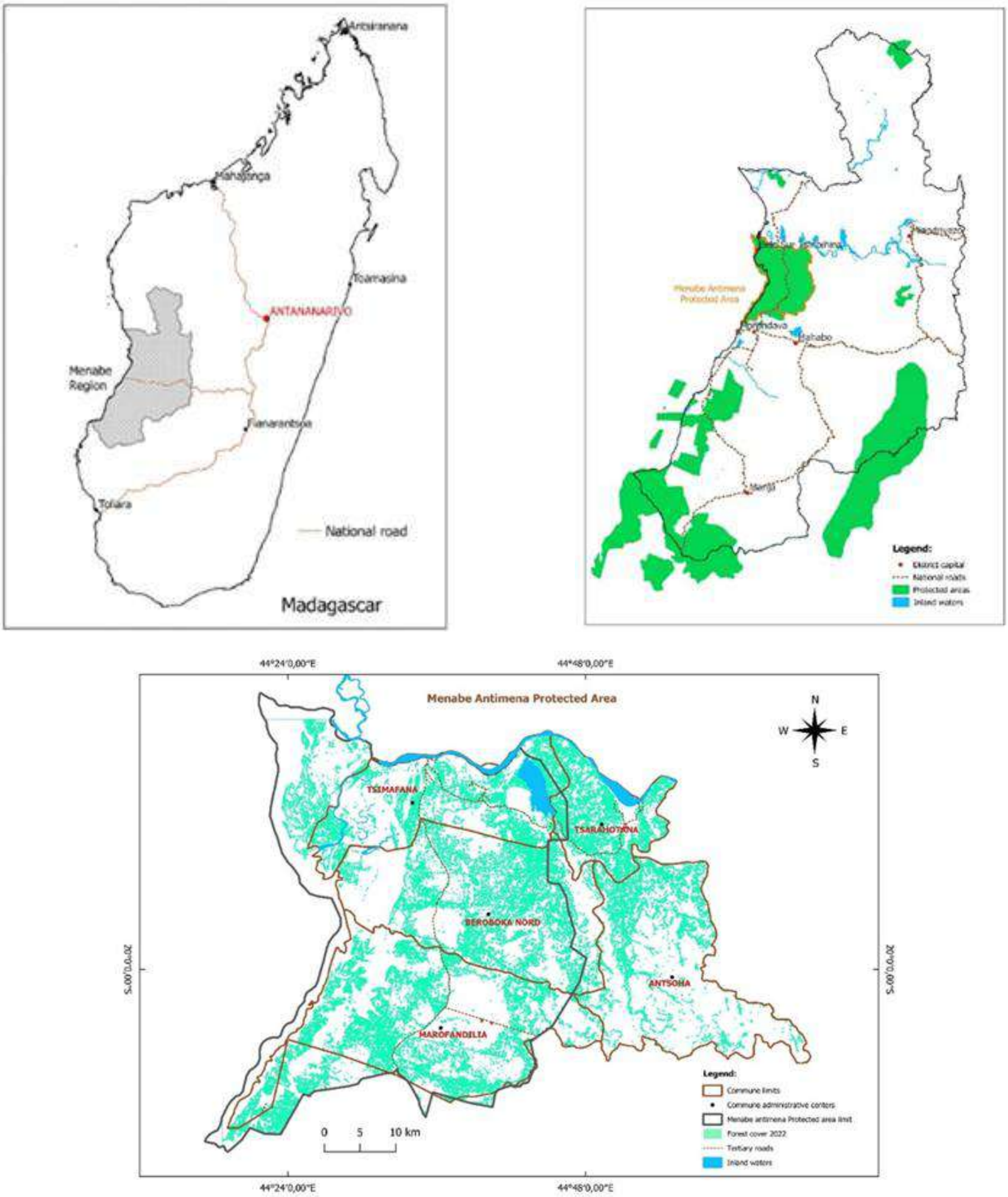


FIGURE 1: Location map of the study areas. Top left: Map of Madagascar showing the location of the Menabe region. Top right: Location map of protected areas within the Menabe region, including Menabe Antimena. Bottom: Map of the Menabe Antimena Protected Area and the five rural communes selected as study sites.

2.2 Data Collection

2.2.1 Unit of Analysis

The unit of analysis selected is the commune, the administrative division constituting the region in Madagascar. The geographical boundaries of the communes, modelled as polygons, were extracted from the official database of the Foiben-Taosarintanin'i Madagasikara (FTM) using QGIS 3.34.11 software. The annual socio-demographic and environmental variables for 2017–2022 were spatially aggregated within the territorial boundaries of the communes selected as study sites.

The data analysed in this study included predictive variables relating to population dynamics, migration statistics and economic activities, in order to assess their influence on the independent variable, namely the fragmentation of forest cover within and around the Menabe Antimena protected area. The analysis of these variables was preceded by field surveys carried out between May and August 2023 to collect and validate the data required for this research.

In order to assess the relationship between human mobility and vegetation dynamics in the Menabe Antimena protected area, we collected and analysed statistical data on the general population and on migrants from the South at the study sites, as well as remote-sensing data from 2017–2022. Where appropriate, analyses of the links between human migration and changes in the spatial structure of the vegetation landscape will be carried out to characterise the level of fragmentation within the protected area.

2.2.2 Migration Data

For the analysis of migration flows, demographic data from official municipal registers on population dynamics, analysed using the methodology applied by Andrianandrasana et al. (2025), were used. It enables the determination of the annual migration intensity rate, which serves as a tool for quantifying the scale of migratory movements relative to the total population studied over the period 2018–2022.

Data from the 2017 population census are not available in official records, either at municipality or national level. The recorded figures were cross-checked against those published in the register of Madagascar's Third General Population and Housing Census of 2018 (RGPH-3) to ensure their consistency in this study.

2.2.3 Forest Data

The forest cover data used in this section are identical to those used by Andrianandrasana et al. (2025). However, this article focuses on assessing forest quality, specifically on analysing the dynamics of forest fragmentation across the entire Menabe Antimena protected area, as well as at the level of the municipalities where the migrant communities are located. To identify forest within the Menabe Antimena protected area, we used a specific forest cover density threshold of 29%, classifying areas with canopy cover below this threshold as non-forested and those at or above it as forested, as recommended and used by Rafanoharana et al. (2023); Andrianambinina et al. (2024); Andrianandrasana et al. (2025). Forest fragments were identified using remote sensing, involving the use of satellite imagery to detect isolated or defined wooded areas. These algorithms were applied using GIS-based image processing. Time series of forest cover maps were utilised to quantify the six years (2017–2022) of forest fragmentation in Menabe Antimena by applying an effective clustering algorithm to determine the size, number and spatial configuration of all observed forest fragments.

In order to scientifically validate the results of the image processing with rigorous statistical robustness across the 216,011 ha of the protected area, a hybrid validation approach combining in situ observations and photo-interpretation was implemented. Twenty (20) polygons were delineated in the field as training control sites, strategically distributed between areas of dense forest and areas with open canopy, both within and outside Menabe Antimena. In order to achieve spatial representativeness in accordance with the standards set by Congalton (1991) and Olofsson et al. (2014), this sample was supplemented in ArcGIS 10.8.2 with a network of stratified random points. Points located in areas that were difficult to access were systematically validated through photo-interpretation of high-resolution historical imagery (Google Earth Pro). This comparative temporal analysis made it possible to definitively compare the automated classifications derived from image processing with the biophysical reality of the soil. Finally, ArcGIS's automatic confusion matrix calculation tool (Compute Confusion Matrix) was used to rigorously generate the overall accuracy rate and the Kappa coefficient.

2.2.4 Overlap between the Menabe Antimena Protected Area and the Rural Municipalities Studied

The five rural municipalities selected as study sites are those where the majority of migrants occupying the Menabe Antimena Protected Area and its green belts are located. A total of 81.38% of Menabe Antimena is attached to these communes, and the rural commune of Marofandilia, followed by the commune of Tsimafana, are the communes most covered by the protected area, with 94.17% and 91.63% of these communes, respectively, lying within the protected area. As for the rural commune of Tsarahotana, only 6.24% of the municipality lies within the protected area, whilst the commune of Antsoha comprises the entire green belt of Menabe Antimena (Table 1).

For the analysis of forest fragmentation dynamics, forest blocks located within municipalities that overlap with those of the protected area's forests are not counted alongside those of the rural municipalities outside the protected area.

TABLE 1
DISTRIBUTION OF THE PROTECTED AREA ACROSS THE STUDIED RURAL COMMUNES

Rural Communes	Total Area of the Commune (ha)	Area Covered by the PA (ha)	PA Coverage Proportion (%)
Antsoha	52,222.62	0	0
Beroboka Nord	63,982.93	55,463.86	86.69
Marofandilia	69,670.47	65,609.39	94.17
Tsarahotana	20,692.08	1,291.54	6.24
Tsimafana	41,560.57	38,083.19	91.63

Source: Statistical processing of geographical information from BNGRC and SAPM (VIRAINA, F.F., 2023).

2.3 Data Analysis

2.3.1 Deforestation Rate in Menabe Antimena

Deforestation is defined as the permanent or temporary conversion of forest to other land-use types (FAO & JRC, 2012). Based on the methodology developed by Hansen et al. (2013), the loss in forest cover is characterised by the transition of a pixel to the "non-forest" class. In tropical forestry, the severity of this rate is generally classified according to the standardised formula by Puyravaud (2003):

TABLE 2
CATEGORISATION OF THE DEFORESTATION PRESSURE LEVEL ACCORDING TO INTENSITY

Annual Rate (%)	Deforestation Pressure Level
< 0.5%	Low (slow dynamics, diffuse or residual anthropogenic pressures)
0.5% to 1%	Medium (deforestation fronts in the process of structuring)
> 1%	High to critical (highly active clearing fronts and massive destruction of the forest cover)

2.3.2 Identification Process and Spatial Analysis of Changes to Forest Fragments in Menabe Antimena

The methodology adopted is based on a geographical and diachronic approach to the study of land use. Data are obtained through remote sensing image processing, supervised classification mapping, predictive modelling and spatial analysis (Tchibozo, 2020). These processes are determined on the basis of three main parameters considered to be fundamental elements for describing the landscape configuration, namely (i) the area of patches, (ii) the perimeter of patches and (iii) the number of patches (Collinge and Forman, 1998; Jaeger, 2000; Bogaert et al., 2004). These parameters were determined for all land-use units and for the years under study. Mapping of land-use dynamics was carried out by vectorising the results of image classification (raster). The classification of land-use patches was generated using ArcGIS 10.3.1 software to produce the various polygons from which several parameters were calculated. Thus, spatial dynamics are measured by assessing changes in land cover types, based on a comparison of the area values of the various land-use units between the study periods (Oloukoï et al., 2006).

In this study, plots represent individual forest fragments or forest blocks. The choice of metrics to be used in the analyses is based on the data available from image processing. The analyses were conducted at the landscape scale, based on the size and spatial distribution of forest block fragments.

2.3.2.1 The Number of Plots

This enables the total number of forest fragments to be counted and provides key indicators of the degree of landscape fragmentation (McGarigal and Marks, 1995):

- **Number of Patches:** This directly quantifies the level of fragmentation of the forest cover. The higher the number of fragments, the more pronounced the fragmentation.
- **Patch Density:** This measures the number of fragments per unit area. A high density characterises a highly fragmented landscape.
- **Average Fragment Size:** This provides fundamental information on the spatial structure of the forest stand. Low values indicate advanced fragmentation of the original forest stands.

Fragment size has been categorised into three classes:

- **Class 1:** Forest with an area of less than 20 ha
- **Class 2:** Forest with an area of 20 to 50 ha
- **Class 3:** Forest with an area of more than 50 ha

2.3.2.2 Spatial Fragmentation Index of the Forest Landscape (F_j)

The landscape fragmentation level was assessed by calculating the fragmentation index (F_j) for each land-use class. This approach, applied to spatial analysis, measures the degree of pixel aggregation within class j in order to express the structural complexity of the image (Bogaert & Hong, 2004; Sambiéni et al., 2015). This index is determined by the following formula:

$$Fj = \frac{(nj-1)}{(mj-1)} \quad (1)$$

Where:

- n_j represents the total number of patches for class j;
- m_j is generally, in a raster file, the number of pixels (Monmonier, 1974).

However, as the calculations in this study were carried out using a vector file, m_j was estimated as the ratio of the total area (a_{tj}) of class j to the area of the smallest patch (a_{minj}).

Therefore:

$$Fj = \frac{(nj-1)}{\frac{at_j}{aminj} - 1} \quad (2)$$

The values of this indicator are standardised and fall within a range of 0 to 1 ($0 \leq F_j \leq 1$). The structural interpretation of the landscape is based on proximity to these two limits: an F_j value close to 0 indicates a low level of fragmentation, characterising an aggregated, continuous and homogeneous spatial class (preserved forest massif). Conversely, a value close to 1 indicates pronounced fragmentation, reflecting an advanced fragmentation of the vegetation cover into a multitude of isolated patches.

2.4 Statistical Analysis

The quantitative data were processed and analysed using RStudio software (v4.3.0). Firstly, a Student's t-test for paired samples was applied to compare the average forest areas between the two ends of the study period (2017 and 2022), in order to verify whether the observed temporal variations are statistically significant or whether they are simply due to chance. Secondly, to assess the impact of migration variables on the spatial structure of the Menabe Antimena forest landscape, the data were subjected to repeated-measures correlation analyses using the rmcorr package (Marusich & Bakdash, 2021). This method estimates the common regression slope and is highly recommended for calculating correlation coefficients across multiple observations repeated over time.

In order to overcome Simpson's paradox which tends to reverse or mask actual correlations when aggregating panel data, a Linear Mixed Model (LMM) was employed to incorporate inter-municipal variability as a random effect. For all these models, the threshold for statistical significance was set at 0.05; any probability value below this threshold ($p < 0.05$) is considered significant (Payne, 2020).

III. RESULTS

3.1 Migration Intensity Index in Menabe Antimena

The number of migrants arriving from southern Madagascar recorded across the five rural municipalities of the Menabe Antimena Protected Area increased by a factor of 3.2 between 2018 and 2022. Relative to the total population, migrants from the south accounted for between 45.39% and 51.16% of the population within Menabe Antimena, with the highest proportions being recorded in the rural municipalities of Beroboka Nord (38.24%), Marofandilia (35.25%) and Antsoha (12.90%) over the period 2018–2022. This proportion reached its maximum in 2020 before declining by 50.9% in 2022. Migration intensity increased linearly, following a constant annual growth rate of 1.4%. Accordingly, 75.66% of the variation in the migration intensity index is explained by temporal change. Consequently, migrants now occupy a substantial proportion of the area, and an increasing process of permanent settlement has become established within the protected area (Figure 2).

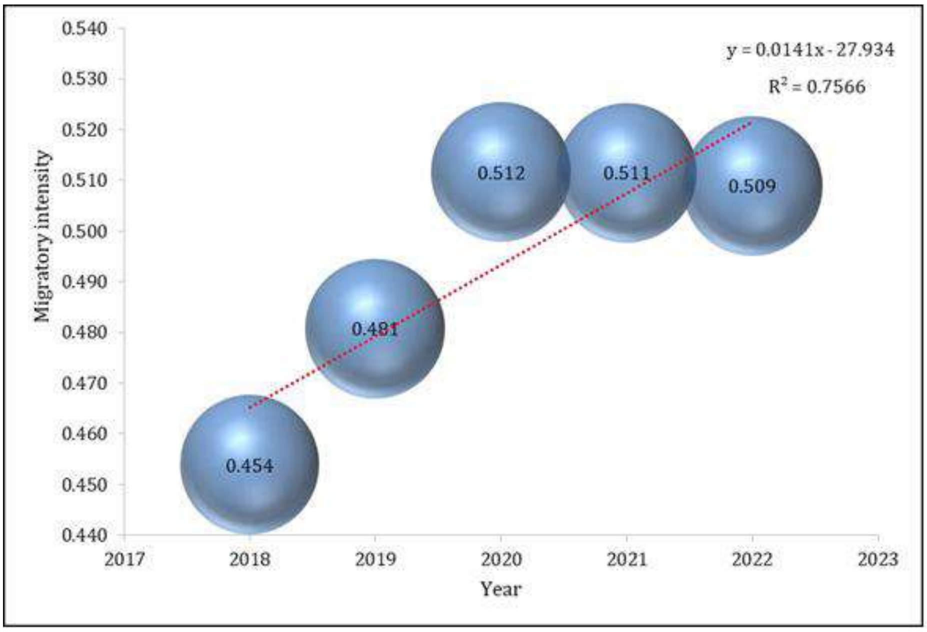


FIGURE 2: Annual migration intensity index of Menabe Antimena (2018–2022)

3.2 Assessment of the Accuracy of the Land-Cover Classification

The overall accuracy of the land-cover classification reached 89.3%, substantially exceeding the standard 85% threshold commonly accepted in remote sensing for the validation of tropical forest cover. This performance is further supported by a Kappa coefficient of 0.78, indicating excellent agreement between the model predictions and the reference observations.

3.3 Vegetation Status of Menabe Antimena in Relation to Deforestation

This study reveals a profound spatio-temporal transformation of the forest landscape across all study sites, characterised overall by a continuous decline in forest cover.

Forest area exhibited considerable annual instability throughout the 2018–2022 period. At the municipal scale, this declining trend was reflected by a minimum annual forest loss of 124.87 ha recorded in Tsimafana in 2020. Conversely, the greatest decline was identified in Marofandilia in 2018, where 3,185.19 ha of forest disappeared within a single year.

Within the Menabe Antimena Protected Area, annual deforestation ranged from a minimum loss of 1,818.80 ha in 2022 to a catastrophic peak of 22,551.90 ha of net forest loss recorded in 2019. The most extensive forest losses occurred predominantly within the boundaries of the protected area. Rural municipalities with a high degree of territorial overlap with the protected area were similarly affected, experiencing systematic forest losses.

Assessment of the annual deforestation rate highlights the intensity of local anthropogenic pressures. According to the standard thresholds used to assess deforestation in tropical environments, the rural municipalities studied exhibited moderate annual rates of forest loss ranging from 0.67% (Tsimafana, 2020) to a highly critical level of 16.94% (Antsoha, 2021), illustrating the extremely rapid disappearance of forest in these areas. In 2019 alone, forest cover within the protected area collapsed to a critical loss rate of 33.00%. By contrast, data for 2020 indicate an exceptional positive balance within the protected area, with more than 16,882.30 ha undergoing conversion and a growth rate exceeding 36.88%. This temporary increase in forest cover, which contrasts with the overall declining trend, may be explained either by a marked slowdown in human activities during the global COVID-19 pandemic or by mapping artefacts resulting from cloud cover in the original raster datasets. Despite this local fluctuation, the territory continues to lose substantial areas of forest each year because the rate of forest clearance consistently exceeds the natural regeneration capacity of the protected area (Figure 3).

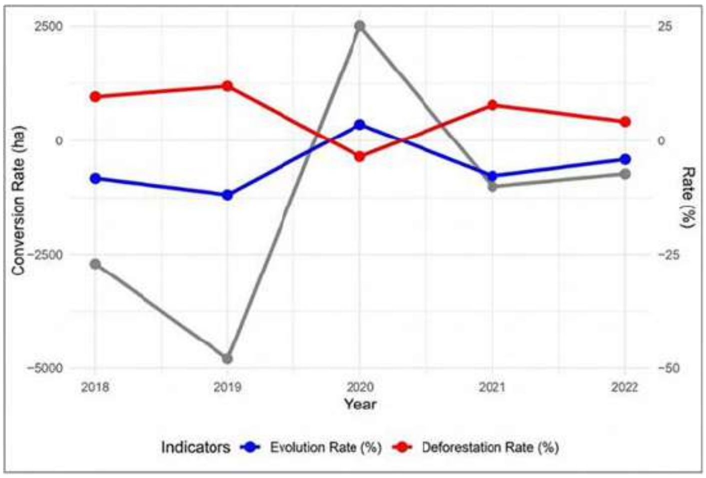


FIGURE 3: Graphical representation of the annual synthesis of the vegetation status change matrix (overall average). The grey curve represents the conversion rate (ha) of the protected area.

3.4 Analysis of the Spatio-Temporal Dynamics of Land Use and Land Cover

The analysis of forest dynamics considered the forested areas of each rural municipality, both within and outside the Menabe Antimena Protected Area. The results show that forest patch density at the different sites ranged from 0.20–0.70 patches/ha in 2017 to 0.25–1.25 patches/ha in 2022. In 2022, the protected area exhibited a markedly higher patch density of 3.92 patches/ha compared with 2.32 patches/ha in 2017. These values correspond to mean patch densities of 0.65 patches/ha in 2022 and 0.39 patches/ha in 2017, respectively. The forested areas of the rural municipalities of Tsarahotana and Antsoha displayed particularly high patch densities, although they were also highly fragmented. Using a paired Student's t-test to compare forest patch densities at time t_1 (2017) and time t_2 (2022), no statistically significant difference was detected between the patch densities recorded in 2017 and those observed in 2022 across all study sites ($t(5) = -2.36$; $p = 0.065 > 0.05$).

The forest landscape, both within and outside the protected area, exhibited a high degree of fragmentation. It was dominated by micro-fragments of forest measuring less than 20 ha, comprising 16,197 forest patches within the protected area (98.86%) and 11,607 forest patches within the protected area's buffer zone (99.08%) in 2017. This pattern of forest subdivision observed in 2017 was also detected in 2022, with an increase of 0.32% within Menabe Antimena (20,622 forest patches of less than 20 ha, representing 99.18%) and an increase of 0.22% in the municipalities located outside the protected area (12,226 forest patches of less than 20 ha, representing 99.30%).

Analysis of variance (ANOVA) revealed a highly significant difference in the number of forest fragments among fragment-size classes (one-way ANOVA: $F = 52.43$; $p = 0.00001 < 0.05$). By contrast, the analysis detected no significant effect of location (inside versus outside the protected area) on the number of fragments ($F = 0.223$; $p = 0.647 > 0.05$). Likewise, the temporal factor showed no significant difference in fragment numbers between 2017 and 2022 ($F = 0.032$; $p = 0.862 > 0.05$) (Figure 4).

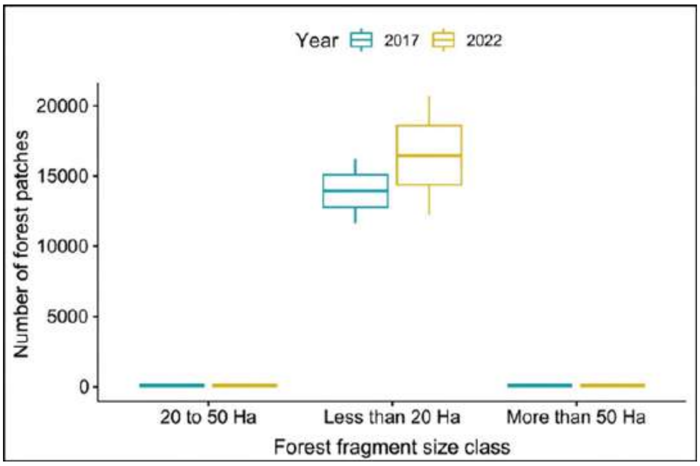


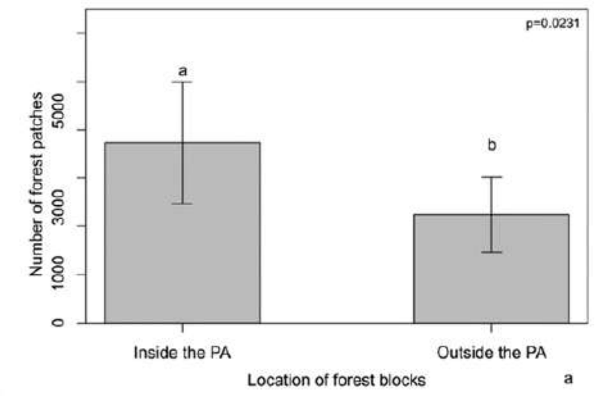
FIGURE 4: Relationship between the number of forest patches and the fragment size class in 2017 and 2022

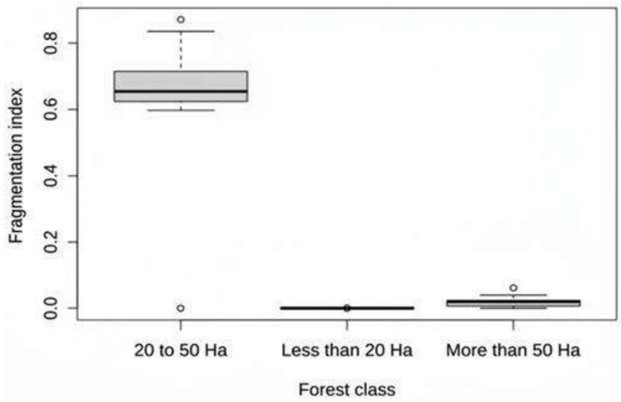
3.5 Dynamics of Forest Landscape Fragmentation in Menabe Antimena

Forest fragmentation dynamics over the period 2017–2022 revealed a generalised increase across the study area. The results indicate that 2022 marked the highest level of landscape fragmentation throughout the study period. Within the protected area, the number of forest fragments increased by 13.94%, rising from 18,251 to 20,796 fragments. Although the surrounding areas remained overall less fragmented, the rate of increase was considerably higher, reaching 25.05%, with the number of fragments increasing from 9,943 to 12,434 (Fig. 5a).

The analysis of variance revealed significant differences in fragmentation indices among forest size classes across the entire study area (ANOVA: $F(2,57) = 148.8$; $p < 0.001$). Between 2017 and 2022, forests ranging from 20 to 50 ha exhibited the highest fragmentation index (0.60–0.87), both within and outside the protected area (Fig. 5b).

These findings demonstrate that forest fragmentation was generally more pronounced within the protected area than in the surrounding landscape. The local population, composed predominantly of migrants, increasingly expanded agricultural land into forested areas, thereby exerting considerable pressure on the protected area and accelerating the process of forest fragmentation.





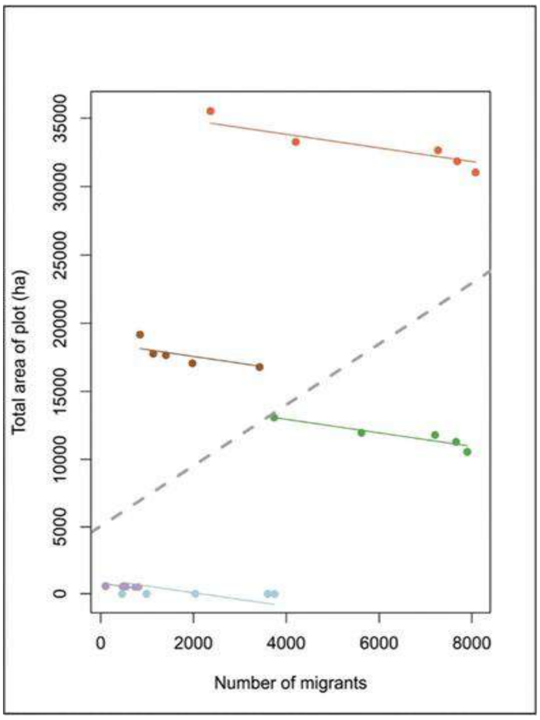
(a) **(b)**

FIGURE 5: Classification of fragmentation across the study sites. (a) According to patch location and (b) According to fragment class.

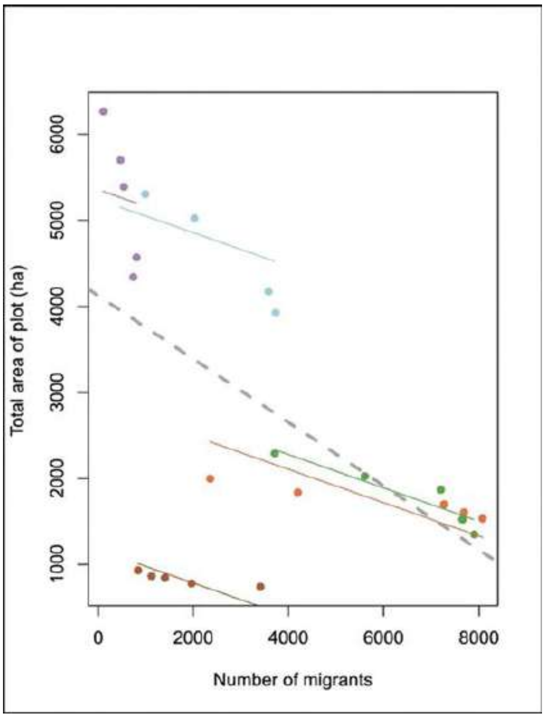
When expressed relative to the area of each municipality, the rural municipality of Marofandilia, located within the protected area, exhibited the highest fragmentation rate, with 8,968 forest fragments distributed across 65,765.53 ha in 2022. It was followed by the rural municipality of Beroboka Nord, which recorded 6,143 forest fragments over an area of 55,374.13 ha during the same year. Across all study sites, forest patch subdivision intensified steadily between 2017 and 2022. Analysis of this temporal trend indicates that the rate of fragmentation remained relatively homogeneous among the different study sites.

3.6 Effects of Migration on Forest Fragment Configuration

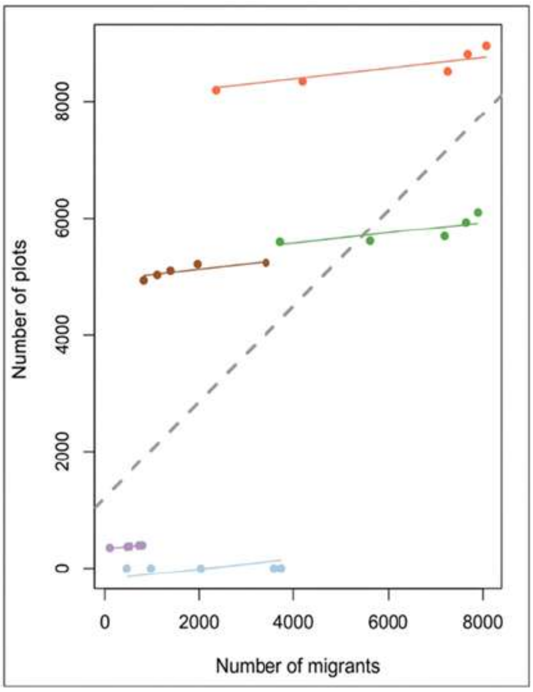
The overall trend reveals a direct relationship between demographic dynamics and the quantitative and spatial configuration of forest cover. The increase in the number of migrants across the rural municipalities of Menabe Antimena was accompanied by a substantial increase in the number of forest fragments and a concomitant reduction in forest area. For forest patches located within the protected area, repeated-measures correlation analysis between the number of migrants and the number of forest patches over the period 2018–2022 revealed a strong, positive and statistically significant relationship ($r = 0.79$; 95% CI: 0.55–0.91; $p < 0.001$) (Fig. 6c). A moderate but statistically significant positive correlation was also observed for the portions of the study area located outside the protected area ($r = 0.53$; 95% CI: 0.12–0.78; $p = 0.014$) (Fig. 6d). By contrast, a strong and statistically significant negative correlation was observed between forest area and the number of migrants in the municipalities located within the protected area ($r = -0.83$; 95% CI: −0.93 to −0.61; $p < 0.001$) (Fig. 6a). For municipalities located outside the protected area, a moderate inverse correlation was likewise found between forest area and migrant influx, and this relationship was statistically significant ($r = -0.59$; 95% CI: −0.81 to −0.21; $p = 0.005$) (Fig. 6b). Overall, these results indicate a significant inverse relationship whereby the increase in the number of forest fragments is associated with a reduction in forest area across the municipalities of the protected area. This process promotes the expansion of forest clearings and increases the prevalence of edge effects within Menabe Antimena. Consequently, land cover within the protected area is now dominated by non-forest formations, including those locally referred to as "Monkas".



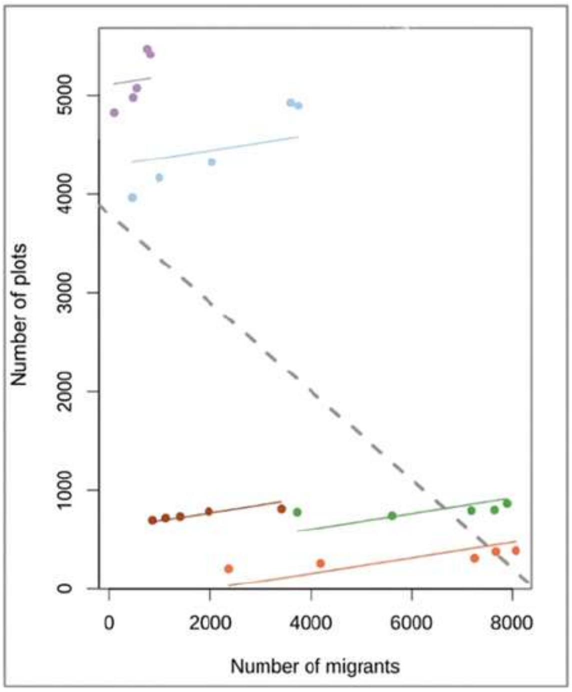
(a)



(b)



(c)



(d)

FIGURE 6: (a-b) Repeated measures correlation between plot area (ha) and the number of migrants from 2018–2022. (c-d) Repeated measures correlation between the number of plots and the number of migrants from 2018–2022. (a) and (c): inside the protected area; (b) and (d): outside the protected area. In colour: the study sites for each year; dashed grey line: overall correlation trend.

The model outputs (Figs. 6a and 6d) reveal a marked reversal in the observed trend when comparing the global and site-specific scales, thereby providing a clear illustration of Simpson's paradox (Bakdash & Marusich, 2017; Kievit et al., 2013; Levick & Rogers, 2011). A combined correlation analysis (grey regression line) misleadingly suggests a negative relationship between forest configuration and increasing migrant numbers ($r = -0.83$ in Fig. 6a and $r = -0.59$ in Fig. 6d). In contrast, the coloured regression lines highlight the dynamics specific to each municipality (site-level scale), demonstrating that both forest fragmentation and changes in forest area consistently progress with increasing migrant settlement. This graphical representation illustrates a typical case of "Simpson's paradox", whereby the initial structural heterogeneity among study sites (site effect) obscures the underlying temporal dynamics. To eliminate this ecological bias, account for inter-municipality variability and accurately estimate the temporal trajectory, a linear mixed-effects model (LMM) was fitted, with study sites included as a random effect to control for spatial heterogeneity. The mixed-effects model confirmed, at the local scale, a positive and highly significant relationship between migrant numbers and the number of forest fragments ($\beta = 0.075$; $z = 2.61$; $p = 0.009$), together with a highly significant negative relationship between migrant numbers and forest area ($\beta = -0.58$; $z = 0.12$; $p < 0.01$).

These estimates therefore confirm a consistent acceleration of forest fragmentation within each municipality, supporting the hypothesis that migrant populations have expanded agricultural activities throughout the study area.

Taken together, these two dynamics reveal a severe process of forest fragmentation and degradation within the Menabe Antimena Protected Area. The reduction in forest area ($\beta = -0.58$), combined with the increasing number of forest fragments ($\beta = 0.075$), results in the disruption of ecological connectivity.

IV. DISCUSSION

4.1 Alarming and Widespread Fragmentation of Menabe Antimena

The results of this study demonstrate a worrying acceleration in the dynamics of forest fragmentation in Menabe Antimena between 2017 and 2022. The annual increase in the number of forest fragments provides direct evidence of an ongoing process of forest subdivision, resulting in a critical loss of the protected area's ecological connectivity (Zou et al., 2025; Rafanoharana et al., 2024). Furthermore, within the protected area itself, this trend is reflected in the emergence of 2,545 new forest patches (representing 14%) over a five-year period. It has been demonstrated that more than 50% of the world's protected areas experienced an intensification of internal anthropogenic pressure between 2000 and 2020, characterised by increased housing construction and the expansion of agricultural land. This phenomenon is strongly correlated with increased internal fragmentation of protected areas (Zhang et al., 2026). This observation confirms, at the local scale, the macro-temporal analyses reported by Andrianambinina et al. (2025) at the scale of Madagascar, highlighting the acceleration of deforestation within the national protected area network itself. In tropical forest regions, these findings are often explained by increasing internal anthropogenic pressures, such as subsistence logging and slash-and-burn agriculture. These observations are consistent with the conclusions of Hending et al. (2023) regarding the dynamics of forest degradation in Madagascar, as well as with the work of Fitz et al. (2022). The latter demonstrate that protected area status does not preclude internal anthropogenic pressures; under the combined effects of population growth and the lack of socio-economic alternatives, local communities continue to engage in agricultural activities and illegal logging, thereby intensifying internal forest fragmentation.

The analysis of fragmentation indices by forest size class reveals that forest blocks ranging from 20 to 50 ha exhibit the highest level of degradation (0.60 to 0.87). This finding indicates that this forest class is undergoing severe landscape fragmentation because, geographically, it is more accessible to neighbouring communities and provides sufficient area to make the establishment of an agricultural frontier economically viable. These forest edges are subject to severe microclimatic changes, which accelerate the mortality of mature trees and promote the encroachment of peripheral bushfires (Hansen et al., 2020).

Consequently, the temporal dynamics of fragmentation observed between 2017 and 2022 demonstrate the current inability of the protected area to maintain the integrity of its ecological functions, thereby posing a direct threat to the water, food, and economic security of neighbouring communities (Jaroensutasinee et al., 2024).

4.2 Diffuse Anthropogenic Transformation of the Forest Landscape

A clear trend towards widespread forest fragmentation has been demonstrated across the study sites. This is reflected in the increasing density of forest patches. This increase indicates that the forest landscape is being divided into smaller and more numerous units throughout the protected area in a spatially homogeneous and temporally consistent manner. An analysis of the current fragmentation trend reveals that the forest is undergoing a rapid forest transition phase, with the landscape now being almost entirely dominated by small forest blocks of less than 20 ha, both inside and outside the protected area. Human activities lead to the anthropogenic transformation of the landscape, in which artificial features become dominant and natural patch types are frequently reduced to a dispersed pattern (Bogaert and Mahamane, 2005). The drivers of fragmentation are therefore associated with population pressure and demographic growth, land subdivision, a low land-to-labour ratio, and traditional agricultural practices (Aslam and Fazal, 2025). This study therefore highlights the statistical significance of the migration variable. The positive association between migration and forest fragmentation indicates that an increase in one is accompanied by an increase in the other.

Such a predominance of small fragments increases edge effects, making the forest more vulnerable to anthropogenic pressures. Furthermore, the fact that the advanced degree of forest fragmentation is observed both inside and outside the protected area, with no significant difference between them, demonstrates that the current protection status is struggling to curb fragmentation despite the various management actions already undertaken. The Category V protected area designation does not alleviate demographic pressure because local populations remain dependent on agricultural activities for their livelihoods.

4.3 Towards an Irreversible Tipping Point in the Intentional Transformation of Forests under Migratory Pressure

Protected status generally reduces forest fragmentation by 82% following designation as a protected area (Zou et al., 2025). Despite its conservation status as an IUCN Category V protected area, Menabe Antimena has experienced intense and continuous fragmentation, reaching its highest level in 2022 with more than 20,000 forest fragments recorded both within the protected area and throughout its surrounding green belt. Category V permits interaction between people and nature within a protected landscape. In the case of Menabe Antimena, this designation has been interpreted as providing an opportunity for agricultural expansion. The implementation of non-participatory conservation policies, characterised by the absence of local community involvement, creates significant imbalances between the local population and its ecosystem. This model generates a sense of exclusion among local communities, fuelling land-use conflicts that are manifested through the excessive and illegal exploitation of natural resources. This finding has been confirmed by Bwalya Umar and Kapembwa (2020) and Aubert et al. (2013), who argued that when local communities are denied access to the resources essential for their livelihoods, they resort to illegal resource exploitation and disregard the boundaries of protected areas as a strategy for economic survival.

A study by Zou et al. (2025) reported that between 58% and 80% of tropical forests became more fragmented between 2000 and 2020. Given the high level of fragmentation within the protected area, the present study indicates that populations with a strong migratory component specifically target forest blocks located inside the protected area for agricultural activities. Consequently, this fragmentation is not a natural process but an anthropogenic one. Accordingly, Brown and Pearce (2023) stated that forest cover and forest structure were negatively correlated with population size. The continuous increase in the number of forest patches between 2017 and 2022 reflects growing pressure on land resources. During the interviews, migrant respondents emphasised that the principal ecosystem service provided by Menabe Antimena is the provisioning service, namely the availability of fertile agricultural land. However, the organisations involved in managing this protected area recognise only supporting, regulating, and socio-cultural ecosystem services (MEDD, 2022), despite their essential contribution to human well-being (Kalinauskas et al., 2024). For communities living adjacent to classified forests, the immediate priority is access to fertile land and soil nutrient reserves, enhanced by the ash resulting from deforestation, in order to ensure food security. This perception directly contradicts policies aimed at conserving the natural heritage (Levers et al., 2021; Rives, 2006).

This phenomenon is particularly evident in sub-Saharan Africa, where high population densities and the scarcity of agricultural land drive communities to seek new areas for cultivation (Hlovor et al., 2021).

Finally, the rate of fragmentation, considered to be homogeneous across all study sites, particularly in the rural communes of Marofandilia and Beroboka Nord, suggests that the landscape has already moved beyond the stage of isolated forest clearings and has entered an irreversible phase of degradation. The protected area has become largely devoid of forest cover, and extensive closed-canopy forest blocks are now rarely observed. What remains are isolated tree trunks or baobabs that have survived repeated fires, together with forest patches characterised by a highly open canopy. Vast degraded areas, locally known as Monkas, have been converted primarily to groundnut cultivation, while cash crops such as cassava have replaced the emblematic forests of the region. After several production cycles, these lands lose their productivity and are subsequently abandoned by local populations.

At the current rate of fragmentation, the forest within the protected area is increasingly approaching complete conversion into agricultural land and degraded areas. Reversing this trend will require a revision of the zoning scheme together with the strict enforcement of legislation, particularly regarding forest clearance and forest fires, in order to conserve and effectively manage the remaining forest.

4.4 The Hidden Dimension of Forest Degradation

This study highlights a pattern of forest fragmentation that is closely associated with migratory movements, particularly within the protected area. Its protected status has proved insufficient to curb forest landscape fragmentation in the face of increasing migratory pressure.

Despite its protected status, the area is subject to more intense migratory pressure, while its highly fertile soils are more sought after than those in the surrounding peripheral zones. Population influx into the rural communes within the protected area, driven by the search for agricultural land, accelerates the structural fragmentation of large forest blocks. This phenomenon demonstrates the strong positive correlation between direct human pressure and the proliferation of small forest patches. The attractiveness of natural resources may explain the increased migratory pressure (Wittemyer et al., 2008). In both the Amazon and tropical Africa, migratory pressure is likewise concentrated in areas where forests remain best preserved, creating a frontier effect (Hänggli et al., 2023). This process reduces the overall forest area and increases the extent of forest edges, progressively transforming the forest landscape into an anthropogenic environment. This observation appears to be supported by Yuan et al. (2024) and Geldmann et al. (2019), who reported that fragmentation is a far more severe issue, affecting 34% of the world's protected areas, and is often regarded as the earliest sign of degradation in tropical ecosystems, even before the complete loss of forest cover. The profound deterioration in habitat quality and the dominance of non-forest areas within the protected area call into question the actual effectiveness of its protection status in the face of persistent anthropogenic pressure.

In light of these findings, the strict conservation model currently applied to the management of the protected area demonstrates its limitations. Strengthening local governance and transferring management responsibilities to local stakeholders, with a view to promoting local economic development, are therefore essential. In this respect, Berenger and Morrissey (2022) demonstrated that, in the Maya Biosphere Reserve in Guatemala, the allocation of sustainable forest concessions to local communities enabled deforestation rates to be reduced to almost zero. Following this model, the development of ecotourism or sustainable forestry value chains in Menabe Antimena could transform local communities, and potentially migrants who have settled permanently in the rural communes of the protected area, into active participants in forest monitoring, by making the forest more economically valuable than slash-and-burn agriculture (tavy or hatsake). Despite the major operational constraints faced by the community-based management organisations already established in Menabe Antimena and throughout Madagascar, scientific studies (Zapata et al., 2026; Kyaw et al., 2024; Laudari et al., 2024) confirm the long-term effectiveness of this decentralised approach in sustainably reversing the trend of structural fragmentation and ensuring the long-term conservation of this landscape, which is characteristic of western Madagascar.

V. CONCLUSION

This study has demonstrated that the anthropogenic footprint associated with migration is a key driver of the regressive spatial and temporal evolution of forest cover within the Menabe Antimena Protected Area. Assessing forest quality represents an essential complement to the quantitative analysis of forest cover. As highly sensitive ecosystems, tropical dry forests respond to anthropogenic pressures through irreversible landscape transformation. This qualitative approach makes it possible to map and quantify the degree of forest degradation while anticipating their trajectories of conversion into non-forest landscapes. Furthermore, it enhances landscape transition modelling in Madagascar by incorporating national demographic drivers. By integrating spatial analysis with demographic data, this study proposes a reproducible methodological framework for quantifying and mapping the vulnerability of other protected areas across Madagascar that are exposed to similar pressures, such as the Ankarafantsika National Park (Muttenzer, 2012; Brou, 2018). This assessment provides a significant contribution to the redesign of national conservation strategies by demonstrating the necessity of integrating internal demographic dynamics into protected area management plans.

The strong correlation between the large-scale arrival of migrants, the proliferation of forest patches resulting from the expansion of anthropogenic landscapes, and land speculation provides compelling evidence of profound changes in both land use and the forest structure of Menabe Antimena. Reversing this trend and stabilising forest cover represent both a humanitarian and an ecological challenge for policymakers and protected area managers alike. It is crucial to address the underlying drivers of migration by reconciling climate resilience with the development of economic opportunities in migrants' areas of origin. Further research should be undertaken to improve the predictive modelling of these landscape dynamics in order, on the one hand, to provide decision-makers with early warning tools and, on the other hand, to integrate socio-demographic data into protected area planning and management strategies. Incorporating these internal migratory dynamics into environmental governance constitutes an essential strategic lever for addressing the biodiversity crisis, while placing Madagascar on a trajectory towards achieving the equity and ecological performance objectives established under the Kunming–Montreal Global Biodiversity Framework by 2030.

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CONFLICT OF INTEREST

The authors of this manuscript declare that they have no conflicts of interest.

REFERENCES

[1] Achard, F., Eva, H. D., Mayaux, P., Stibig, H. J., & Belward, A. (2004). Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. *Global Biogeochemical Cycles*, *18*(2). https://doi.org/10.1029/2003GB002142

[2] Agrawal, A. (2018). *Réévaluation de l'importance relative de la pression démographique, des forces du marché et des institutions sur l'état des forêts, à partir d'une analyse des conseils villageois de gestion forestière du Kumaon, dans l'Himalaya moyen indien* [Research report]. University of Florida.

[3] Ahmed, H., Jallat, H., Hussain, E., Saqib, N. U., Saqib, Z., Khokhar, M. F., et al. (2023). Quantitative assessment of deforestation and forest degradation in Margalla Hills National Park (MHNP): Employing landsat data and socio-economic survey. *Forests*, *14*, 201. https://doi.org/10.3390/f14020201

[4] Andrianambinina, F. O. D., Ganzhorn, J. U., Waeber, P. O., & Wilmé, L. (2025). Complex deforestation patterns in and around the protected areas of Madagascar from 2015 to 2023. *Land*, *14*(4), 698. https://doi.org/10.3390/land14040698

[5] Andrianambinina, F. O. D., Rafanoharana, S. C., Rasamuel, H. A. T., Waeber, P. O., Ganzhorn, J. U., & Wilmé, L. (2024). Decrease of deforestation in protected areas of Madagascar during the Covid-19 years. *Madagascar Conservation & Development*, *18*(1), 15-21. https://doi.org/10.4314/mcd.v18i1.2

[6] Andrianandrasana, H. T., Jones, N., Viraina, F. F., Malesios, C., Campera, M., Sama, Z., Long, P. R., Panichelli-Batalla, S., Richardson, N. M., & Savage, J. (2025). Links between poverty, climate-induced migration and deforestation in western Madagascar. *Environmental Development*, *56*. https://doi.org/10.1016/j.envdev.2025.101284

[7] Aslam, M., & Fazal, S. (2025). Exploring the impact of land fragmentation on the performance of agriculture: A systematic review. *Discover Agriculture*. https://doi.org/10.1007/s44279-025-00207-6

[8] Asner, G. P., Rudel, T. K., Aide, T. M., Defries, R., & Emerson, R. (2009). A contemporary assessment of change in humid tropical forests. *Conservation Biology*, *23*(6), 1386-1395. https://doi.org/10.1111/j.1523-1739.2009.01333.x

[9] Aubert, S., Rambintsaotra, S., & Razafiarijaona, J. (2013). L'insécurité foncière dans et autour des Aires Protégées de Madagascar : un obstacle à surmonter pour la conservation de la biodiversité et le développement rural. *Développement durable et territoires*, *4*(1). https://doi.org/10.4000/developpementdurable.9661

[10] Bakdash, J. Z., & Marusich, L. R. (2017). Repeated measures correlation. *Frontiers in Psychology*, *8*, 456. https://doi.org/10.3389/fpsyg.2017.00456

[11] Bechard, L. (2018). *Les migrations environnementales en 2018 : l'agenda 2030 des Nations Unies et la responsabilité des pays du Nord*. http://hdl.handle.net/11143/12844

[12] Berenger, E., & Morrissey, S. (2022). Successful 20 years of community forest management in Guatemala informs an Integrated Community Forest Management pathway to support scaling. In *XV World Forestry Congress, 2-6 May 2022, Seoul, Republic of Korea*. FAO. https://openknowledge.fao.org/handle/20.500.14283/y2661e

[13] Bogaert, J., & Mahamane, A. (2005). Ecologie du paysage : cibler la configuration et l'échelle spatiale. *Annales des Sciences Agronomiques*, *7*(1), 39-68. https://doi.org/10.4314/asab.v7i1.43277

[14] Bogaert, J., Ceulemans, R., & Salvador-Van Eysenrode, D. (2004). Decision tree algorithm for detection of spatial processes in landscape transformation. *Environmental Management*, *33*, 62-73. https://doi.org/10.1007/s00267-003-0027-0

[15] Bogaert, J., & Hong, S. K. (2004). Landscape ecology: Monitoring landscape dynamics using spatial pattern metrics. In S. K. Hong et al. (Eds.), *Ecological issues in a changing world* (pp. 1-15). Springer. https://doi.org/10.1007/978-1-4020-2689-8_8

[16] Brou, Y. T. (2018). Pressions agro-démographiques dans les espaces forestiers protégés de Madagascar: l'exemple du Parc National d'Ankarafantsika. *Carnets de Recherches de l'océan Indien*, (2). https://hal.archives-ouvertes.fr/hal-02474941

[17] Brown, K., & Pearce, D. W. (2023). *The causes of tropical deforestation: The economic and statistical analysis of factors giving rise to the loss of the tropical forests*. Routledge. https://doi.org/10.4324/9781003428190

[18] Bwalya Umar, B., & Kapembwa, J. (2020). Economic benefits, local participation, and conservation ethic in a game management area: Evidence from Mambwe, Zambia. *Tropical Conservation Science*, *13*, 1940082920971754. https://doi.org/10.1177/1940082920971754

[19] Caron, S., Garvey, S. M., Gewirtzman, J., Schultz, K., Bhatnagar, J. M., Driscoll, C., ... & Templer, P. H. (2023). L'urbanisation et la fragmentation ont des effets opposés sur la disponibilité de l'azote dans les sols des écosystèmes forestiers tempérés. *Global Change Biology*, *29*(8), 2156-2171. https://doi.org/10.1111/gcb.16611

[20] Collinge, S. K., & Forman, R. T. T. (1998). A conceptual model of land conversion processes: Prediction and evidence from a microlandscape experiment with grassland insect. *Oikos*, *82*, 66-84. https://doi.org/10.2307/3546918

[21] Congalton, R. G. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, *37*(1), 35-46.

[22] Edwards, D. P., Socolar, J. B., Mills, S. C., Burivalova, Z., Koh, L. P., & Wilcove, D. S. (2019). Conservation of tropical forests in the anthropocene. *Current Biology*, *29*(19), R1008-R1020. https://doi.org/10.1016/j.cub.2019.08.026

[23] FAO & JRC. (2012). *Global Forest Land-use Change 1990–2005* (FAO Forestry Paper No. 169). Food and Agriculture Organization of the United Nations and European Commission Joint Research Centre.

[24] Fischer, R., Taubert, F., Müller, M. S., Groeneveld, J., Lehmann, S., Wiegand, T., & Huth, A. (2021). Accelerated forest fragmentation leads to critical increase in tropical forest edge area. *Science Advances*, *7*(37), eabg7012. https://doi.org/10.1126/sciadv.abg7012

[25] Fitz, J., Adenle, A. A., & Speranza, C. I. (2022). Increasing signs of forest fragmentation in the Cross River National Park in Nigeria: Underlying drivers and need for sustainable responses. *Ecological Indicators*, *139*, 108943. https://doi.org/10.1016/j.ecolind.2022.108943

[26] Fu, X., Li, Z., Ma, J., Zhou, M., Chen, L., & Peng, J. (2025). Ecosystem resilience response to forest fragmentation in China: Thresholds identification. *Journal of Environmental Management*, *380*, 125180. https://doi.org/10.1016/j.jenvman.2025.125180

[27] Geldmann, J., Manica, A., Burgess, N. D., Coad, L., & Balmford, A. (2019). A global-scale assessment of changes in human pressure on protected areas. *Conservation Biology*, *33*(5), 1160-1170.

[28] Goodman, S. M., Raherilalao, M. J., & Wohlhauser, S. (Eds.). (2018). *The terrestrial protected areas of Madagascar: Their history, description, and biota* (Vol. III: Western and Southwestern Madagascar – synthesis). Association Vahatra.

[29] Hänggli, A., Levy, S. A., Armenteras, D., Bovolo, C. I., Brandão, J., Rueda, X., & Garrett, R. D. (2023). A systematic comparison of deforestation drivers and policy effectiveness across the Amazon biome. *Environmental Research Letters*, *18*(7), 073001. https://doi.org/10.1088/1748-9326/acd408

[30] Hansen, M. C., Wang, L., Song, X. P., Tyukavina, A., Turubanova, S., Potapov, P. V., & Stehman, S. V. (2020). The fate of tropical forest fragments. *Science Advances*, *6*(11), eaax8574. https://doi.org/10.1126/sciadv.aax8574

[31] Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., et al. (2013). High-resolution global maps of 21st-century forest cover change. *Science*, *342*, 850-853. https://doi.org/10.1126/science.1244693

[32] Hauer, M. E., Jacobs, S. A., & Kulp, S. A. (2024). Climate migration amplifies demographic change and population aging. *Proceedings of the National Academy of Sciences*, *121*(3), e2206192119. https://doi.org/10.1073/pnas.2206192119

[33] Hending, D., Randrianarison, H., Andriamavosoloarisoa, N. N. M., Ranohatra-Hending, C., McCabe, G., Cotton, S., & Holderied, M. W. (2025). Impact of forest fragmentation and associated edge effects on tropical forest biodiversity in North West Madagascar, assessed via ecoacoustics. *Animal Conservation*. https://doi.org/10.1111/acv.70037

[34] Hending, D., Randrianarison, H., Andriamavosoloarisoa, N. N. M., Ranohatra-Hending, C., Holderied, M., McCabe, G., & Cotton, S. (2023). Forest fragmentation and its associated edge-effects reduce tree species diversity, size, and structural diversity in Madagascar's transitional forests. *Biodiversity and Conservation*, *32*(10), 3329-3353. https://doi.org/10.1007/s10531-023-02657-0

[35] Hisham, T. W. B., & Hua, A. K. (2026). Spatial analysis of forest fragmentation impacts on ecosystem services in Petaling, Malaysia (2005–2023). *Journal of Landscape Ecology*, *19*(2). https://doi.org/10.2478/jlecol-2026-0020

[36] Hlovor, A. K. D., Adjonou, K., Dangbo, F. A., Abotsi, K. E., Afelu, B., & Kokou, K. (2021). Dynamique du couvert forestier dans la partie méridionale des Monts Togo, Afrique de l'Ouest. *Revue Ivoirienne des Sciences et Technologie*, *37*, 300-313.

[37] Holden, S. T., & Otsuka, K. (2014). The roles of land tenure reforms and land markets in the context of population growth and land use intensification in Africa. *Food Policy*, *48*, 88-97. https://doi.org/10.1016/j.foodpol.2014.03.005

[38] IOM (International Organization for Migration). (2024). Indice de solution et de mobilité - Région Menabe, Madagascar. Institut mondial des données. Matrice de suivi des déplacements.

[39] Jaeger, J. A. G. (2000). Landscape division, splitting index, and effective mesh size: New measures of landscape fragmentation. *Landscape Ecology*, *15*, 115-130. https://doi.org/10.1023/A:1008129329289

[40] Jallat, H., Khokhar, M. F., Kudus, K. A., Nazre, M., Saqib, N. U., Tahir, U., et al. (2021). Monitoring carbon stock and land-use change in 5000-year-old juniper forest stand of Ziarat, Balochistan, through a synergistic approach. *Forests*, *12*, 1-15. https://doi.org/10.3390/f12010051

[41] Jaroensutasinee, K., Jaroensutasinee, M., Chuachart, O., & Sparrow, E. (2024). Protected area size affecting habitat fragmentation: A case study of protected areas in Thailand. In *Sustainable forest management: Surpassing climate change and land degradation*. IntechOpen. https://doi.org/10.5772/intechopen.1004276

[42] Jones, J. P. G., Mandimbiniaina, R., Kelly, R., et al. (2018). Human migration to the forest frontier: Implications for land use change and conservation management. *Geo: Geography and Environment*. https://doi.org/10.1002/geo2.50

[43] Kalinauskas, M., Shuhani, Y., Pinto, L. V., Inácio, M., & Pereira, P. (2024). Mapping ecosystem services in protected areas: A systematic review. *Science of the Total Environment*, *912*, 169248. https://doi.org/10.1016/j.scitotenv.2023.169248

[44] Kievit, R. A., Frankenhuis, W. E., Waldorp, L. J., & Borsboom, D. (2013). Simpson's paradox in psychological science: A practical guide. *Frontiers in Psychology*, *4*, 513. https://doi.org/10.3389/fpsyg.2013.00513

[45] Kyaw, K. T. W., Ota, T., Mizoue, N., & Chicas, S. D. (2024). Uncovering the conservation effectiveness of community forests: A case study from Shan State in Myanmar. *Biological Conservation*, *300*, 110846. https://doi.org/10.1016/j.biocon.2024.110846

[46] Lamy, T., Liss, K., Gonzalez, A., & Bennett, E. (2016). Landscape structure affects the provision of multiple ecosystem services. *Environmental Research Letters*, *11*(12), 124017. https://doi.org/10.1088/1748-9326/11/12/124017

[47] Laudari, H. K., Sapkota, L. M., Maraseni, T., Subedi, P., Pariyar, S., Kaini, T. R., ... & Volkova, L. (2024). Community forestry in a changing context: A perspective from Nepal's mid-hill. *Land Use Policy*, *138*, 107018. https://doi.org/10.1016/j.landusepol.2023.107018

[48] Levers, C., Romero-Muñoz, A., Baumann, M., De Marzo, T., Fernández, P. D., Gasparri, N. I., ... & Kuemmerle, T. (2021). Agricultural expansion and the ecological marginalization of forest-dependent people. *Proceedings of the National Academy of Sciences*, *118*(44), e2100436118. https://doi.org/10.1073/pnas.2100436118

[49] Levick, S. R., & Rogers, K. H. (2011). Context-dependent vegetation dynamics in an African savanna. *Landscape Ecology*, *26*(4), 515-528. https://doi.org/10.1007/s10980-011-9578-2

[50] Li, D., Yang, Y., Xia, F., Sun, W., Li, X., & Xie, Y. (2022). Exploring the influences of different processes of habitat fragmentation on ecosystem services. *Landscape and Urban Planning*, *227*, 104544. https://doi.org/10.1016/j.landurbplan.2022.104544

[51] Ma, J., Li, J., Wu, W., & Liu, J. (2023). Global forest fragmentation change from 2000 to 2020. *Nature Communications*, *14*(1), 3752. https://doi.org/10.1038/s41467-023-39221-x

[52] Mahapatra, S., Majhi, B. K., Sarkar, M. S., Datta, D., Mishra, A. P., & Rathnayake, U. (2025). Understanding forest fragmentation dynamics and identifying drivers for forest cover loss using random forest models to develop effective forest management strategies in North-East India. *Results in Engineering*, *26*, 104640. https://doi.org/10.1016/j.rineng.2025.104640

[53] Markolf, M., Schäffler, L., & Kappeler, P. M. (2019). *Microcebus berthae*. The IUCN Red List of Threatened Species. https://www.iucnredlist.org/species/41573/115579496

[54] Marusich, L. R., & Bakdash, J. Z. (2021). rmcorrShiny: A web and standalone application for repeated measures correlation. *F1000Research*, *10*, 697. https://doi.org/10.12688/f1000research.55027.2

[55] McGarigal, K., & Marks, B. J. (1995). *FRAGSTATS: Spatial pattern analysis program for quantifying landscape structure* (USDA Forest Service General Technical Report PNW-351). https://doi.org/10.2737/PNW-GTR-351

[56] MEDD (Ministère de l'Environnement et du Développement Durable). (2022). *Plan d'Aménagement et de Gestion de l'Aire Protégée Menabe Antimena (2022-2026)*.

[57] Monmonier, M. S. (1974). Measures of pattern complexity for choroplethic maps. *The American Cartographer*, *1*(2), 159-169. https://doi.org/10.1559/152304074784107728

[58] Muraoka, K., Jin, S., & Jayne, T. S. (2018). Land access, land rental and food security: Evidence from Kenya. *Land Use Policy*, *70*, 611-622. https://doi.org/10.1016/j.landusepol.2017.10.045

[59] Muttenzer, F. (2012). Community forest management on the agricultural frontier: Charcoal makers, immigrant associations and land claims in Ankarafantsika, North-West Madagascar. *Les Cahiers d'Outre-Mer*, *65*(258), 249-272. https://doi.org/10.4000/com.6604

[60] Myers, N., Mittermeier, R., Mittermeier, C., et al. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*, 853-858. https://doi.org/10.1038/35002501

[61] Nicoletti, A., Melde, S., Guadagno, L., & Bilsborrow, R. E. (2023). Human mobility in the context of environmental and climate change: Recent data collection tools from the International Organization for Migration to address key methodological and conceptual issues. *International Migration*, *61*(5), 47-59. https://doi.org/10.1111/imig.13043

[62] Olofsson, P., Foody, G. M., Herold, M., Stehman, S. V., Woodcock, C. E., & Wulder, M. A. (2014). Good practices for estimating area and assessing accuracy of land change. *Remote Sensing of Environment*, *148*, 42-54.

[63] Oloukoï, J., Mama, V. J., & Agbo, B. F. (2006). Modélisation de la dynamique de l'occupation des terres dans le département des collines au Bénin. *Revue Télédétection*, *6*(4), 305-323.

[64] Panigrahi, S., & Vidyarthi, V. K. (2024). Assessing the suitability of McKee et al. (1993) drought severity classification across India. *Natural Hazards*, *120*(14), 13543-13572. https://doi.org/10.1007/s11069-024-06762-3

[65] Payne, R. (2020). *Anova and design* (21st ed.). VSN International. https://genstat.kb.vsni.co.uk/wp-content/uploads/sites/2/AnovaGuide.pdf

[66] Peptenatu, D., Andronache, I., Ahammer, H., Radulovic, M., Costanza, J. K., Jelinek, H. F., ... & Newman, E. A. (2023). A new fractal index to classify forest fragmentation and disorder. *Landscape Ecology*, *38*(6), 1373-1393. https://doi.org/10.1007/s10980-023-01640-y

[67] Perea, M. (2024). Exploring the effects of forest fragmentation on ecosystem health and resilience. *Journal of Biodiversity & Endangered Species*, *12*, 530. https://doi.org/10.37421/2332-2543.2024.12.530

[68] Puyravaud, J. P. (2003). Standardizing the calculation of the annual rate of deforestation. *Forest Ecology and Management*, *177*(1-3), 593-596.

[69] Rabemananjara, Z. H. (2014). Migration causing forest degradation in Madagascar: Prevention or adaptation to the effects? *Pinnacle Natural Resources & Conservation*, *1*(1), 194-201.

[70] Rafanoharana, S. C., Andrianambinina, F. O. D., Rasamuel, H. A., Waeber, P. O., Wilmé, L., & Ganzhorn, J. U. (2024). Projecting forest cover in Madagascar's protected areas to 2050 and its implications for lemur conservation. *Oryx*, *58*(2), 155-163. https://doi.org/10.1017/S0030605323001175

[71] Rafanoharana, S. C., Andrianambinina, F. O. D., Rasamuel, H. A., Waeber, P. O., Ganzhorn, J. U., & Wilmé, L. (2023). Tree canopy density thresholds for improved forests cover estimation in protected areas of Madagascar. *Environmental Research Communications*, *5*(7), 071003. https://doi.org/10.1088/2515-7620/ace87f

[72] Rahman, M. F., & Islam, K. (2021). Effectiveness of protected areas in reducing deforestation and forest fragmentation in Bangladesh. *Journal of Environmental Management*, *280*, 111711. https://doi.org/10.1016/j.jenvman.2020.111711

[73] Rakotoarisoa, S. E., Andriajaona, A., Andriamihajarivo, T., Andriamparany, S., et al. (Eds.). (2025). *Madagascar Protected Area Outlook 2025: A conservation assessment of terrestrial Protected Areas in Madagascar*. https://conservationallies.org/outlook/

[74] Rakotonarivo, O. S., Mueller, V., Rakotoarisoa, M., Rakoto Harison, H., & Bell, A. R. (2026). Beyond blame: Migration's limited role in Madagascar's deforestation. *Conservation Letters*, *19*(1), e70018. https://doi.org/10.1111/con4.70018

[75] Ravonjimalala, H. R. (2019). *Modélisation spatiale des changements d'occupation du sol et de la fragmentation de la forêt dense sèche du Sud-ouest de Madagascar : cas de la commune Analamisampy* [Doctoral dissertation, Université de Antananarivo].

[76] Rives, F. (2006). *Faire le deuil de la forêt primaire pour sauver les forêts ? étude des pratiques et des représentations paysannes de la forêt pour élaborer des stratégies de restauration dans le corridor forestier de Ankeniheny Zahamena est de Madagascar* [Doctoral dissertation, ENGREF].

[77] Salvaterra & INDRI. (2017). *Analyse des moteurs de déforestation et de dégradation dans les écorégions des forêts humides de l'Est et des forêts sèches de l'Ouest de Madagascar* (Rapport de synthèse - Livrable 4). Bureau National de Coordination REDD+ (BNC REDD+), Ministère de l'Environnement, de l'Écologie et des Forêts, République de Madagascar.

[78] Sambiéni, K. R., Toyi, M. S., & Mama, A. (2015). Perception paysanne sur la fragmentation du paysage de la forêt classée de l'Ouémé Supérieur au nord du Bénin. *Vertigo*, *15*(12). https://doi.org/10.4000/vertigo.16477

[79] Scales, I. R. (2011). Farming at the forest frontier: Land use and landscape change in Western Madagascar, 1896-2005. *Environment and History*, *17*(4), 499-524. https://doi.org/10.3197/096734011X13150366551481

[80] Scholte, P., & De Groot, W. T. (2010). From Debaste to insight: Three models of immigration to protected areas. *Conservation Biology*, *24*(2), 630-632. https://doi.org/10.1111/j.1523-1739.2009.01314.x

[81] Senior, R. A., Hill, J. K., & Edwards, D. P. (2019). Global loss of climate connectivity in tropical forests. *Nature Climate Change*, *9*(8), 623-626. https://doi.org/10.1038/s41558-019-0529-2

[82] Sist, P. (2025). *Sustainable management of tropical forests*. Éditions Quæ. https://doi.org/10.35690/978-2-7592-4188-0

[83] Sunderlin, W. D., & Pokam, J. (2002). Economic crisis and forest cover change in Cameroon: The roles of migration, crop diversification, and gender division of labor. *Economic Development and Cultural Change*, *50*(3). https://doi.org/10.1086/342358

[84] Taubert, F., Fischer, R., Groeneveld, J., Lehmann, S., Müller, M. S., Rödig, E., Wiegand, T., & Huth, A. (2018). Global patterns of tropical forest fragmentation. *Nature*, *554*, 519-522. https://doi.org/10.1038/nature25508

[85] Tchibozo, E. A. M. (2020). Modélisation de la dynamique spatio-temporelle de l'occupation du sol et analyse des changements du territoire de La Lama au Bénin. *European Scientific Journal*, *16*(6). https://doi.org/10.19044/esj.2020.v16n6p500

[86] Tovondrazane, C. A., et al. (2020). Dynamique spatio-temporelle de succession forestière dans la forêt des Mikea et ses périphériques, Sud-ouest de Madagascar.

[87] Triplet, P. (2009). *Manuel de gestion des aires protégées d'Afrique francophone*. Awely. https://hal.archives-ouvertes.fr/hal-00669157

[88] Veron, J. (2020). Migrations et changement climatique: Un phénomène aux dimensions incertaines. In T. De Montbrial & D. David (Eds.), *Ramses 2021: Le grand basculement ?* (pp. 78-83). Institut français des relations internationales. https://doi.org/10.3917/ifri.demon.2020.01.0078

[89] Vieilledent, G., Grinand, C., Rakotomalala, F., Ranaivosoa, R., Rakotoarijaona, J. R., Allnutt, T. F., & Achard, F. (2018). Combining global tree cover loss data with historical national forest cover maps to look at six decades of deforestation and forest fragmentation in Madagascar. *Biological Conservation*, *222*, 189-197. https://doi.org/10.1016/j.biocon.2018.04.008

[90] Vimal, R., Navarro, L. M., Jones, Y., Wolf, F., Le Moguédec, G., & Réjou-Méchain, M. (2021). The global distribution of protected areas management strategies and their complementarity for biodiversity conservation. *Biological Conservation*, *256*, 109014. https://doi.org/10.1016/j.biocon.2021.109014

[91] Vinke, K., Rottmann, S., Gornott, C., Zabre, P., Schwerdtle, P. N., & Sauerborn, R. (2022). Is migration an effective adaptation to climate-related agricultural distress in sub-Saharan Africa? *Population and Environment*, *43*, 319-345. https://doi.org/10.1007/s11111-021-00393-7

[92] Wade, T. G., Riitters, K. H., Wickham, J. D., & Jones, K. B. (2003). Distribution and causes of global forest fragmentation. *Conservation Ecology*, *7*(2). https://www.jstor.org/stable/26271943

[93] Wainger, L. A., King, D. M., Mack, R. N., Price, E. W., & Maslin, T. (2010). Can the concept ecosystem services be practically applied to improve natural resource management decisions? *Ecological Economics*, *69*, 978-987. https://doi.org/10.1016/j.ecolecon.2009.12.011

[94] Wilmet, L., Toto Volahy, A., & Hudson, M. (2022). *Hypogeomys antimena*. The IUCN Red List of Threatened Species. https://doi.org/10.2305/IUCN.UK.2022-1.RLTS.T10714A216087357.fr

[95] Wittemyer, G., Elsen, P., Bean, W. T., Burton, A. C. O., & Brashares, J. S. (2008). Accelerated human population growth at protected area edges. *Science*, *321*(5885), 123-126.

[96] Yuan, R., Zhang, N., & Zhang, Q. (2024). The impact of habitat loss and fragmentation on biodiversity in global protected areas. *Science of the Total Environment*, *931*, 173004. https://doi.org/10.1016/j.scitotenv.2024.173004

[97] Zapata, S. V., Vargas, G. A., Castano, E., Munoz, C., Londoño, Y., Zamudio-Mir, M. C., ... & Eslava, A. (2026). Against the odds: Community forestry in the San Lucas Mountains, Colombia. *World Development*, *198*, 107231. https://doi.org/10.1016/j.worlddev.2025.107231

[98] Zhang, N., Shang, C., Wu, J., & Zhang, Q. (2026). Impacts of surrounding land development on fragmentation within global protected areas. *Resources, Conservation and Recycling*, *227*, 108749. https://doi.org/10.1016/j.resconrec.2025.108749

[99] Zinner, D., Wygoda, C., Razafimanantsoa, L., Rasoloarison, R., Andrianandrasana, H. T., Ganzhorn, J. U., & Torkler, F. (2014). Analysis of deforestation patterns in the central Menabe, Madagascar, between 1973 and 2010. *Regional Environmental Change*, *14*(1), 157-166. https://doi.org/10.1007/s10113-013-0475-x

[100] Zou, Y., Crowther, T. W., Smith, G. R., Ma, H., Mo, L., Bialic-Murphy, L., & Zohner, C. M. (2025). Fragmentation increased in over half of global forests from 2000 to 2020. *Science*, *389*(6765), 1151-1156. https://doi.org/10.1126/science.adr6450.

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Genomic Selection in Animal Breeding: Principles, Applications, and Future Perspectives

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***Abstract*—** *Genomic selection (GS) has transformed modern animal breeding by enabling the prediction of genetic merit using dense genome-wide molecular markers rather than relying solely on pedigree and phenotypic information. Since its conceptual introduction in 2001, GS has become a cornerstone of genetic improvement programs in livestock species, particularly dairy cattle, and has subsequently expanded to beef cattle, sheep, goats, swine, poultry, and aquaculture. The integration of high-density single nucleotide polymorphism (SNP) genotyping with advanced statistical prediction models has substantially increased the accuracy of breeding value estimation, shortened generation intervals, and accelerated rates of genetic gain. Compared with conventional best linear unbiased prediction (BLUP) and marker-assisted selection (MAS), genomic selection captures the combined effects of thousands of loci distributed throughout the genome, making it highly effective for complex quantitative traits governed by many genes of small effect. Recent advances, including single-step genomic BLUP, Bayesian prediction methods, whole-genome sequence analysis, functional genomics, multi-omics integration, artificial intelligence, and precision livestock farming technologies, have further enhanced the scope and efficiency of genomic prediction. These innovations are facilitating simultaneous improvement in productivity, fertility, feed efficiency, disease resistance, animal welfare, and environmental sustainability. Moreover, genomic information is increasingly being integrated with genome editing technologies such as CRISPR to support precision breeding strategies. This review summarizes the historical evolution, fundamental principles, methodological developments, and practical applications of genomic selection in livestock breeding while highlighting emerging innovations and future research directions that are expected to shape next-generation animal improvement programs.*

Keywords*— *Genomic selection; Genomic estimated breeding value; Genomic prediction; Single nucleotide polymorphism; Livestock breeding; Genomic BLUP; Animal genetics; GBLUP; ssGBLUP; Quantitative genetics; Marker-assisted selection; SNP; Heritability.

I. INTRODUCTION

Genetic improvement has long been one of the primary drivers of increased productivity, efficiency, and profitability in livestock production. Traditionally, breeding programs have relied on phenotypic performance records, pedigree information, and statistical methods such as Best Linear Unbiased Prediction (BLUP) to estimate breeding values. Although these approaches have generated substantial genetic progress over the past several decades, their effectiveness is constrained by long generation intervals, delayed availability of phenotypic records, and reduced prediction accuracy for traits with low heritability or those expressed late in life [1, 2].

The rapid development of molecular genetics and high-throughput genotyping technologies has fundamentally changed animal breeding strategies. The availability of dense genome-wide single nucleotide polymorphism (SNP) markers has enabled direct estimation of genomic relationships among individuals and facilitated prediction of breeding values based on DNA information rather than pedigree alone [1, 3]. This strategy, known as genomic selection (GS), estimates the combined effects of thousands of markers distributed across the entire genome, thereby capturing the genetic architecture underlying complex quantitative traits.

Unlike conventional marker-assisted selection, which focuses on a limited number of significant quantitative trait loci (QTL), genomic selection simultaneously exploits information from all available genome-wide markers regardless of their individual statistical significance [1, 4]. This approach has markedly improved the accuracy of genomic estimated breeding values (GEBVs), particularly for young selection candidates without phenotypic records, enabling earlier and more reliable selection decisions [2, 5].

The widespread adoption of genomic selection in dairy cattle since 2008 has demonstrated remarkable increases in annual genetic gain, reduced breeding costs, and shortened generation intervals. Similar advances are now being realized in beef cattle, sheep, goats, swine, poultry, and aquaculture species through continued improvements in genomic resources, computational methodologies, and sequencing technologies [3, 6–8]. Consequently, genomic selection has become one of the most influential innovations in modern quantitative genetics and animal breeding, laying the foundation for sustainable and precision livestock improvement.

II. EVOLUTION OF GENOMIC SELECTION

The evolution of animal breeding has been characterized by continuous advances in quantitative genetics, statistical methodologies, and molecular biology. For much of the twentieth century, selection decisions were based primarily on observable phenotypes and pedigree records. The introduction of Best Linear Unbiased Prediction (BLUP) in the 1970s revolutionized genetic evaluation by integrating pedigree and performance information to estimate breeding values with greater accuracy. Although conventional BLUP substantially improved selection efficiency, it remained dependent on extensive phenotypic recording and accurate pedigree information, limiting genetic progress for traits expressed late in life, those with low heritability, or traits difficult or expensive to measure [1, 3].

The rapid development of molecular genetics during the 1990s generated considerable enthusiasm for marker-assisted selection (MAS), which aimed to improve breeding efficiency by identifying quantitative trait loci (QTL) associated with economically important traits. While several major genes with large effects were successfully identified, MAS generally failed to achieve widespread implementation because most economically important traits, including milk yield, growth rate, fertility, and disease resistance, are polygenic and controlled by numerous loci with individually small effects. Consequently, only a small proportion of the total genetic variance could be explained by significant QTL, limiting the overall effectiveness of MAS in commercial breeding programs [9].

A major breakthrough occurred when Meuwissen, Hayes, and Goddard proposed the concept of genomic selection (GS) in 2001. Rather than identifying only statistically significant markers, genomic selection assumes that all markers distributed across the genome contribute to the prediction of genetic merit. Dense genome-wide single nucleotide polymorphism (SNP) markers are used simultaneously to estimate marker effects, enabling the calculation of Genomic Estimated Breeding Values (GEBVs) without requiring prior knowledge of the causal mutations [1]. This paradigm shift fundamentally changed livestock breeding by exploiting linkage disequilibrium between markers and quantitative trait loci throughout the genome.

The practical implementation of genomic selection became feasible following several technological advances. High-density SNP genotyping arrays, such as the bovine 50K SNP chip introduced in 2008, enabled rapid and cost-effective genome-wide genotyping of thousands of animals [10]. Simultaneously, improvements in computational algorithms and mixed-model methodologies facilitated efficient estimation of genomic breeding values in large breeding populations [5]. As a result, genomic selection was rapidly adopted in dairy cattle breeding programs across North America, Europe, Australia, and New Zealand, where it substantially reduced generation intervals while improving prediction accuracy and annual rates of genetic gain [3, 11].

Since its successful implementation in dairy cattle, genomic selection has expanded to beef cattle, sheep, goats, pigs, poultry, and aquaculture species. Continuous improvements in sequencing technologies, genotype imputation, whole-genome sequence data, and large international reference populations have further enhanced prediction accuracy and broadened the scope of genomic applications across livestock species [4, 6].

III. PRINCIPLES OF GENOMIC SELECTION

Genomic selection is founded on the principle that dense genome-wide molecular markers capture the majority of genetic variation influencing complex quantitative traits. Unlike traditional pedigree-based evaluations, genomic selection estimates realized genomic relationships among individuals using thousands of SNP markers, thereby providing a more accurate representation of shared genetic inheritance [1, 5].

A genomic selection program begins with the establishment of a reference (training) population, consisting of animals possessing both reliable phenotypic records and genome-wide SNP genotypes. Statistical models are developed using this population to estimate the effects of individual markers distributed throughout the genome. These estimated marker effects are subsequently applied to a validation or candidate population, where animals are genotyped but may not yet possess phenotypic records. The resulting Genomic Estimated Breeding Values (GEBVs) enable selection decisions at an early age, substantially shortening the generation interval and increasing the rate of genetic improvement [1, 4].

The accuracy of genomic prediction depends on several interrelated factors, including the size and quality of the reference population, marker density, the extent of linkage disequilibrium (LD) between markers and causal variants, trait heritability, and the statistical prediction model employed [5, 6]. Linkage disequilibrium refers to the non-random association of alleles at different loci, which allows markers to serve as proxies for nearby causal variants. Dense SNP coverage ensures that virtually every quantitative trait locus is in LD with one or more markers, allowing the cumulative effects of thousands of loci to be incorporated into genomic evaluations. Consequently, genomic selection is particularly effective for complex traits controlled by many genes of small additive effect, where conventional marker-assisted selection performs poorly.

Compared with pedigree-based BLUP, genomic selection captures Mendelian sampling variation among full siblings, allowing genetically superior individuals to be identified before phenotypic performance becomes available. This improvement has significantly increased selection intensity while reducing breeding costs associated with progeny testing. Modern genomic evaluation systems now combine pedigree, phenotypic, and genomic information within unified statistical frameworks, providing more reliable genetic evaluations across diverse livestock populations and production systems [3, 11].

IV. GENOMIC SELECTION METHODOLOGY

Genomic selection (GS) integrates genome-wide molecular information with quantitative genetic models to predict the genetic merit of animals. Unlike conventional pedigree-based evaluations, GS uses thousands of single nucleotide polymorphism (SNP) markers distributed across the genome to estimate Genomic Estimated Breeding Values (GEBVs). The methodology begins with the establishment of a reference (training) population, comprising animals with both reliable phenotypic records and dense SNP genotypes. Marker effects estimated from this population are subsequently used to predict GEBVs for validation or candidate populations, which generally possess genotype data but limited or no phenotypic information [1, 5].

A prerequisite for successful genomic prediction is the presence of linkage disequilibrium (LD) between SNP markers and the underlying quantitative trait loci (QTL). Dense marker panels ensure that most causal variants are associated with nearby markers, allowing statistical models to capture the cumulative effects of thousands of loci influencing complex quantitative traits [12]. Prediction accuracy is determined by several factors, including the size and genetic diversity of the reference population, marker density, trait heritability, genetic relationships between training and validation populations, and the statistical model employed [13].

Several statistical approaches have been developed for genomic prediction. Genomic Best Linear Unbiased Prediction (GBLUP) replaces the pedigree-based relationship matrix with a genomic relationship matrix (G) constructed from SNP genotypes, thereby estimating realized genomic relationships among individuals [11]. Because GBLUP assumes equal variance across marker effects, it is computationally efficient and has become the standard method in many livestock breeding programs. An important advancement is the single-step GBLUP (ssGBLUP) methodology, which combines pedigree, phenotypic, and genomic information into a unified evaluation system through the H matrix, enabling simultaneous evaluation of genotyped and non-genotyped animals without bias [14].

Bayesian genomic prediction methods—including BayesA, BayesB, BayesCπ, and Bayesian LASSO—allow heterogeneous marker variances and are particularly useful when a limited number of loci exert relatively large effects. These methods improve prediction accuracy for certain economically important traits but require greater computational resources than GBLUP [15, 16]. More recently, machine learning and deep learning algorithms have emerged as complementary tools capable of modeling nonlinear interactions, dominance effects, epistasis, and high-dimensional genomic datasets, particularly when integrated with whole-genome sequence information and other omics data [17].

TABLE 1
COMPARISON OF GENOMIC PREDICTION METHODS

Method	Key Feature	Advantages	Limitations
GBLUP	Equal variance across markers	Computationally efficient	Assumes equal marker effects
ssGBLUP	Combines pedigree + genomic info	Unified evaluation of genotyped and non-genotyped animals	Requires accurate pedigree
BayesA	Heterogeneous variances	Captures large effects	Computationally intensive
BayesB	Mixture model with some zero effects	Better for traits with few QTL	Complex implementation
BayesCπ	Variable selection approach	Flexible model	Requires tuning
Bayesian LASSO	Shrinkage estimation	Handles many markers	Computationally demanding
Machine Learning	Nonlinear interactions	Models epistasis and dominance	Requires large datasets

Advances in genotype imputation, whole-genome sequencing, transcriptomics, metabolomics, and functional genomics are further enhancing the biological interpretation and predictive performance of genomic evaluations. These developments are expected to improve the identification of causal variants while supporting more precise selection strategies for complex traits associated with productivity, health, fertility, resilience, and environmental sustainability [8].

V. APPLICATIONS OF GENOMIC SELECTION

5.1 Dairy Cattle

Dairy cattle breeding represents the most successful application of genomic selection. The introduction of genomic evaluations around 2008 revolutionized sire selection by allowing accurate prediction of breeding values shortly after birth, thereby replacing lengthy and expensive progeny-testing programs [11]. The reduction in generation interval from approximately five years to less than two years has nearly doubled the annual rate of genetic gain for economically important traits, including milk yield, milk composition, fertility, longevity, feed efficiency, and disease resistance [8]. Contemporary dairy breeding programs increasingly employ single-step GBLUP, large multinational reference populations, and whole-genome sequence data to improve prediction accuracy further while supporting selection for methane reduction, heat tolerance, and improved animal welfare.

5.2 Beef Cattle

The adoption of genomic selection in beef cattle has accelerated genetic improvement for growth rate, carcass quality, feed efficiency, fertility, calving ease, and disease resistance. Beef breeding often involves multiple breeds with smaller reference populations than dairy cattle, creating additional challenges for prediction accuracy. Nevertheless, genomic information substantially improves selection decisions, particularly for young bulls and replacement females lacking progeny records. International collaborations and breed-specific genomic reference populations continue to enhance genomic prediction across commercial beef production systems [18].

5.3 Sheep and Goats

Genomic selection has become increasingly valuable in sheep and goat breeding, particularly for traits that are difficult, expensive, or impossible to measure directly on selection candidates. These include resistance to gastrointestinal parasites, milk production, reproductive efficiency, wool quality, growth performance, and adaptation to harsh production environments. Although relatively small population sizes and limited phenotypic recording have slowed implementation compared with dairy cattle, declining genotyping costs and international reference populations are expanding genomic breeding programs in small ruminants. Genomic evaluations are also facilitating conservation and genetic improvement of indigenous breeds possessing valuable adaptive characteristics [8].

5.4 Swine

Commercial swine breeding has rapidly incorporated genomic selection into nucleus breeding programs. Genomic evaluations improve prediction accuracy for growth performance, feed conversion efficiency, carcass composition, reproductive performance, robustness, and disease resistance while reducing generation intervals. Because pigs produce large family sizes and have relatively short reproductive cycles, genomic selection enables rapid dissemination of superior genetics throughout commercial production systems. Integration of genomic prediction with reproductive technologies further accelerates cumulative genetic gain [15].

5.5 Poultry

The poultry industry has widely adopted genomic selection to improve egg production, egg quality, growth rate, feed efficiency, carcass yield, skeletal health, immune competence, and resistance to infectious diseases. Poultry breeding programs generate extensive pedigree and phenotypic datasets, making them highly suitable for genomic prediction. Genomic information also enables selection for sex-limited traits and traits expressed late in life, which are difficult to evaluate using conventional breeding approaches. Emerging applications integrating genomic selection with precision livestock farming, sensor technologies, artificial intelligence, and genome editing are expected to further enhance sustainable poultry production under changing environmental conditions [19].

5.6 Aquaculture

Genomic selection is increasingly being applied in aquaculture species, including Atlantic salmon, rainbow trout, tilapia, and shrimp. In Atlantic salmon, genomic selection has been used to improve growth rate, disease resistance (particularly against infectious pancreatic necrosis and sea lice), and flesh quality traits. In rainbow trout, genomic prediction has been applied to enhance resistance to bacterial cold-water disease and improve fillet yield. In tilapia, genomic selection is being explored for growth performance and salinity tolerance. Shrimp breeding programs are increasingly incorporating genomic information to select for resistance to white spot syndrome virus and other pathogens. Although reference populations in aquaculture are generally smaller than in terrestrial livestock, declining genotyping costs and the development of species-specific SNP arrays are accelerating the adoption of genomic selection in this sector [8, 20].

TABLE 2
APPLICATIONS OF GENOMIC SELECTION ACROSS LIVESTOCK SPECIES

Species	Key Traits Improved	Reference Population Size	Adoption Status
Dairy Cattle	Milk yield, composition, fertility, longevity, feed efficiency	Large (10,000+)	Widely adopted
Beef Cattle	Growth rate, carcass quality, feed efficiency, fertility	Moderate to large	Increasing adoption
Sheep and Goats	Parasite resistance, milk production, wool quality, growth	Small to moderate	Emerging
Swine	Growth, feed conversion, carcass composition, reproduction	Large	Widely adopted
Poultry	Egg production, growth, feed efficiency, carcass yield	Large	Widely adopted
Aquaculture	Growth, disease resistance, flesh quality	Small to moderate	Emerging

VI. ADVANTAGES OF GENOMIC SELECTION

Genomic selection (GS) has fundamentally transformed livestock improvement by enabling the estimation of genetic merit directly from genome-wide marker information. Compared with conventional pedigree-based Best Linear Unbiased Prediction (BLUP), GS substantially increases the accuracy of breeding value estimation, particularly for young animals lacking phenotypic records or progeny information [3]. The ability to identify genetically superior individuals shortly after birth considerably shortens the generation interval, thereby accelerating annual rates of genetic gain.

One of the greatest advantages of GS is its effectiveness for complex quantitative traits controlled by numerous genes of small effect. Unlike marker-assisted selection (MAS), which targets only a limited number of major quantitative trait loci (QTL), GS simultaneously utilizes information from thousands of single nucleotide polymorphisms (SNPs) distributed throughout the genome. Consequently, genomic prediction captures a much larger proportion of additive genetic variance, resulting in more reliable Genomic Estimated Breeding Values (GEBVs) for economically important traits [9].

Genomic selection has also broadened breeding objectives beyond productivity alone. Modern breeding programs increasingly incorporate fertility, longevity, feed efficiency, disease resistance, heat tolerance, methane emission, resilience, and animal welfare into genomic evaluations. These traits are often difficult or expensive to measure using conventional breeding methods but become more amenable to improvement through genomic prediction. Furthermore, the adoption of single-step GBLUP, genotype imputation, and international reference populations has enhanced prediction accuracy while reducing implementation costs, allowing genomic selection to be extended to multiple livestock species [14].

Economic benefits include reduced expenditure on progeny testing, faster dissemination of superior genetics, and greater efficiency of breeding programs. In dairy cattle, genomic selection has nearly doubled the annual rate of genetic improvement while reducing generation intervals from approximately five years to less than two years. Similar benefits are increasingly being realized in beef cattle, sheep, goats, pigs, poultry, and aquaculture species [8].

VII. CHALLENGES AND LIMITATIONS

Despite its considerable advantages, genomic selection faces several biological, computational, and economic challenges. The accuracy of genomic prediction depends heavily on the size, quality, and genetic diversity of the reference population. Small or poorly characterized reference populations often produce lower prediction accuracy, particularly for low-heritability traits or across genetically distant breeds [4].

Prediction accuracy also declines when genomic evaluations are applied across populations with different linkage disequilibrium structures or allele frequencies. Consequently, many breeding programs require breed-specific reference populations, increasing both logistical complexity and cost. In developing countries, limited infrastructure, insufficient phenotypic recording systems, and the high cost of large-scale genotyping remain major barriers to widespread implementation [7].

Another important limitation involves the use of dense SNP panels, which primarily capture linkage disequilibrium with causal variants rather than the causal mutations themselves. Recombination over successive generations gradually weakens marker–QTL associations, requiring periodic updating of reference populations and re-estimation of marker effects. In addition, conventional genomic prediction models predominantly estimate additive genetic effects, whereas dominance, epistasis, genotype-by-environment interactions, and epigenetic influences remain incompletely characterized [11].

The growing availability of whole-genome sequence data presents both opportunities and challenges. Although sequence information may improve identification of causal variants, it substantially increases computational demands, data storage requirements, and statistical complexity. Efficient integration of high-dimensional genomic datasets with transcriptomic, proteomic, metabolomic, and phenomic information remains an active area of research [19].

Ethical and societal considerations also merit attention. The increasing use of genomic information in breeding decisions raises questions about data privacy, intellectual property, and the potential for reduced genetic diversity in breeding populations. Balancing the benefits of genomic selection with ethical considerations will be important for sustainable implementation [20].

VIII. FUTURE PERSPECTIVES

Future developments in genomic selection will increasingly integrate whole-genome sequencing, functional genomics, and multi-omics technologies to improve the biological interpretation of genomic predictions and enhance the identification of causal variants. Rather than relying solely on linkage disequilibrium between markers and quantitative trait loci, future genomic evaluations are expected to incorporate transcriptomic, epigenomic, metabolomic, and proteomic information into unified predictive models [17].

Artificial intelligence (AI), machine learning, and deep learning algorithms are emerging as powerful tools for analyzing complex genomic datasets and modeling nonlinear genetic interactions that are not adequately captured by traditional statistical approaches. Simultaneously, precision livestock farming technologies—including automated sensors, wearable devices, computer vision, and real-time health monitoring systems—will generate high-quality phenotypic data that can be integrated with genomic information to improve prediction accuracy and accelerate genetic progress.

Another promising direction involves combining genomic selection with CRISPR/Cas-mediated genome editing, enabling the identification and precise modification of favorable alleles associated with disease resistance, feed efficiency, climate resilience, and product quality. Although ethical, regulatory, and societal considerations remain important, the integration of genome editing with genomic selection has the potential to accelerate sustainable livestock improvement [20].

Global breeding objectives are also shifting toward sustainability. Future breeding programs will increasingly emphasize reduced greenhouse gas emissions, improved nitrogen utilization, enhanced resilience to climate change, improved animal welfare, antimicrobial resistance, and adaptation to emerging diseases. International collaboration, open genomic databases, and expanding multinational reference populations are expected to improve prediction accuracy across breeds and production environments while making genomic technologies more accessible worldwide [6].

IX. CONCLUSION

Genomic selection represents one of the most significant innovations in modern animal breeding, fundamentally transforming genetic evaluation through the use of genome-wide molecular information. By combining dense SNP genotyping with advanced statistical prediction models, genomic selection has substantially improved the accuracy of breeding value estimation, accelerated genetic gain, and reduced generation intervals across livestock species. Its successful implementation in dairy cattle has stimulated rapid adoption in beef cattle, sheep, goats, swine, poultry, and aquaculture, where continued improvements in genotyping technologies and computational methodologies are expanding its practical applications.

Recent advances such as single-step GBLUP, Bayesian genomic prediction, whole-genome sequencing, multi-omics integration, artificial intelligence, and precision livestock farming are further enhancing the efficiency and scope of genomic selection. Nevertheless, challenges related to reference population size, computational demands, across-breed prediction, and implementation costs remain important considerations. Continued international collaboration, improved phenotypic recording, and integration of functional genomics with genome editing technologies are expected to further strengthen genomic breeding programs. Consequently, genomic selection will remain a central component of sustainable livestock improvement, supporting increased productivity, improved animal health and welfare, enhanced environmental resilience, and long-term global food security.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Meuwissen, T. H. E., Hayes, B. J., & Goddard, M. E. (2001). Prediction of total genetic value using genome-wide dense marker maps. *Genetics*, *157*(4), 1819-1829. https://doi.org/10.1093/genetics/157.4.1819

[2] Schaeffer, L. R. (2006). Strategy for applying genome-wide selection in dairy cattle. *Journal of Animal Breeding and Genetics*, *123*(4), 218-223. https://doi.org/10.1111/j.1439-0388.2006.00595.x

[3] Meuwissen, T., Hayes, B., & Goddard, M. (2016). Genomic selection: A paradigm shift in animal breeding. *Animal Frontiers*, *6*(1), 6-14. https://doi.org/10.2527/af.2016-0002

[4] Eggen, A. (2012). The development and application of genomic selection as a new breeding paradigm. *Animal Frontiers*, *2*(1), 10-15. https://doi.org/10.2527/af.2011-0027

[5] VanRaden, P. M. (2008). Efficient methods to compute genomic predictions. *Journal of Dairy Science*, *91*(11), 4414-4423. https://doi.org/10.3168/jds.2007-0980

[6] Silva, M. V. B., et al. (2014). The development of genomics applied to dairy breeding. *Livestock Science*, *166*, 66-75. https://doi.org/10.1016/j.livsci.2014.05.017

[7] Ibtisham, F., Zhang, L., Xiao, M., An, L., Ramzan, M. B., Nawab, A., Zhao, Y., Li, G., & Xu, Y. (2017). Genomic selection and its application in animal breeding. *The Thai Journal of Veterinary Medicine*, *47*(3), Article 1. https://doi.org/10.56808/2985-1130.2838

[8] Weller, J. I., Ezra, E., & Ron, M. (2017). Invited review: A perspective on the future of genomic selection in dairy cattle. *Journal of Dairy Science*, *100*(10), 8633-8644. https://doi.org/10.3168/jds.2017-12879

[9] Hill, W. G. (2014). Applications of population genetics to animal breeding, from Wright, Fisher and Lush to genomic prediction. *Genetics*, *196*(1), 1-16. https://doi.org/10.1534/genetics.112.147850

[10] Van Tassell, C. P., et al. (2008). SNP discovery and allele frequency estimation by deep sequencing of reduced representation libraries. *Nature Methods*, *5*(3), 247-252. https://doi.org/10.1038/nmeth.1185

[11] Legarra, A., Aguilar, I., & Misztal, I. (2009). A relationship matrix including full pedigree and genomic information. *Journal of Dairy Science*, *92*(9), 4656-4663. https://doi.org/10.3168/jds.2009-2061

[12] Habier, D., Fernando, R. L., & Dekkers, J. C. M. (2007). The impact of genetic relationship information on genome-assisted breeding values. *Genetics*, *177*(4), 2389-2397. https://doi.org/10.1534/genetics.107.081190

[13] Daetwyler, H. D., Villanueva, B., & Woolliams, J. A. (2008). Accuracy of predicting the genetic risk of disease using a genome-wide approach. *PLoS ONE*, *3*(10), e3395. https://doi.org/10.1371/journal.pone.0003395

[14] Christensen, O. F., & Lund, M. S. (2010). Genomic prediction when some animals are not genotyped. *Genetics Selection Evolution*, *42*(1), Article 2. https://doi.org/10.1186/1297-9686-42-2

[15] Garrick, D. J., Taylor, J. F., & Fernando, R. L. (2009). Deregressing estimated breeding values and weighting information for genomic regression analyses. *Genetics Selection Evolution*, *41*, Article 55. https://doi.org/10.1186/1297-9686-41-55

[16] Habier, D., Fernando, R. L., Kizilkaya, K., & Garrick, D. J. (2011). Extension of the Bayesian alphabet for genomic selection. *BMC Bioinformatics*, *12*, Article 186. https://doi.org/10.1186/1471-2105-12-186

[17] Zhang, B., & Fan, T. (2022). Knowledge structure and emerging trends in the application of deep learning in genetics research: A bibliometric analysis (2000–2021). *Frontiers in Genetics*, *13*, Article 951939. https://doi.org/10.3389/fgene.2022.951939

[18] Magalhães, A. F. B., Schenkel, F. S., Garcia, D. A., Gordo, D. G. M., Tonussi, R. L., Espigolan, R., Silva, R. M. O., Braz, C. U., Fernandes Júnior, G. A., Baldi, F., Carvalheiro, R., Boligon, A. A., de Oliveira, H. N., Chardulo, L. A. L., & de Albuquerque, L. G. (2019). Genomic selection for meat quality traits in Nelore cattle. *Meat Science*, *148*, 32-37.
https://doi.org/10.1016/j.meatsci.2018.09.010

[19] Wallen, S. E., Lillehammer, M., & Meuwissen, T. H. E. (2017). Strategies for implementing genomic selection for feed efficiency in dairy cattle breeding schemes. *Journal of Dairy Science*, *100*(8), 6327-6336. https://doi.org/10.3168/jds.2016-11458

[20] Çelik, Ş. (2024). Genomic selection in animal breeding: A bibliometric review. *Frontiers in Genetics*, *15*, Article 1402140.
https://doi.org/10.3389/fgene.2024.1402140.

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Circular Rural Economy and Economic Leakage Reduction: Insights from a Community-Based Resilience Framework from Rural India

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Abstract— *Rural communities across the Global South are increasingly exposed to a convergence of climate variability, geopolitical instability, supply-chain disruptions, and economic volatility. While conventional rural development approaches have primarily focused on agricultural productivity, market integration, and income enhancement, these strategies often overlook structural vulnerabilities associated with economic leakage, external dependency, and limited adaptive capacity. This paper proposes the Circular Rural Economy (CRE) framework as an integrated approach to strengthening rural resilience through local value retention, economic diversification, and collective enterprise development.*

Drawing upon resilience theory, circular economy principles, sustainable livelihoods, and local economic development literature, the study introduces the GLIDE (Group Livelihoods for Development) Framework as an operational model for translating Circular Rural Economy principles into practice. Using evidence from GLIDE pilot interventions across multiple Indian states, the paper demonstrates how economic leakage analysis can identify opportunities for local production, wealth retention, and community-led enterprise development. Findings suggest that significant proportions of village expenditures are directed toward externally sourced goods and services that can potentially be produced using local resources, skills, and institutions.

The paper further develops the concept of Economic Leakage Resilience Theory (ELRT), which posits that resilience increases as communities retain a greater share of locally generated wealth and reduce dependence on external supply chains. To support measurement and policy application, a Rural Resilience Index (RRI) is proposed, integrating economic, social, ecological, institutional, and adaptive dimensions of resilience while explicitly incorporating economic leakage as a key indicator.

The study argues that Circular Rural Economy should be viewed not only as a livelihood promotion strategy but also as a climate adaptation, economic localization, and geopolitical resilience framework. By strengthening local production systems, collective enterprises, and community institutions, the GLIDE framework offers a scalable pathway toward resilient, self-reliant, and sustainable rural development. The findings contribute to emerging debates on rural resilience, localization, and adaptive development, while providing practical policy insights aligned with India's Atmanirbhar Bharat agenda and the Sustainable Development Goals.

Keywords— Circular Rural Economy; Rural Resilience; Economic Leakage; Climate Adaptation; Community Enterprises; Local Economic Development; GLIDE Framework; Atmanirbhar Bharat; Sustainable Livelihoods; Rural Transformation.

I. INTRODUCTION

The twenty-first century has fundamentally altered the nature of rural vulnerability. Historically, rural development policies concentrated on increasing agricultural production, expanding infrastructure, facilitating credit access, and integrating villages into broader market systems. These interventions were largely designed under assumptions of climatic stability, predictable market conditions, and uninterrupted economic globalization.

Today, those assumptions no longer hold.

Rural communities increasingly confront a convergence of environmental, economic, and geopolitical risks. Climate change has intensified droughts, floods, heatwaves, and rainfall variability. Simultaneously, geopolitical conflicts, global supply-chain disruptions, and commodity market volatility have increased the costs of agricultural production and household consumption. The COVID-19 pandemic, the Russia–Ukraine conflict, disruptions in maritime trade routes, and global inflationary pressures have demonstrated how events occurring thousands of kilometers away can profoundly affect village economies.

India's rural economy remains particularly vulnerable to such disruptions. Nearly half of India's cultivated land remains rain-fed, while a substantial proportion of the rural population continues to depend directly or indirectly on agriculture. Variability in monsoon performance therefore translates directly into fluctuations in rural incomes, food security, employment opportunities, and migration patterns.

The recent downward revision of monsoon forecasts by the India Meteorological Department further underscores the urgency of developing resilient rural economic systems capable of withstanding climatic uncertainty. However, climate variability alone does not explain contemporary rural vulnerability. Equally significant is the persistent outflow of financial resources from villages through the purchase of externally manufactured goods and services.

This phenomenon, commonly referred to as economic leakage, has received limited attention within mainstream rural development discourse despite its significant implications for local prosperity. Every year, substantial amounts of village income are transferred outside rural communities through expenditures on fertilizers, packaged foods, detergents, livestock feed, consumer goods, and other products that could potentially be produced locally.

This paper argues that reducing economic leakage constitutes an underexplored but critical pathway toward strengthening rural resilience.

Recent climate extremes, including the growing risk of Super El Niño events, demonstrate that rural resilience requires more than short-term relief measures. While crop insurance, weather advisories, and contingency plans provide temporary protection, Circular Rural Economy offers a long-term livelihood safety net by reducing dependence on external inputs and strengthening local economic circulation.

The Circular Rural Economy framework presented in this paper seeks to address this challenge by promoting localized production systems, community-owned enterprises, wealth retention mechanisms, and collective economic action. The framework is operationalized through the GLIDE (Group Livelihoods for Development) methodology, which has been piloted across several Indian states. The paper contributes to three bodies of literature:

1) Circular economy and local economic development
2) Climate adaptation and resilience studies
3) Rural livelihoods and community-based development

Most importantly, it proposes a novel perspective that conceptualizes economic leakage reduction as a climate adaptation and resilience strategy.

II. CIRCULAR ECONOMY AND RURAL DEVELOPMENT

The circular economy emerged as a response to the limitations of linear economic systems characterized by extraction, production, consumption, and disposal. While early circular economy scholarship focused primarily on industrial systems, contemporary research increasingly recognizes the relevance of circular principles to rural economies.

Circular systems seek to maximize resource productivity, minimize waste, regenerate ecological assets, and retain value within economic systems. In rural contexts, this includes local food processing, biomass utilization, composting, decentralized manufacturing, renewable energy production, and community enterprises. The application of circular economy principles in rural settings offers opportunities to strengthen local value chains, enhance resource efficiency, and reduce dependence on imported inputs.

However, much of the existing literature focuses on environmental outcomes rather than economic resilience. Consequently, there remains a need for frameworks that explicitly connect circular economic processes to rural adaptation and community resilience.

III. CONCEPTUAL FRAMEWORK: CIRCULAR RURAL ECONOMY

The Circular Rural Economy framework proposed in this paper is founded on a simple proposition: **Rural resilience increases when communities retain a greater proportion of locally generated wealth and reduce dependence on externally supplied goods and services.**

This represents a transition from a linear development model—where villages produce for external markets and spend incomes on externally manufactured goods—to a circular model where local resources, enterprises, and consumption continuously regenerate economic value within the community.

The framework consists of five interconnected components:

1) **Resource Mapping:** Identification of local resources, skills, institutions, ecological assets, and production capacities.
2) **Economic Leakage Analysis:** Assessment of financial outflows associated with externally sourced goods and services.
3) **Enterprise Opportunity Identification:** Identification of products and services that can be produced locally using available resources.
4) **Collective Enterprise Development:** Formation of producer groups, women's enterprises, youth enterprises, and community-owned business structures.
5) **Wealth Retention and Reinvestment:** Retention of financial resources within the local economy through repeated circulation and reinvestment.

FIGURE 1: Circular Rural Economy Framework

IV. CLIMATE CHANGE, MONSOON VARIABILITY, AND RURAL RISK

4.1 Climate Change and the Emerging Rural Development Challenge

Climate change has emerged as one of the most significant threats to rural livelihoods in the twenty-first century. While its impacts are global, rural communities in developing countries face disproportionate risks due to their dependence on natural resources, climate-sensitive livelihoods, and limited adaptive capacity. In India, where nearly half of cultivated land remains rain-fed and a large proportion of the workforce depends directly or indirectly on agriculture, climate variability has profound implications for economic stability, food security, and social well-being.

Historically, agricultural planning and rural development strategies were designed around relatively predictable monsoon patterns. However, increasing scientific evidence indicates that climate change is altering both the intensity and distribution of rainfall, increasing the frequency of droughts, floods, heatwaves, and extreme weather events. These changes challenge conventional assumptions regarding agricultural productivity and expose the vulnerability of communities whose livelihoods remain heavily dependent on seasonal climatic conditions.

Recent assessments by the Intergovernmental Panel on Climate Change (IPCC) suggest that South Asia will experience increasing rainfall variability, rising temperatures, more frequent heat stress events, and intensified hydrological extremes over the coming decades. These trends are expected to disproportionately affect smallholder farmers, tribal communities, and economically marginalized rural populations.

The challenge facing rural India is therefore not merely one of adapting agricultural practices but of strengthening the overall resilience of rural economic systems.

4.2 Monsoon Variability and Rural Vulnerability

The Indian monsoon remains the most critical determinant of rural economic performance. It influences crop yields, groundwater recharge, livestock productivity, labor demand, and household incomes. Even sectors not directly engaged in agriculture often depend upon monsoon-induced economic activity. Traditionally, monsoon performance was evaluated through seasonal rainfall totals. However, emerging climate research demonstrates that aggregate rainfall figures often mask significant variations in timing, intensity, and distribution.

Three forms of climate risk are particularly relevant:

- **Variability in monsoon onset and withdrawal:** Delayed or early monsoon onset disrupts planting schedules, affecting crop establishment and yields.
- **Intra-seasonal dry spells:** Extended dry periods during critical crop growth stages can significantly reduce yields even when total seasonal rainfall is normal.
- **Extreme rainfall events:** Heavy downpours cause flooding, soil erosion, and crop damage, while also reducing the effectiveness of rainfall for groundwater recharge.

These changes complicate agricultural planning and increase uncertainty for rural households. The downward revision of monsoon forecasts by meteorological agencies in recent years has heightened concerns regarding future agricultural stability. While climate forecasts cannot predict localized impacts with certainty, they reinforce the need for development strategies that reduce dependence on a single seasonal livelihood source.

4.3 Climate Change Beyond Agriculture

Climate impacts extend far beyond crop production. The consequences of climate variability cascade through entire rural economies. Crop failure reduces household income, which subsequently affects consumption, education expenditures, healthcare access, and local market demand. Reduced agricultural activity decreases wage employment opportunities for landless labourers and seasonal workers. Livestock productivity may decline due to fodder shortages, water scarcity, and heat stress. These interconnected impacts create what may be described as a rural vulnerability cascade.

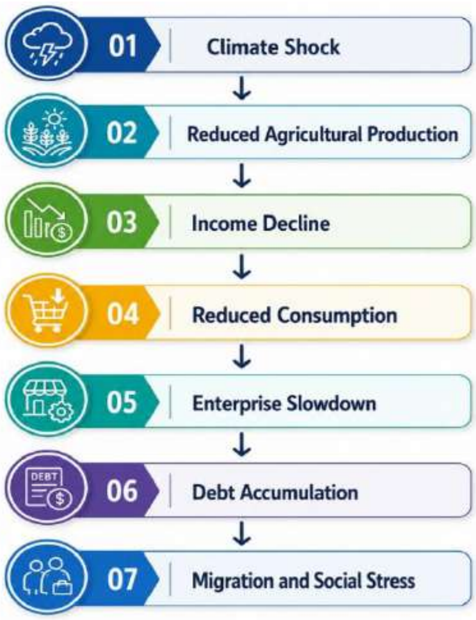


FIGURE 2: Climate Vulnerability Cascade

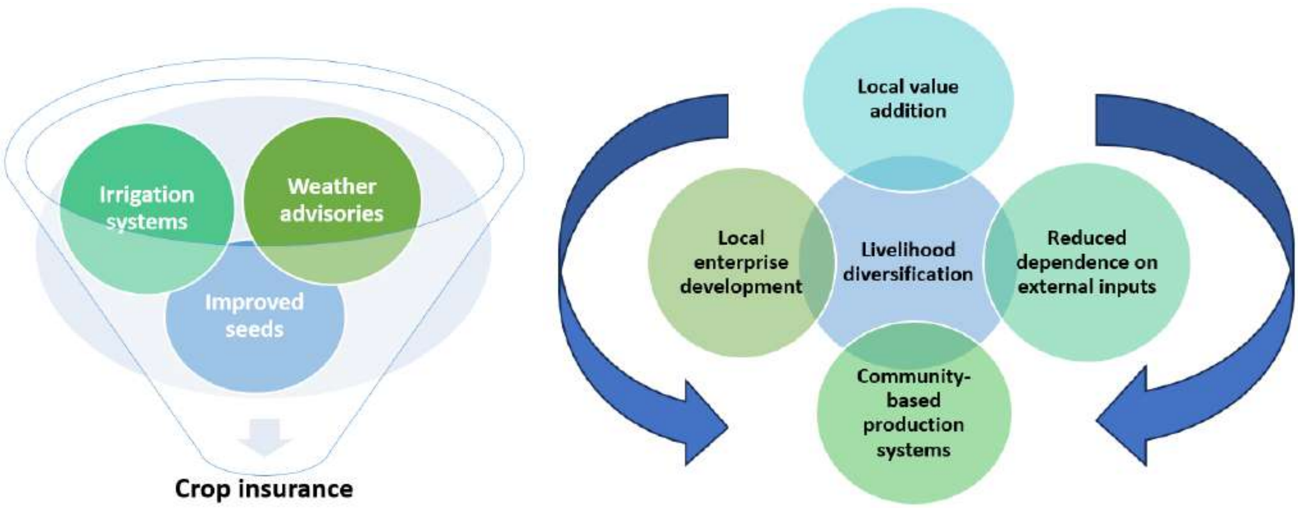
This cascade demonstrates why climate adaptation cannot be restricted to agriculture alone. Resilient rural economies require diversified livelihood systems capable of absorbing shocks without triggering systemic economic decline.

4.4 Climate Adaptation Through Economic Diversification

Conventional climate adaptation strategies often focus on:

- Improved crop varieties and agricultural practices
- Water harvesting and irrigation infrastructure
- Weather-based crop insurance
- Early warning systems and climate advisories

While these interventions are important, they do not address the fundamental vulnerability created by dependence on a single livelihood source. Diversified economic systems are generally more resilient because losses in one sector can be compensated by activities in others. For example, local food processing, livestock-based enterprises, non-timber forest product value addition, soap production, composting, and decentralized manufacturing can continue generating income even during periods of agricultural stress.



From this perspective, community enterprises function not merely as income-generating activities but as adaptive mechanisms that enhance resilience.

4.5 Climate Resilience as a Community Property

Climate resilience is frequently conceptualized at the household level. However, resilience is also a collective characteristic of communities and institutions. A village possessing strong producer groups, active women's organizations, local enterprises, and robust social networks is often better able to recover from shocks than a collection of isolated households. Community institutions facilitate resource sharing, collective action, knowledge exchange, and mutual support during crises. The Circular Rural Economy framework therefore emphasizes collective entrepreneurship and local economic ecosystems rather than individual enterprise promotion alone.

In this context, resilience emerges not solely from technological adaptation but from strengthened social, economic, and institutional relationships.

V. GEOPOLITICAL RISK AND RURAL VULNERABILITY

5.1 The Globalization of Rural Risk

The contemporary rural economy is increasingly influenced by global events. Although villages may appear geographically distant from international conflicts and geopolitical tensions, their economic systems are deeply interconnected with global markets.

Over the past three decades, globalization has expanded access to goods, technologies, and markets. However, it has also increased dependence on external production systems and international supply chains.

The COVID-19 pandemic revealed the fragility of these systems. Restrictions on transportation, labor movement, and manufacturing disrupted supply chains across the world. Rural communities experienced shortages of agricultural inputs, increased transportation costs, and reduced market access.

Similarly, geopolitical conflicts have exposed vulnerabilities associated with dependence on imported fertilizers, fuel, and industrial inputs. The result is a new form of rural risk in which local livelihoods are influenced by events occurring far beyond local control.

5.2 Fertilizer, Fuel, and Agricultural Dependency

Modern agriculture depends heavily on industrial inputs. Among the most significant are:

- Chemical fertilizers
- Diesel fuel
- Agrochemicals
- Agricultural machinery
- Processed livestock feed

Many of these inputs are linked directly or indirectly to global commodity markets. When international conflicts disrupt production or transportation systems, rural producers experience higher costs regardless of local conditions. For smallholder farmers, rising input prices reduce profitability and increase indebtedness. In many cases, farmers are unable to transfer increased costs to consumers because commodity prices remain volatile and market power is concentrated among intermediaries.

Consequently, geopolitical instability translates into economic vulnerability at the village level.

5.3 Economic Leakage and Structural Vulnerability

While climate change and geopolitical instability are often discussed separately, they interact through a common mechanism: economic dependency. Most rural communities import a substantial proportion of the goods they consume, including:

- Food products (processed foods, edible oils, packaged snacks)

- Agricultural inputs (fertilizers, pesticides, seeds, feed)
- Household consumables (detergents, soaps, toiletries, kitchenware)
- Building materials (cement, tiles, paint, fittings)
- Clothing and textiles

Every purchase transfers financial resources outside the village economy. This continuous outflow of wealth weakens local economic resilience and reduces the community's capacity to absorb external shocks.

FIGURE 3: Economic Leakage Pathway

From a resilience perspective, economic leakage represents a hidden but significant driver of rural vulnerability.

5.4 Geopolitical Resilience Through Localization

The Circular Rural Economy framework proposes localization as a strategy for reducing exposure to external shocks. Localization does not imply economic isolation. Rather, it refers to increasing the proportion of essential goods and services produced within the local economy while maintaining selective engagement with broader markets. Examples include:

- Community compost enterprises reducing fertilizer dependency
- Local feed production reducing livestock input costs
- Village-based food processing reducing reliance on external suppliers
- Women's enterprises producing household consumables for local markets

Such activities strengthen local economic circulation and reduce vulnerability to supply-chain disruptions. Importantly, localization also creates employment opportunities, increases community ownership, and enhances adaptive capacity.

5.5 Economic Swaraj in the Twenty-First Century

The concept of Economic Swaraj, rooted in Gandhian thought, emphasized local self-reliance and decentralized production systems. Historically, this concept was often interpreted as a philosophical or ethical ideal.

However, climate change, supply-chain disruptions, and geopolitical instability have renewed its practical relevance. Economic Swaraj should not be understood as isolation from national or global markets. Rather, it represents the capacity of communities to meet a significant proportion of their essential needs through local production while engaging external markets from a position of strength rather than dependency.

In the context of contemporary rural development, Economic Swaraj can be viewed as a resilience strategy that simultaneously addresses climate adaptation, economic vulnerability, and community empowerment. The GLIDE framework operationalizes this principle by transforming villages from passive consumers within external economic systems into active participants in localized value creation and wealth retention.

In this context, Economic Swaraj becomes not merely a philosophical aspiration but a practical resilience strategy. Local production of essential goods acts as an economic shock absorber, protecting communities from supply-chain disruptions, input price volatility, and global market uncertainties.

VI. THE GLIDE FRAMEWORK AS AN OPERATIONAL MODEL FOR CIRCULAR RURAL ECONOMY

The Group Livelihoods for Development (GLIDE) Framework operationalizes the Circular Rural Economy approach by helping communities identify local economic opportunities through economic leakage analysis, resource mapping, and collective enterprise development. Unlike conventional livelihood programmes that focus primarily on production enhancement or market linkage, GLIDE begins by examining household expenditure patterns to identify goods and services that are routinely imported into the village economy.

The framework consists of five interrelated stages:

1) **Resource Mapping:** Identifying local resources, skills, institutions, and production capacities
2) **Economic Leakage Analysis:** Assessing financial outflows through household expenditure surveys
3) **Enterprise Opportunity Identification:** Identifying locally producible goods and services
4) **Collective Enterprise Development:** Forming producer groups and community-owned enterprises
5) **Wealth Retention and Reinvestment:** Strengthening local economic circulation

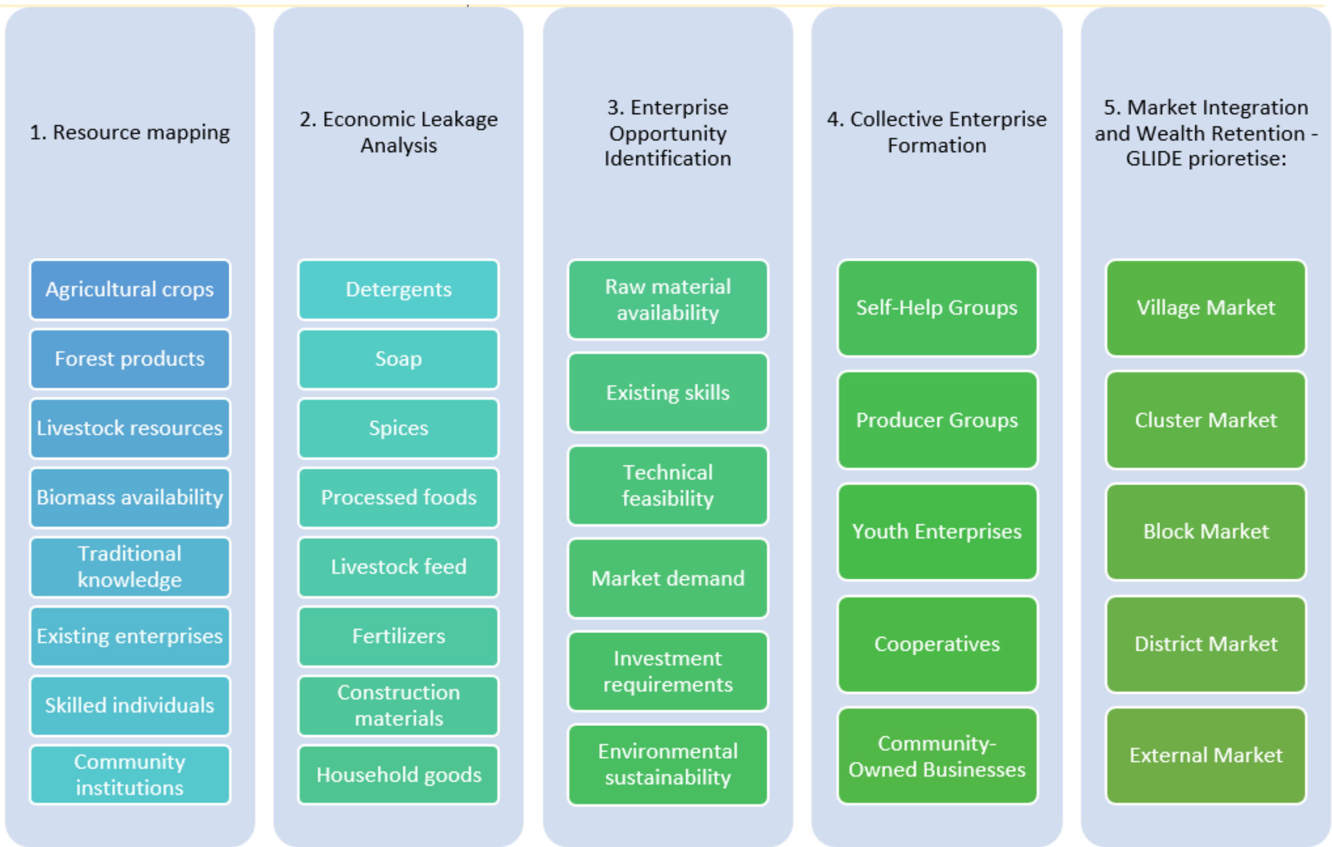


FIGURE 4: GLIDE Framework Stages

Through participatory exercises, communities identify products currently purchased from external markets and assess their feasibility for local production using available resources, skills, and institutions. A distinguishing feature of GLIDE is its emphasis on group-based enterprises involving women's self-help groups, youth collectives, producer groups, and community organizations. These collective structures reduce risk, improve resource mobilization, and strengthen social capital.

Beyond enterprise creation, GLIDE functions as a grassroots business incubator where rural youth and women gain practical skills in financial literacy, cost analysis, pricing, and market assessment, enabling them to convert local resources into viable enterprises. The framework also transforms the role of NGOs and civil society organisations from resource providers to ecosystem facilitators and enterprise mentors, ensuring greater community ownership and long-term sustainability.

From a resilience perspective, GLIDE extends beyond livelihood promotion. By encouraging local production of essential goods such as food products, agricultural inputs, household consumables, and livestock feed, the framework reduces dependence on external supply chains and enhances local adaptive capacity. In this sense, community enterprises function as decentralized resilience assets capable of mitigating climate, market, and geopolitical shocks.

Implementation Lessons from GLIDE Adoption: Field experiences indicate three pathways of adoption: hybrid integration with conventional livelihood programmes, funder-driven implementation constrained by external targets, and full adoption of the circular model. The strongest outcomes emerged where GLIDE was implemented as a standalone community-led ecosystem, highlighting the importance of institutional alignment and local ownership.

VII. MULTI-STATE EVIDENCE FROM GLIDE PILOTS

The GLIDE framework has been implemented across several Indian states, including Maharashtra, Madhya Pradesh, Odisha, Gujarat, Andhra Pradesh, Tamil Nadu, Chhattisgarh, and Uttar Pradesh. Although long-term impact evaluations are still evolving, pilot experiences demonstrate the framework's potential to identify economic leakages, mobilize local resources, and stimulate community enterprise development.

The following cases illustrate the diversity and potential of the GLIDE approach.

TABLE 1
GLIDE PILOT IMPLEMENTATION DATA

Location	Households	Identified Market Leakage	Replacement Opportunity	Groups Formed
Adgaon Khurd, Maharashtra	400	₹18.24 crore annual expenditure; 80 locally producible products	₹4.22 crore	7
Ujjain, Madhya Pradesh	800	₹47.42 crore annual expenditure; 110 locally producible products	₹6.16 crore	—
Dryland village cluster	300	₹13.96 crore annual expenditure; 131 locally producible products	₹1.10 crore	—
Wardha, Maharashtra	70–300 HH cluster	₹3.12 crore annual expenditure; 70 locally producible products	₹2.20 crore	—

Several common findings emerged across pilot locations. First, economic leakage was found to be substantial regardless of geography or livelihood system. Second, local production potential was consistently underestimated by communities prior to the exercise. Third, women's groups emerged as critical drivers of enterprise development and local economic circulation. Finally, collective enterprises enhanced both economic viability and community participation.

Several communities also demonstrated the capacity to continue enterprise development with minimal external support, suggesting that GLIDE can evolve from a project intervention into a self-replicating model driven by local leadership.

These findings suggest that economic leakage analysis can serve as a powerful development planning tool. Rather than focusing solely on increasing production, the GLIDE framework emphasizes retaining wealth within local economies, thereby strengthening livelihood diversification, community self-reliance, and resilience to external shocks.

VIII. EXPERIENCE FROM CASE STUDIES

The principles underlying the Circular Rural Economy framework are not unique to India. Across the world, communities have experimented with localized economic systems, cooperative enterprises, and resilience-oriented development models that emphasize local production, collective ownership, and resource circulation.

8.1 Anchoring Resilience: How a Women Enterprise Group is Rewriting the Rules of Climate-Smart Agriculture

When the rains stop coming on time, it isn't just soil that cracks. It's the quiet dread in a mother's chest as she watches her child's dinner pot thin out. It's the way a farmer's hands tremble over a field that gave life to her grandmother, but might fail her now. Across villages like Amarpur, Super El Niño isn't a headline. It's the neighbor who sold her last goat. It's the season that took too much.

But in Amarpur, something different is taking root. Udyogini's guidance, a Women Enterprise Group of smallholder farmers decided they were done waiting for rescue. Done with the loneliness of farming alone, season after season, watching the sky and praying. They chose each other.

It starts with gathering, not just planning: Before a single mustard seed is sown, the women sit together on woven mats. Kids play nearby. Someone brings tea. And they map their future out loud—how many hectares, what yields they need to feed their families *and* their dreams. This isn't corporate strategy. It's survival made sacred. They agree to grow organic, MRL-safe mustard because they want their oil to be something they're proud to feed their own children. The cold-pressed oil unit isn't just a machine to them. It's proof they can own the whole chain, from soil to shelf. Every planned hectare whispers: *we won't be caught off guard again.*

They're healing the land with memory and courage: Monoculture broke hearts here before. One failed crop meant empty plates. So they brought back diversity—and dignity. The seeds they sow now are drought-resilient, chosen for Amarpur's stubborn soil. But the real revolution? Their community seed bank. It means no more begging seed dealers when the rains fail. No more debt traps. It's a clay pot full of next year's hope, kept in the hands of women who've been told for generations that they couldn't manage resources. Now they're preserving ancestral traits and their own autonomy, one seed at a time.

Ancestral hands, scientific tools: These women know compost. Their mothers knew compost. But now, vermibags turn that knowledge into precision. Kitchen scraps become black gold, and they watch their soil come alive again—a small, stubborn miracle. And when storms gather, the warnings don't come too late. A WhatsApp ping. A voice call in the local dialect. *"Cover the seedlings by evening."* That message can mean the difference between despair and a harvest. It means someone, somewhere, is watching the weather for *her*.

No one farms alone anymore: In the fields, you'll see it: a woman helping her neighbor tie up mustard stalks, even though her own plot needs work. They follow shared SOPs not because a manual said so, but because trust tastes better than chemicals. When harvest comes, the relief is collective. Some seed goes back to the bank—an offering to next season, a promise to each other. The rest becomes oil, sold with the quiet confidence of women who know exactly what went into it.

This is what resilience looks like. Not a report. Not a buzzword. It's the easing of shoulders when the weather app pings. It's the sound of their own oil unit humming. It's knowing that if the rains fail, they won't fail each other. Backed by Udyogini, these women aren't just adapting to climate shocks. They're rewriting what security feels like—one shared decision, one saved seed, one bottle of oil at a time. And that's something worth feeling.

8.2 Additional Examples from India

India also offers several examples that align with Circular Rural Economy principles. The Kudumbashree Mission in Kerala has demonstrated the transformative potential of women-led collective enterprises. Through self-help groups, micro-enterprises, and local economic activities, Kudumbashree has strengthened women's participation, enhanced incomes, and contributed to community development.

The cooperative dairy movement led by Amul in Gujarat remains one of the most successful examples of localized value addition and producer-owned economic development. By integrating millions of small producers into a cooperative network, Amul enabled wealth retention within rural communities while achieving national-scale market success.

The transformation of Hiware Bazar demonstrates how community participation, natural resource management, and local planning can reverse rural decline. Through watershed development, collective action, and livelihood diversification, the village significantly improved economic and ecological outcomes.

These examples demonstrate the broader economic multiplier effect of localized economies, where financial resources circulate repeatedly within communities, generating employment, entrepreneurship, and greater adaptive capacity.

IX. METHODOLOGY AND RURAL RESILIENCE INDEX (RRI)

This paper adopts a conceptual and practice-informed approach by integrating insights from circular economy literature, resilience theory, and implementation experiences from the GLIDE (Group Livelihoods for Development) framework across rural India. The analysis is based on economic leakage assessments, participatory resource mapping exercises, and documented experiences from GLIDE pilot locations. Rather than presenting a formal impact evaluation, the paper proposes an analytical framework for understanding how local value retention and collective enterprise development can contribute to climate and economic resilience.

To support future empirical assessment of Circular Rural Economy interventions, this paper proposes a Rural Resilience Index (RRI) comprising five interconnected dimensions: economic resilience, social resilience, ecological resilience, institutional resilience, and adaptive capacity, with economic leakage incorporated as a cross-cutting indicator of community vulnerability and resilience.

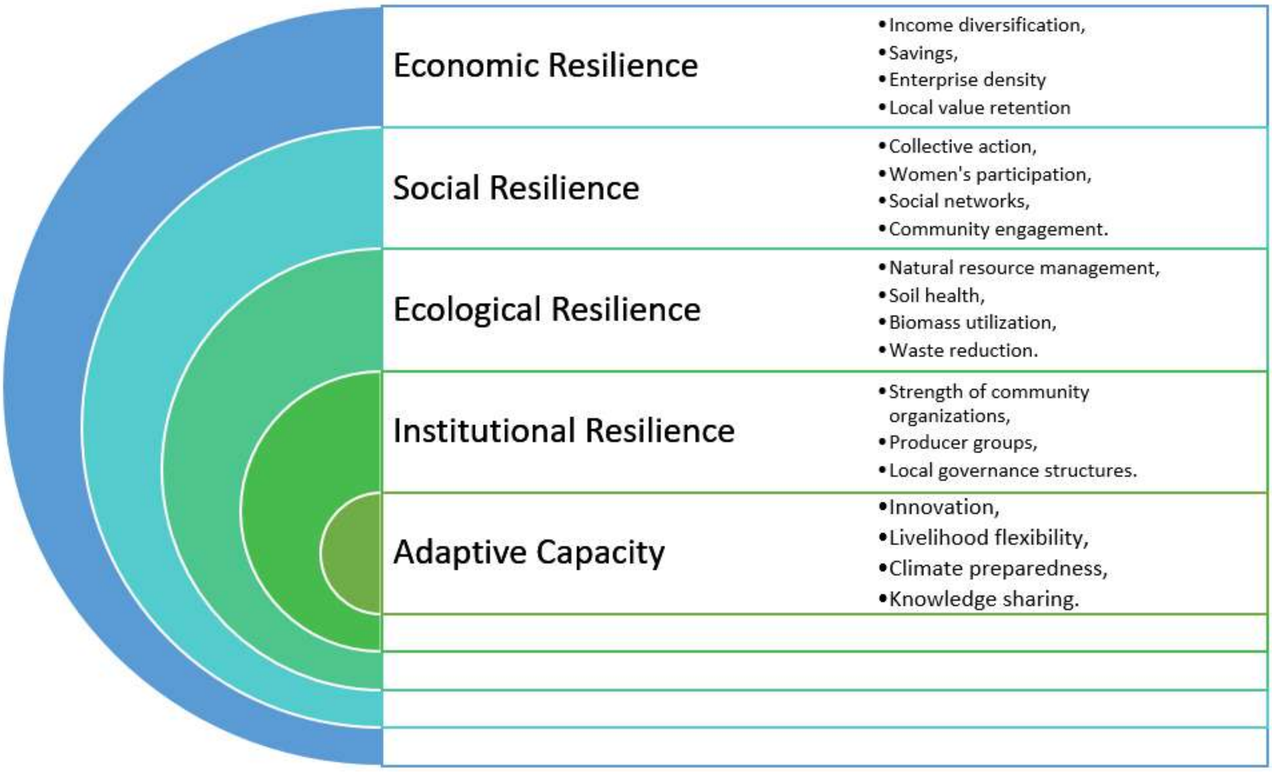


FIGURE 9: Rural Resilience Index (RRI) Framework

Proposed Rural Resilience Index (RRI):

$$RRI = (ER + SR + EcR + IR + AC) / 5 - EL \quad (1)$$

Where:

- ER = Economic Resilience
- SR = Social Resilience
- EcR = Ecological Resilience
- IR = Institutional Resilience

- AC = Adaptive Capacity
- EL = Economic Leakage (cross-cutting indicator)

Indicators for Each Dimension:

Dimension	Potential Indicators
Economic Resilience	Income diversification, local enterprise density, employment generation, asset ownership
Social Resilience	Social capital, community networks, collective action, trust, gender equity
Ecological Resilience	Natural resource health, biodiversity, soil quality, water availability
Institutional Resilience	Local governance, rule of law, institutional capacity, community organizations
Adaptive Capacity	Skills, education, information access, innovation, flexibility
Economic Leakage	Proportion of household expenditure on locally sourced goods, local value retention

The inclusion of economic leakage (EL) distinguishes the index from existing resilience frameworks by recognizing that communities retaining a greater proportion of local wealth are likely to exhibit stronger adaptive capacity and reduced vulnerability to external shocks. Consequently, the RRI provides a practical tool for assessing the resilience outcomes of Circular Rural Economy interventions such as GLIDE.

X. DISCUSSION

The findings presented in this paper suggest that the Circular Rural Economy (CRE) framework offers a promising alternative to conventional rural development approaches in an era characterized by climate uncertainty, economic volatility, and geopolitical instability. While traditional development models have focused primarily on increasing production, improving market access, and integrating rural producers into larger value chains, the CRE framework shifts attention toward local value retention, economic diversification, and resilience building.

A central contribution of this study is the recognition of economic leakage as an important but underexplored determinant of rural vulnerability. Most rural development interventions focus on increasing income generation without examining how quickly income exits the local economy through purchases of externally produced goods and services. The GLIDE framework demonstrates that substantial portions of rural expenditure are directed toward products that could potentially be produced locally. This finding suggests that rural development strategies should not only focus on increasing incomes but also on strengthening mechanisms that retain wealth within local economies.

The concept of economic leakage is particularly relevant in the context of climate change. Climate shocks often reduce agricultural production and household incomes. Communities that depend heavily on external suppliers for essential goods become doubly vulnerable because reduced incomes coincide with rising costs and supply-chain disruptions. In contrast, communities with diversified local enterprises are better positioned to absorb shocks because they possess alternative income sources and local production capabilities. Thus, economic localization can be viewed as a form of climate adaptation.

The study also highlights the importance of collective entrepreneurship as a resilience mechanism. Across the GLIDE pilots, women's groups, youth collectives, producer organizations, and community enterprises emerged as critical actors in identifying opportunities and mobilizing local resources. This finding aligns with resilience literature, which emphasizes the role of social capital, collective action, and community institutions in responding to crises. Collective enterprises not only generate economic benefits but also strengthen social networks that facilitate cooperation and knowledge sharing during periods of stress.

Another significant implication concerns the relationship between localization and globalization. The Circular Rural Economy framework does not advocate economic isolation or withdrawal from broader markets. Rather, it promotes a balanced approach in which communities satisfy a greater proportion of essential needs locally while engaging external markets strategically. Such an approach enhances resilience without sacrificing opportunities for growth and innovation.

The proposed Rural Resilience Index (RRI) further contributes to the literature by integrating economic, social, ecological, institutional, and adaptive dimensions of resilience while explicitly incorporating economic leakage. Existing resilience frameworks often emphasize ecological and social variables but rarely account for the circulation of financial resources within local economies. The inclusion of economic leakage therefore provides a novel perspective for assessing community resilience.

At a broader level, the findings support emerging arguments that resilience should be viewed not merely as the ability to recover from shocks but as the capacity to reorganize economic systems in ways that reduce future vulnerabilities. From this perspective, the GLIDE framework represents more than a livelihood intervention; it constitutes a community-based strategy for adaptive transformation. By linking local enterprise development, resource utilization, and wealth retention, the framework offers a practical pathway toward sustainable rural development.

XI. POLICY IMPLICATIONS: FROM RURAL DEVELOPMENT TO RURAL RESILIENCE

The findings of this study suggest that rural development policy must evolve from a narrow focus on income generation and productivity enhancement toward a broader framework of resilience-building. Climate change, monsoon uncertainty, global supply-chain disruptions, fertilizer price volatility, and geopolitical instability collectively reveal the limitations of development models dependent on external markets and imported inputs.

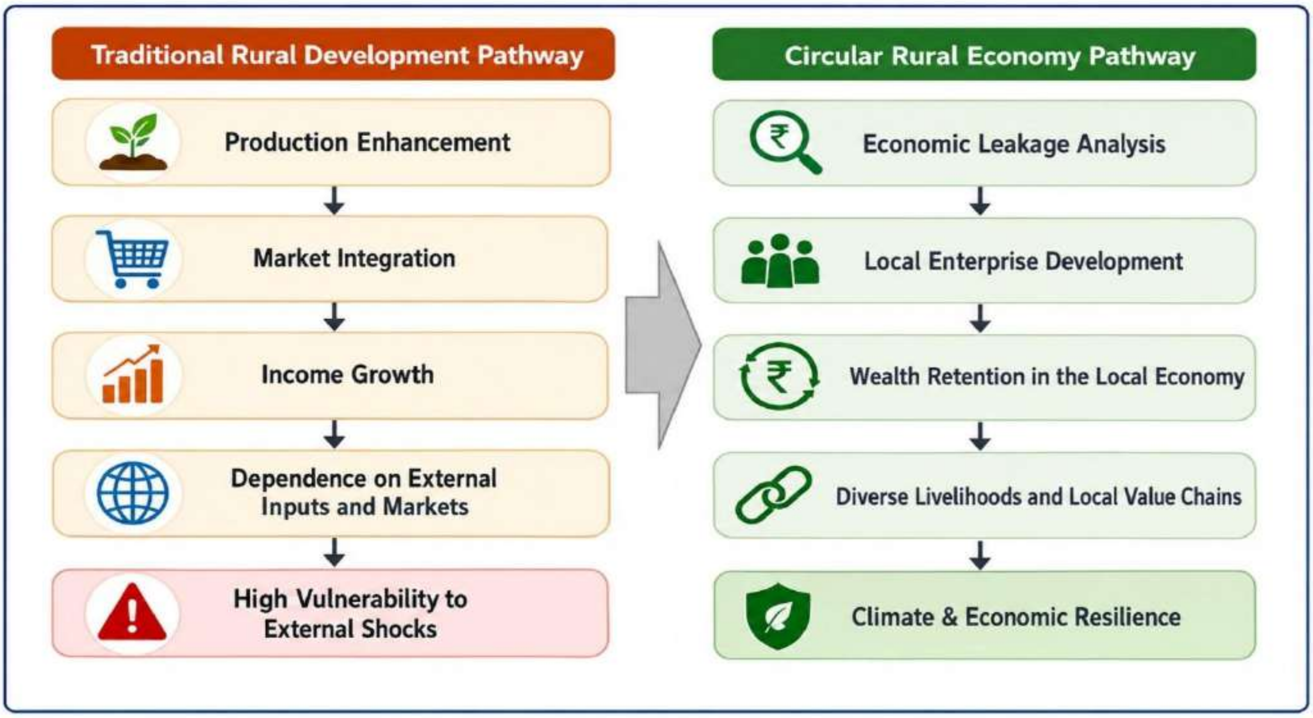


FIGURE 8: Policy Transformation Pathway

The Circular Rural Economy framework offers a practical pathway for strengthening local adaptive capacity by reducing economic leakage, promoting community enterprises, and enhancing local wealth circulation. Rather than treating livelihood promotion, climate adaptation, and economic self-reliance as separate policy domains, the framework integrates them within a single rural resilience strategy.

Alignment with Atmanirbhar Bharat: The emphasis on localized production and reduced external dependency aligns closely with the vision of Atmanirbhar Bharat. By promoting village-level enterprise ecosystems, the framework contributes to economic self-reliance while generating employment and strengthening local value chains.

Alignment with National Rural Livelihoods Mission (NRLM): GLIDE provides an operational mechanism through which Self-Help Groups (SHGs) can move beyond microcredit and engage in structured economic planning. Economic leakage assessments can help SHGs identify viable enterprise opportunities linked to existing local demand.

Alignment with Climate Adaptation Policies: Most adaptation programmes focus on agriculture, irrigation, and infrastructure. The findings suggest that local enterprise development should be recognized as an adaptation strategy because diversified livelihoods reduce dependence on climate-sensitive activities.

Alignment with Sustainable Development Goals: The framework contributes simultaneously to:

- SDG 1: No Poverty

- SDG 2: Zero Hunger
- SDG 5: Gender Equality
- SDG 8: Decent Work and Economic Growth
- SDG 11: Sustainable Communities
- SDG 12: Responsible Consumption and Production
- SDG 13: Climate Action

A Rural Resilience Policy Framework: Instead of measuring success only through income growth, policymakers should track:

- Economic leakage reduction
- Local enterprise density
- Women's enterprise participation
- Wealth retention rates
- Livelihood diversification
- Rural Resilience Index (RRI)

This would shift development planning from short-term welfare outcomes toward long-term resilience outcomes.

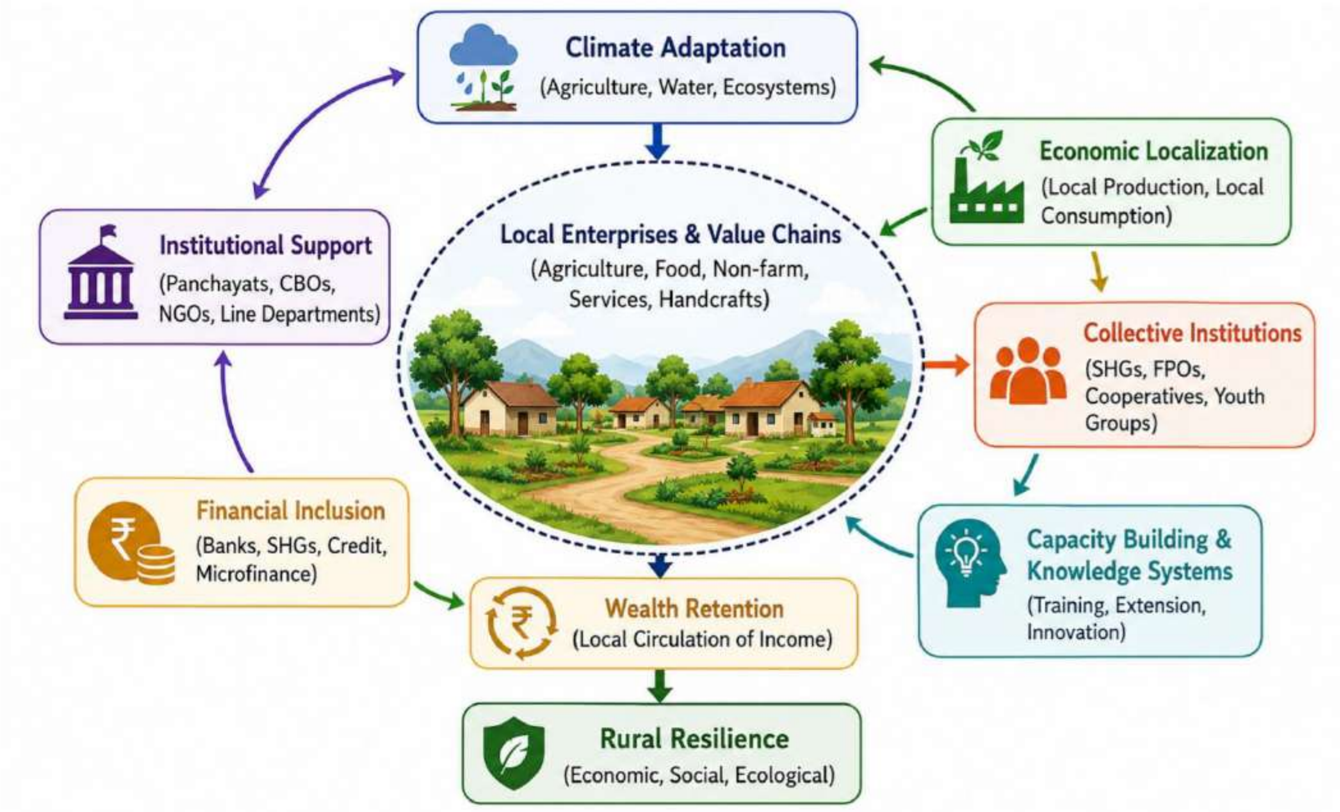


FIGURE 9: Policy Integration Framework

Limitations and Future Research: This paper presents a conceptual and practice-informed framework based on implementation experiences from GLIDE interventions across rural India. While the findings offer important insights into the relationship between economic leakage reduction and community resilience, future empirical research is required to validate the proposed Economic Leakage Resilience Theory and operationalize the Rural Resilience Index across diverse geographical and socio-economic contexts.

XII. CONCLUSION: CIRCULAR RURAL ECONOMY AS A RESILIENCE PARADIGM

This paper has argued that climate change, geopolitical instability, and economic globalization are transforming the nature of rural vulnerability. Contemporary rural communities face risks that extend beyond agricultural productivity and increasingly involve supply-chain disruptions, input price shocks, market volatility, and climate uncertainty.

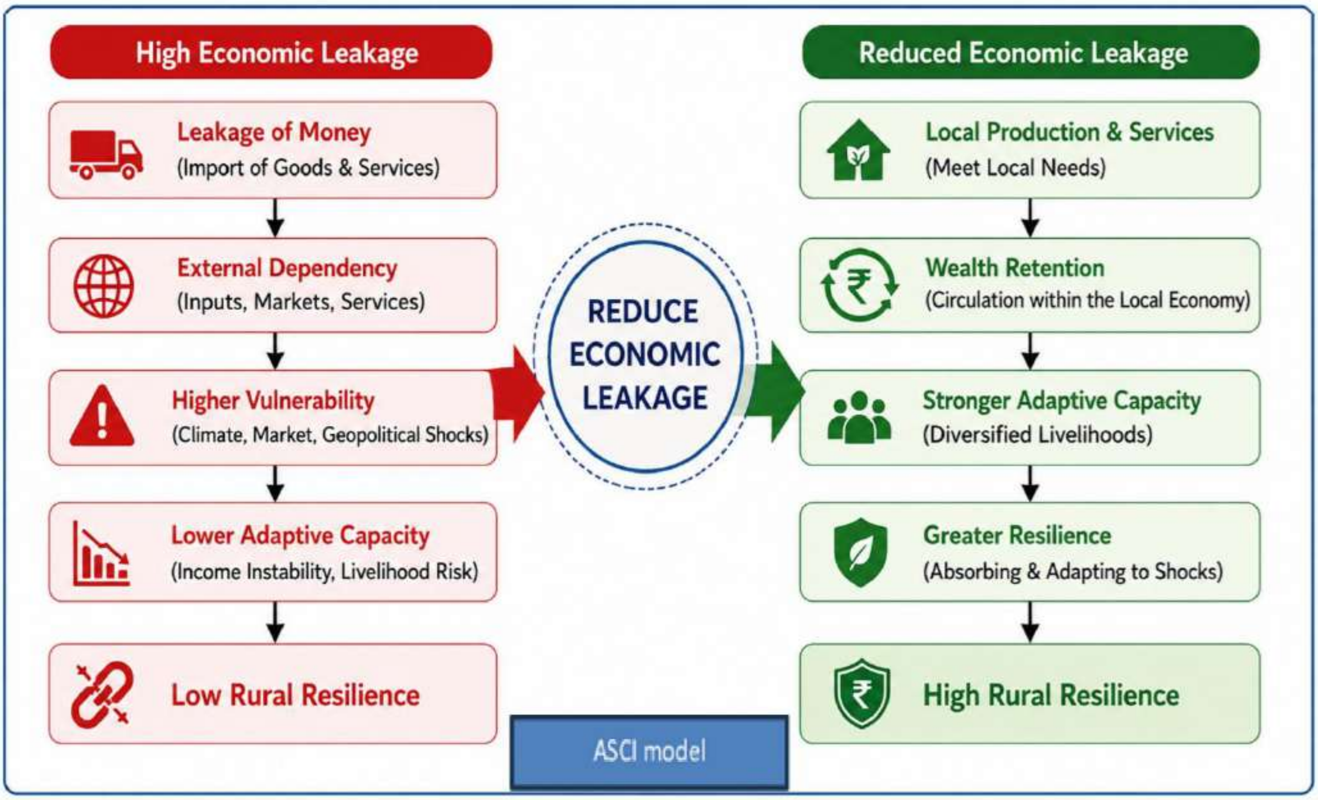


FIGURE 10: Economic Leakage Resilience Theory (ELRT)

In this context, conventional development models focused primarily on production enhancement and market integration are no longer sufficient. While these interventions remain important, they do not adequately address the structural vulnerabilities created by economic dependency and wealth leakage from rural economies.

The Circular Rural Economy framework offers an alternative development paradigm centered on local value retention, collective entrepreneurship, and economic resilience. Rather than viewing villages merely as production sites linked to external markets, the framework conceptualizes them as economic ecosystems capable of generating, circulating, and reinvesting value internally.

Evidence emerging from GLIDE pilots across multiple Indian states demonstrates that significant opportunities exist for local enterprise development and wealth retention. Communities consistently identified products currently imported into villages that could potentially be produced locally using existing resources, skills, and institutions. These findings suggest that rural resilience can be strengthened not only by increasing income but also by reducing economic leakage. The study introduces the concept of Economic Leakage Resilience Theory (ELRT), which proposes that resilience increases as communities retain a greater proportion of locally generated wealth.

The proposed Rural Resilience Index further extends existing resilience frameworks by integrating economic, social, ecological, institutional, and adaptive dimensions while explicitly incorporating economic leakage as a measurable indicator.

Resilience Transformation Pathway: The transformative potential of GLIDE lies in shifting rural development from charity to capacity-building, from individual livelihoods to collective enterprises, and from external dependency to localized resilience.

Ultimately, the significance of the GLIDE framework extends beyond livelihood promotion. It represents a practical model for building decentralized resilience infrastructure within rural communities. By integrating economic localization, climate adaptation, community institutions, and collective enterprise development, Circular Rural Economy provides a pathway toward sustainable and self-reliant rural futures.

FIGURE 11: Resilience Transformation Pathway

As climate and geopolitical uncertainties continue to intensify, the challenge for policymakers is no longer simply how to increase rural production, but how to build rural systems capable of enduring, adapting, and thriving amid uncertainty. The

Circular Rural Economy framework offers one such pathway and positions GLIDE as a scalable model for resilience-centered rural transformation in India and beyond.

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CONFLICT OF INTEREST

The authors declare that they have no competing financial interests or personal relationships that could have influenced the work reported in this paper.

REFERENCES

[1] Adger, W. N. (2000). Social and ecological resilience: Are they related? *Progress in Human Geography*, 24(3), 347–364. https://doi.org/10.1191/030913200701540465

[2] Adger, W. N. (2006). Vulnerability. *Global Environmental Change*, 16(3), 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

[3] Berkes, F., & Ross, H. (2013). Community resilience: Toward an integrated approach. *Society & Natural Resources*, 26(1), 5–20. https://doi.org/10.1080/08941920.2012.736605

[4] Carpenter, S. R., Walker, B., Anderies, J. M., & Abel, N. (2001). From metaphor to measurement: Resilience of what to what? *Ecosystems*, 4(8), 765–781. https://doi.org/10.1007/s10021-001-0045-9

[5] Chambers, R., & Conway, G. (1992). *Sustainable rural livelihoods: Practical concepts for the 21st century*. IDS Discussion Paper 296. Brighton: Institute of Development Studies.

[6] Ellen MacArthur Foundation. (2015). *Towards the circular economy: Economic and business rationale for an accelerated transition*. Cowes: Ellen MacArthur Foundation.

[7] Flora, C. B., & Flora, J. L. (2013). *Rural communities: Legacy and change* (4th ed.). Boulder, CO: Westview Press.

[8] Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems analyses. *Global Environmental Change*, 16(3), 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002

[9] Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, 1(1), 24–40. https://doi.org/10.1016/j.eist.2011.02.002

[10] Gunderson, L. H., & Holling, C. S. (Eds.). (2002). *Panarchy: Understanding transformations in human and natural systems*. Washington, DC: Island Press.

[11] Hickel, J. (2020). *Less is more: How degrowth will save the world*. London: Penguin Random House.

[12] Hopkins, R. (2008). *The transition handbook: From oil dependency to local resilience*. Totnes: Green Books.

[13] Intergovernmental Panel on Climate Change (IPCC). (2023). *Climate change 2023: Synthesis report*. Geneva: IPCC.

[14] Jacobs, J. (1969). *The economy of cities*. New York: Random House.

[15] Kumar, N., & Kumar, P. (2020). Climate change and Indian agriculture: A review of impacts and adaptation. *Current Science*, 118(3), 344–350.

[16] Latouche, S. (2009). *Farewell to growth*. Cambridge: Polity Press.

[17] Meadows, D. H. (2008). *Thinking in systems: A primer*. White River Junction, VT: Chelsea Green Publishing.

[18] Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511807763

[19] Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, 325(5939), 419–422. https://doi.org/10.1126/science.1172133

[20] Pelling, M. (2011). *Adaptation to climate change: From resilience to transformation*. London: Routledge.

[21] Pretty, J. (2008). Agricultural sustainability: Concepts, principles and evidence. *Philosophical Transactions of the Royal Society B*, 363(1491), 447–465. https://doi.org/10.1098/rstb.2007.2163

[22] Putnam, R. D. (2000). *Bowling alone: The collapse and revival of American community*. New York: Simon & Schuster.

[23] Raworth, K. (2017). *Doughnut economics: Seven ways to think like a 21st-century economist*. London: Chelsea Green Publishing.

[24] Sachs, J. D. (2015). *The age of sustainable development*. New York: Columbia University Press.

[25] Scoones, I. (1998). *Sustainable rural livelihoods: A framework for analysis*. IDS Working Paper 72. Brighton: Institute of Development Studies.

[26] Sen, A. (1999). *Development as freedom*. Oxford: Oxford University Press.

[27] Shucksmith, M. (2018). Re-imagining the rural: From rural idyll to rural resilience. *Journal of Rural Studies*, 59, 163–172.

[28] TEEB (The Economics of Ecosystems and Biodiversity). (2010). *Mainstreaming the economics of nature: A synthesis of the approach, conclusions and recommendations of TEEB*. Geneva: TEEB.

[29] United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development*. New York: United Nations.

[30] United Nations Development Programme (UNDP). (2022). *Human development report 2021/2022: Uncertain times, unsettled lives*. New York: UNDP.

[31] United Nations Office for Disaster Risk Reduction (UNDRR). (2015). *Sendai framework for disaster risk reduction 2015–2030*. Geneva: UNDRR.

[32] Walker, B., & Salt, D. (2006). *Resilience thinking: Sustaining ecosystems and people in a changing world*. Washington, DC: Island Press.

[33] World Bank. (2022). *Climate and development report: India*. Washington, DC: World Bank.

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Understanding Livestock Technology Adoption and Farmer Decision-Making through Participatory Rural Appraisal: Evidence from an Adopted Village in Maharashtra, India

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Abstract— *The present exploratory and participatory study was purposively conducted in Shirol village of Udgir tehsil in Latur district of Maharashtra. The village was adopted by the College of Veterinary and Animal Sciences, Udgir under the Unnat Bharat Abhiyan Scheme. This study explores the dynamics of livestock technology adoption among farmers in Shirol village, utilizing Participatory Rural Appraisal (PRA) techniques. Recognizing the critical role of animal husbandry in rural Indian livelihoods, the research investigates how farmers make decisions regarding modern agricultural practices within a mixed-farming context. Using a whole-village participatory approach, primary data was gathered through PRA tools, specifically technology mapping, matrix ranking, and consequence diagram. The findings revealed that technologies are not simply adopted, but are discontinued, over-adopted, rejected, or reinvented as well based on practical field problems. Matrix ranking demonstrated that farmers prioritize simple, low-cost, and highly effective practices. Furthermore, farmers showed remarkable adaptability by reinventing tools such as creating homemade concentrate feeds and crafting low-cost poultry equipment to minimize daily expenses. While technologies like artificial insemination and vaccination ranked lower in overall farmer preference due to a heavy dependence on external veterinary services and specialized technicians. Ultimately, the integration of these livestock technologies has significantly enhanced animal health, milk yields, and overall socio-economic conditions in the region. However, realizing their full potential is hindered by high initial costs, limited awareness, and irregular technical support. The study concludes that strengthening field-level extension services and improving veterinary accessibility are vital steps toward promoting sustainable livestock development and maximizing technological benefits for rural communities.*

Keywords— Participatory Rural Appraisal (PRA), Matrix ranking, Consequence diagram, Livestock technology, Technology adoption, Decision-making, Dairy farming, Goat rearing, Backyard poultry, Maharashtra.

I. INTRODUCTION

In India more than 20.5 million people depend on animal husbandry for their livelihood, thereby making livestock a vital source of additional income (Jain et al., 2023). Despite having a vast bovine population of 302.79 million (20th Livestock Census, 2024), the per capita milk production remains one of the lowest globally. However, recent studies have shown that adoption of improved technologies has worked for increase in the production as well as productivity of livestock, generating marketable surplus of milk and other livestock produce. In India, most of the farming is mixed type of farming in which farmers keep milch animals along with goat keeping and poultry to supplement income from livestock production, so this makes decision-making more complex than other types of farming. The term 'Participatory Rural Appraisal (PRA)' is being used to describe approaches and methods growing to enable local people to share, enhance and analyze their knowledge of life and conditions, thereby, to plan, to act and reach development (McCracken et al., 1988). To study impact of adoption of various livestock technologies and farmers' decision-making patterns, participatory rural appraisal techniques were used in the present study.

II. MATERIALS AND METHODS

The present research was purposively conducted in Shirol village of Udgir tehsil in Latur district of Maharashtra, which was adopted by the College of Veterinary and Animal Sciences, Udgir under the Unnat Bharat Abhiyan. Shirol village has 2915 human population (Census, 2011) and 1466 livestock population (20th Livestock Census, 2024). Livestock ownership in this village mainly consists of cattle rearing followed by goat and poultry. The study was conducted by a team of multidisciplinary experts. An exploratory and participatory research design was adopted using a whole-village approach. Primary data was collected through various PRA tools viz. technology mapping, matrix ranking, and consequence/impact diagrams to gather information on farmers' decision-making behaviour regarding technology adoption, the criteria affecting adoption, and the outcomes connected with the use of improved livestock technologies.

Technology map was prepared separately to illustrate the presence of various livestock technologies in the village as well as the farmers' decision behaviour. These maps depicted technologies that were adopted, discontinued, over-adopted, rejected, or modified (reinvented) for different types of domestic animals. The identification of livestock technologies was carried out through transect walks across the village along with key informants, including direct observation, interaction, and focussed discussion. Following this, matrix ranking was conducted to analyze the factors influencing different patterns of technology-related decisions among farmers. Finally, based on the matrix ranking results, a consequence diagram was developed to understand the outcomes and impacts of livestock technology adoption.

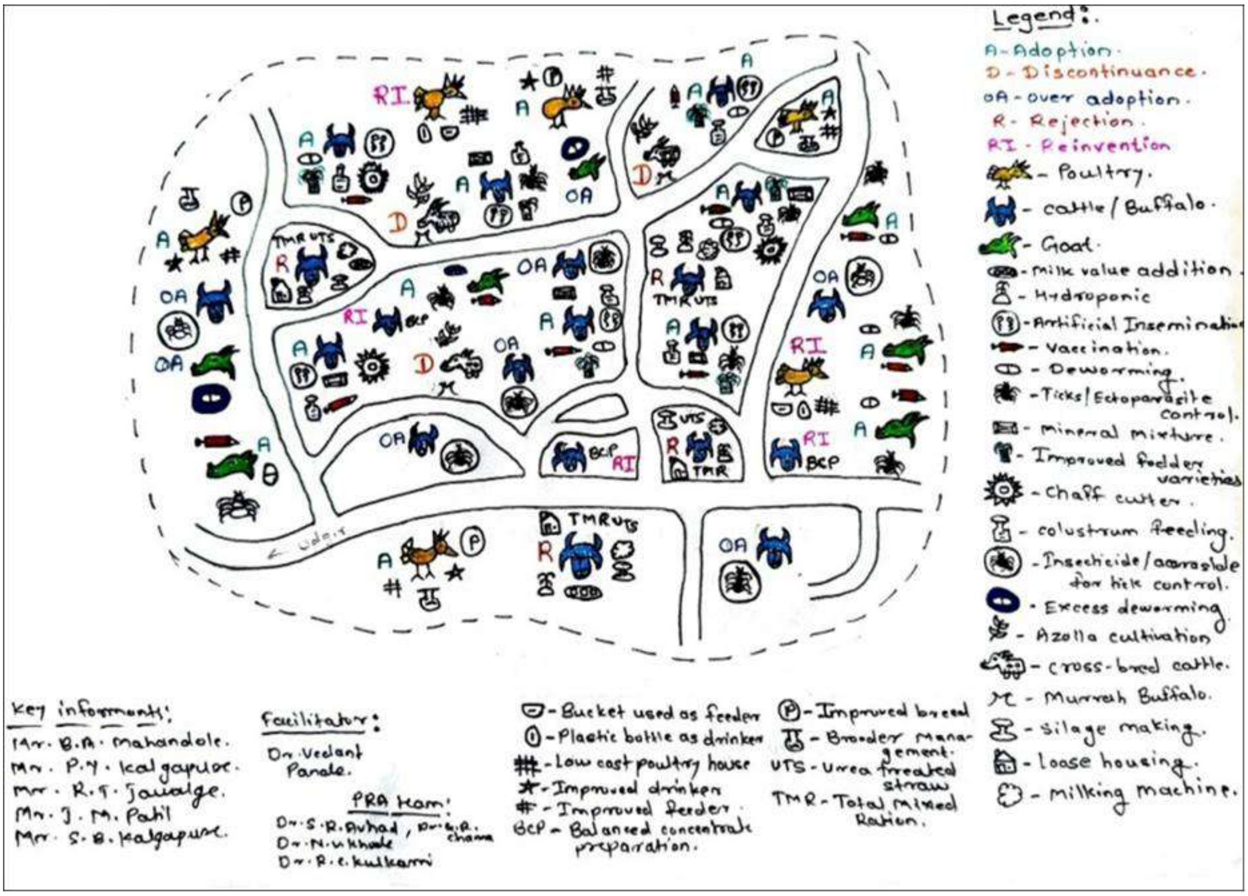

FIGURE 1: Technology map of Shirol village

III. RESULTS AND DISCUSSION

3.1 Impact of Livestock Technology Adoption

The technology map (Fig. 1) reveals the different decision-making behaviour of farmers. Adoption is defined as the continued use of a technology as the best course of action. According to Chambers (1994), the aim of PRA is to help strengthen the capacity of villagers to plan, make decisions, and to take action towards improving their own situation. In this adopted village the impact of the livestock technology adoption was analysed. In village situations, technologies may be adopted, discontinued, over-adopted, rejected, or reinvented depending on farmers' experiences and constraints. Several livestock technologies were widely adopted by farmers in the adopted village Shirol, as they were perceived to be simple, beneficial, and supported by veterinary extension services. In dairy farming, practices such as artificial insemination, vaccination against major diseases (FMD, HS, BQ, and LSD) were practiced. These findings are in consonance with Reddy and Krishna (2002). In case of deworming, tick and ectoparasite control practices, the results corroborate with Ntume et al. (2015), who reported the widespread adoption of these practices by farmers. Regarding nutrition-related livestock practices viz. mineral mixture feeding, cultivation of improved fodder varieties like DHN-6 and Super Napier, the findings are similar to Vinod Prakash et al. (2013). Use of chaff cutters and timely colostrum feeding to newborn calves were also regularly practiced by the respondents. These results corroborate the findings of Swathi Lekshmi et al. (2009a). Similarly, in goat farming, vaccination against PPR and enterotoxaemia along with deworming and ectoparasite control were widely practiced due to their direct role in reducing mortality and maintaining herd health. In backyard poultry farming, the use of improved drinkers and feeders, proper brooder management for chicks, and rearing of improved breeds such as Improved Aseel were commonly adopted as they enhanced chick survival, reduced feed wastage, and increased egg and meat production.

Certain livestock technologies that were initially adopted by farmers were later discontinued due to practical difficulties, high management requirements, or lack of expected benefits under local conditions. For instance, Azolla cultivation, which had been promoted as a low-cost protein supplement, was discontinued by many farmers because maintaining Azolla pits required regular labour, water management, and protection from contamination, which farmers found inconvenient. Similarly, the rearing of crossbred cattle such as Holstein Friesian and Jersey, as well as Murrah buffalo, was discontinued by some farmers due to their high feed and water requirements, greater susceptibility to diseases, and poor adaptability to local climatic conditions compared to indigenous breeds. The higher cost of maintenance and management challenges led farmers to gradually abandon these technologies.

During the course of investigation it was observed that some technologies were over-adopted by farmers, meaning they were used beyond the recommended dose or frequency. In dairy farming, insecticides or acaricides used for ectoparasite control were often applied in excessive quantities or sprayed more frequently than the recommended dosage on animals and in animal sheds. This has led to excess cost on medicine and also drug resistance in animals. This practice was largely followed due to farmers' strong concern about tick infestation and their perception that higher doses would provide quicker and more effective control. Kumar et al. (2014) have reported resistance to the insecticides or acaricides drugs used for ectoparasite control in dairy animals. Similarly, in goat farming, deworming drugs were sometimes administered in higher doses or more frequently than the recommended schedule. Further investigation revealed that farmers often believe that repeated or higher-dose deworming would improve animal health and growth. Such overuse and overdose practices were mainly associated with limited technical knowledge regarding proper dosage and intervals, and could potentially lead to problems such as drug resistance, unnecessary expenditure, and potential health risks to animals.

Several technologies were recommended by experts from various agencies but were rejected by farmers because they were perceived as impractical, costly, or unsuitable for smallholder livestock systems. In dairy farming, practices such as silage making, preparation of balanced concentrate feed at home, total mixed ration (TMR) feeding, urea-treated straw feeding, and hydroponic fodder production were not accepted due to the requirement of technical knowledge, infrastructure, and additional labour. However, Walli (2010) reported widespread adoption of these feeding practices, which may be due to variation in geographical and agro-climatic conditions. While studying problems faced by farmers in Shirol village, the shortage of labour was reported as the second most important problem faced by farmers after the high cost of concentrate feed. Similarly, value addition of milk into products like paneer, use of milking machines, and adoption of loose housing systems were rejected because of small herd sizes, lack of processing facilities, limited market access, or financial constraints. Farmers preferred traditional practices that required less investment and were easier to manage under their existing farm conditions. The findings corroborate with Nahar et al. (2022), who reported the various constraints in adoption of value addition of dairy food products.

In many cases, livestock owners modified or adapted some technologies according to locally available resources and their economic capacity, resulting in reinvented technologies. In dairy farming the common reinvention was preparation of concentrate feed mixture. Farmers prepared homemade concentrate feed mixtures using locally available ingredients such as maize, wheat bran, soybean bran, tur bran, chick pea (chana dal), and cotton seed/ground nut oil cakes instead of purchasing commercial feed, thereby reducing feed costs while maintaining nutritional supplementation. Some backyard poultry farmers developed innovative low-cost alternatives by using plastic bottles as drinkers and converting buckets or tins into feeders. Backyard poultry houses were also constructed using locally available materials such as wooden planks, bamboo, and iron cages to provide basic shelter for birds. These local practices reflected farmers' creativity in modifying technologies to suit their socio-economic and environmental conditions.

3.2 Matrix Ranking of Livestock Technology

Matrix ranking involves placing items or activities in order based on single or joint criteria. Ranking was carried out to find out preference of farmer community members, their criteria of ranking, and priority order. It is very useful in understanding the decision-making procedure. Here, the technologies are listed vertically and their respective criteria horizontally. The technology which is considered most important is listed and ranked as I, II, III, and so on. The respective column total gives the details; the highest column total gives the technology considered most important by the farmers and the highest row total gives the criteria considered most important by the farmers.

In Shirol, among the technologies shown in Table 1, high yielding fodder cultivation secured the highest total score (45.76) and was ranked first, indicating that farmers consider it the most favourable technology. It received consistently high scores across all criteria, particularly for low cost (9.72), quick results (9.64), and milk yield impact (9.68). This suggests that farmers perceive improved fodder cultivation as an economically viable and highly effective strategy for enhancing dairy productivity. However, Swathi Lekshmi et al. (2009b) reported improved breed as the most important adopted technology and high yield as the most important criteria. Mineral mixture feeding ranked second with a total score of 44.48, reflecting its observed importance in improving animal nutrition and milk production. Deworming was ranked third (42.00), suggesting that farmers recognize the importance of parasite control for maintaining animal health and productivity. Its relatively balanced scores across all criteria indicate that it is considered a practical and beneficial management practice. Chaff cutter usage ranked fourth (39.12), primarily due to its moderate scores in ease of use (7.88) and availability (8.16), reflecting its role in improving fodder utilization efficiency. Tick and ecto-parasite control ranked fifth (35.96), showing that although farmers acknowledge its quick results (9.04) and milk yield impact (8.40), relatively lower scores in cost (5.00) and ease of use (5.68) may limit its wider adoption.

TABLE 1
MATRIX RANKING OF LIVESTOCK TECHNOLOGIES IN SHIROL VILLAGE

Technology	Low cost	Ease of use	Availability	Quick results	Milk yield impact	Total score for technology	Final Rank
High yielding fodder cultivation	9.72	9.24	9	9.64	9.68	45.76	I
Mineral mixture	9.64	9.56	8.96	9.2	8.96	44.48	II
Deworming	8.56	8.28	8.44	8.24	8.48	42	III
Chaff cutter	7.24	7.88	8.16	7.96	7.88	39.12	IV
Ticks/ecto-parasites control	5	5.68	7.84	9.04	8.4	35.96	V
Artificial insemination	7.96	5	8.44	4.96	8.2	34.56	VI
Vaccination	8.92	5	4.8	4.44	8.88	32.04	VII
Total score for criteria	**57.04**	**50.64**	**55.64**	**53.48**	**60.48**		

Note: Scores are based on farmer rankings (out of 10) for each criterion. Higher scores indicate greater perceived importance or performance.

Technologies like artificial insemination and vaccination were placed in lower ranks, sixth (34.56) and seventh (32.04), respectively. Despite their recognized impact on milk yield and disease prevention, these technologies scored low on ease of use and availability. This reflects dependence on veterinary services, limited technical knowledge among farmers, or accessibility constraints in the village. In case of criteria totals, milk yield impact received the highest cumulative score (60.48), followed by low cost (57.04) and availability (55.64), indicating that farmers prioritize technologies that directly enhance productivity and which are affordable and accessible. In contrast, ease of use (50.64) received relatively lower emphasis.

The matrix ranking analysis indicates that farmers in the village prioritize livestock technologies that are low-cost, easily accessible, and capable of enhancing milk yield. Practices related to feed and nutrition management, such as high yielding fodder cultivation and mineral mixture supplementation, were perceived as the most effective and practical technologies. In contrast, technologies requiring external technical support or institutional services, such as artificial insemination and vaccination, received lower rankings despite their long-term benefits. This highlights the importance of strengthening extension services, improving accessibility of veterinary inputs, and enhancing farmers' awareness to promote the adoption of scientifically recommended livestock technologies.

3.3 Consequence/Impact of Technology Adoption

Consequences of technology adoption are the impacts caused by technology in terms of changes that occurred in a social system as a result of adoption or rejection of a technology. According to Chambers (1994), local people can express their ideas of how a technology may cause impact on their lives in terms of flows, linkages, connections, and causality. Consequence/impact of adoption of technologies in Shirol village is shown in Fig. 2. The adoption of improved livestock technologies by farmers in Shirol village has played an important role in upgrading livestock productivity, improving animal health, and strengthening rural livelihoods. These technologies have influenced the productivity of animals and also improved the socio-economic conditions of farmers. Thus, adoption of technologies plays an important role in overall development of the rural community. Technology adoption has generated several positive outcomes such as increased income, improved animal health, and employment opportunities, although certain adoption-associated limitations and challenges were also observed.

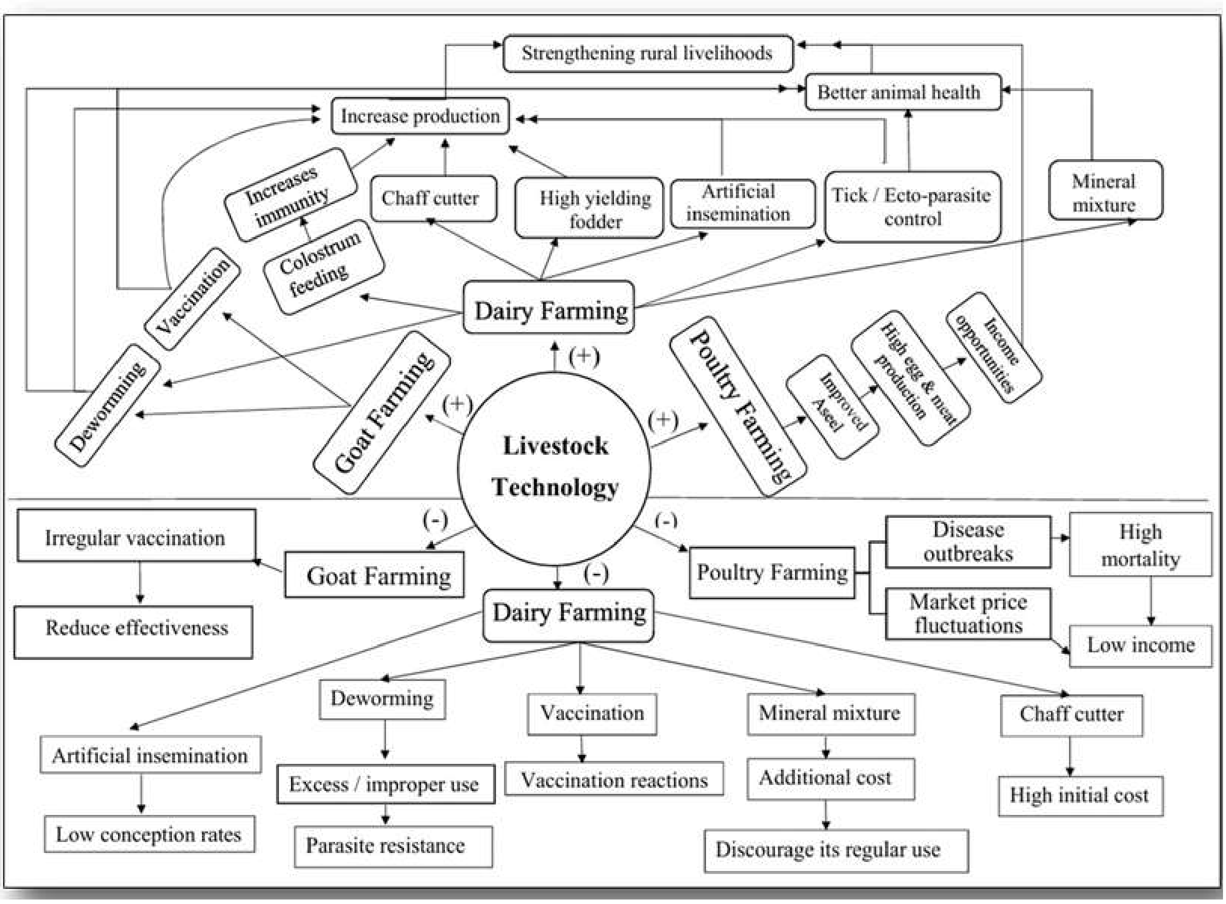

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FIGURE 2: Consequence/impact diagram of Shirol village

The adoption of artificial insemination (AI) has significantly contributed to genetic improvement in cattle and buffalo. Access to superior germplasm has improved breed quality, resulting in higher milk yield and better reproductive performance. However, the success of AI depends on proper heat detection and timely insemination, and poor management may result in low conception rates. Vaccination against major livestock diseases such as Foot and Mouth Disease (FMD), Haemorrhagic Septicaemia (HS), Black Quarter (BQ), and Lumpy Skin Disease (LSD) has played an important role in preventing disease outbreaks and reducing livestock mortality. However, irregular vaccination schedules, lack of awareness, and occasional vaccine reactions may limit its effectiveness.

Deworming and tick or ectoparasite control have improved livestock health by reducing parasite load. However, excessive or improper use of medicines may lead to parasite resistance, while the cost of treatment and lack of awareness about proper schedules may affect regular adoption of this technology. Mineral mixture feeding is an important nutritional practice to overcome mineral deficiencies in livestock. However, the additional cost and low awareness of long-term benefits sometimes discourage its regular use. Similarly, cultivation of improved fodder varieties such as DHN-6 and Super Napier has improved fodder availability due to their high agricultural yield and better nutritional value. This practice enhances milk production and reduces dependence on purchased feed, although it requires irrigation and proper management; however, lack of awareness and delayed feeding may reduce its benefits. The use of chaff cutters has improved feeding efficiency by reducing fodder wastage and making fodder easier to consume and digest. These results validate the findings of Chander (2010). However, the initial cost of the equipment and the risk of injury during operation may discourage some farmers. Colostrum feeding to newborn calves is another important managemental practice that strengthens calf immunity and improves survival rates.

In goat farming, vaccination against diseases such as Peste des Petits Ruminants (PPR) and Enterotoxaemia has reduced mortality and improved the health of goats. Deworming and ectoparasite control further improve growth rate, feed utilization, and overall production. However, irregular vaccination and limited veterinary services may reduce the effectiveness of these measures.

Backyard poultry rearing in Shirol village has benefited from improved managemental practices like use of improved drinkers and feeders, brooder management for chicks, and improved breeds like Aseel. Poultry farming also generates secondary employment and provides livelihood opportunities for women and small farmers. However, poultry production may face constraints such as disease outbreaks, market price fluctuations, and the need for better management practices.

IV. CONCLUSION

The pattern of adoption, discontinuance, over-adoption, rejection, and reinvention of livestock technologies reflected farmers' practical experiences, resource availability, and socio-economic conditions. Technologies that were simple, economically beneficial, and supported by veterinary services were readily adopted, while those requiring higher investment, technical expertise, or intensive management were often discontinued or rejected. Farmers also demonstrated considerable adaptability by modifying and reinventing technologies using locally available resources to suit their needs. The matrix ranking indicates that farmers in the village prioritize livestock technologies that are low-cost, easily accessible, and capable of producing immediate improvements in milk yield. Practices directly related to feed and nutrition management, such as high yielding fodder cultivation and mineral mixture supplementation, were perceived as the most effective and practical technologies. The adoption of improved livestock technologies in Shirol village has enhanced animal productivity, livestock health, and farmers' socio-economic conditions. Dairy, goat, and poultry technologies have increased income opportunities, improved nutritional security, and generated rural employment.

Recommendations:

1. **Strengthening Extension Services:** Field-level extension services should be strengthened to provide farmers with regular technical guidance on the proper use of livestock technologies, including dosage, frequency, and safety practices.
2. **Improving Veterinary Accessibility:** Veterinary services should be made more accessible through mobile veterinary units, telemedicine, and increased frequency of veterinary visits to remote villages.
3. **Farmer Training and Awareness:** Regular training programmes should be conducted to enhance farmers' awareness of the long-term benefits of technologies like artificial insemination and vaccination, and to discourage over-adoption practices.

4. **Promoting Farmer-to-Farmer Learning:** Successful farmers should be encouraged to share their experiences with others through farmer field schools and demonstration plots.
5. **Support for Reinvented Technologies:** The government and extension agencies should recognize and support farmers' innovations, such as homemade concentrate feed and low-cost poultry equipment, through recognition and scaling-up mechanisms.
6. **Affordable Technology Access:** Subsidies or low-interest loans should be provided to farmers to reduce the financial burden of adopting high-cost technologies like chaff cutters and improved fodder cultivation.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Chambers, R. (1994). The origins and practice of participatory rural appraisal. World Development, *22*(7), 953-969.
[2] Chander, M. (2010). Chaff cutters and fodder chaffing: A simple technology worth adoption. Successes and Failures with Animal Nutrition Practices and Technologies in Developing Countries, 133.
[3] Gaurav Jain, A. Singh, J. Singh and R. Jain. (2023). Overview of Basic Livestock Statistics in India. Advances in Veterinary Sciences, *8*, 69-84.
[4] Kumar, D., P. K. Sanyal, N. Wahane, S. Pal, S. Bisen and K. R. Baghel (2014). Evidence of anthelmintic resistance in ruminants of Jashpur district of Chhattisgarh. Indian Journal of Small Ruminants (The), *20*(2), 62-65.
[5] McCracken, J.A., J.N. Pretty and G.R. Conway, G. R. (1988). An introduction to rapid rural appraisal for agricultural development. International Inst. for Environment and Development, London (United Kingdom)
[6] Ministry of Fisheries, Animal Husbandry and Dairying. (2024). Department of Animal Husbandry, Dairying & Fisheries. Basic Animal Husbandry Statistics - 2024. Livestock Census : 2024.
[7] Ministry of Home Affairs. (2011). Census Tables. 15th Census.
[8] Nahar, A., F. A. Mila, R. J. Culas and M. R. Amin. (2022). Assessing the factors and constraints for value chain development of dairy food products in Bangladesh. Heliyon, *8*(10).
[9] Ntume, B., A. S Nalule and Baluka, S. A. (2015). The role of social capital in technology adoption and livestock development. Livestock Research for Rural Development, *27*(9): 181.
[10] Reddy, G.P. and P.S. Janaki Krishna, (2002). Participatory approaches in Agricultural Research: A case study of Andhra Pradesh. Netherland, Biotechnology Programme. Manage. Extn. Res. Rev., 13-27.
[11] Swathi Lekshmi, P. S., R. Venugopalan and K. Padmini, (2009). PRA methods for studying the impact of technology adoption in crop and poultry enterprises in a rural village. Indian Journal of Social Research, *50*(1): 1-14.
[12] Vinod Prakash, A. K. Singh and H. C. Singh. (2013). "PRA tools for real technology dissemination planning: a case study of Bhawanipura village of Etawah district.": 661-664.
[13] Walli T. K. (2010). Urea treatment of straws. Successes and failures with animal nutrition practices and technologies in developing countries. Proceedings of the FAO Electronic Conference, 1-30 September 2010, Rome, Italy. pp-11.

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Genetic Mechanisms Associated with Physiological, Nutritional Traits and Grain Yield in Pearl Millet (*Pennisetum glaucum* L.)

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Abstract— *One hundred genotypes of pearl millet including three checks were tested during* kharif *2024 in an Alpha Lattice design to understand the genetic mechanisms associated in governing the inheritance of grain yield, nutritional (iron, zinc, and protein content in seeds), and physiological traits (harvest index, relative water content, and SPAD chlorophyll meter reading). Higher variability for iron and zinc; moderate variability for grain yield, harvest index, and protein; and low variability for relative water content and SPAD chlorophyll meter reading were recorded. High heritability and high genetic advance as percent of mean were noted for iron content, zinc content, grain yield per plant, protein content, and harvest index, indicating predominance of additive gene action, and an early and simple selection would be advisable. High heritability coupled with moderate genetic advance over percent mean registered for relative water content indicated the operation of additive gene actions and might consistently manifest in future generations, resulting in increased effectiveness of the breeding program. Moderate heritability along with low genetic advance for SPAD chlorophyll meter reading revealed governance of non-additive genes and can be improved by heterosis breeding as simple selection might not be effective*.

Keywords— Pearl millet, Variability, Physiological traits, Nutritional traits, Genetic advance, Heritability, Iron content, Zinc content, Protein content, Biofortification.

I. INTRODUCTION

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) is a coarse cereal and ranks sixth among major cereal crops in terms of area in the world after rice, wheat, maize, barley, and sorghum. The protogynous nature of its hermaphrodite flowers makes pearl millet extensively cross-pollinated. Pearl millet has become a preferred crop for growing in arid and semi-arid regions because of its drought tolerance and low inorganic fertilizer requirement. It is also nutritionally superior and rich in micronutrients such as iron and zinc and can mitigate malnutrition and hidden hunger. Genetic variability, heritability, and genetic advance offer insights into the kind and degree of genetic control over significant agronomic and economic variables. Heritability estimates indicate the observed variation that is genetically inherited, whereas genetic variability provides the basis for selection. Heritability along with genetic advance helps breeders to adopt specific selection procedures. The study in pearl millet was conducted to estimate genetic parameters for physiological, nutritional traits, and grain yield so as to infer the gene actions associated in governing the traits.

II. MATERIALS AND METHODS

The experimental material for the present study comprised of 97 pearl millet inbred lines and three checks i.e., ABV04 (Composite variety), SBH 888 (Hybrid), and Pittaganti (local variety). The experiment was laid out in an Alpha Lattice Design with two replications. All the genotypes were sown in nursery in July 2024 and transplanted to the main field in August 2024 at ARS, Ananthapuramu. Each genotype was sown in one row of four meters length with a spacing of 45 cm between rows and 15 cm between the plants within the rows. The crop was provided with 60 N + 30 P_2O_5 + 20 K_2O kg ha^{-1}. Half of the N and the entire P and K were applied as a basal dose, and the second half of N was applied as top dressing after 35 days of sowing. All the recommended cultural and agronomic practices were followed for raising a healthy crop during the crop period.

Observations on grain yield and harvest index were recorded on five randomly selected competitive plants of each genotype in each replication. The harvest index was calculated for each genotype by applying the formula of Donald (1962). The RWC was calculated by the formula of Weatherley (1950) and expressed in percentage. Estimation of seed iron and zinc content was done as per the procedure given by Tandon (1999). The nitrogen content of the pearl millet genotypes was determined by the Kjeldahl method using a KEL PLUS distillation unit. The crude protein content of the sample was calculated as 6.25 times its nitrogen content and expressed as percentage.

The genotype means for each trait over two replications were subjected to statistical analysis. The statistical package used was R. The differences among genotypes for different traits were tested for significance by using analysis of variance technique on the basis of model proposed by Panse and Sukhatme (1961). The genotypic and phenotypic variances, genotypic coefficient of variation (GCV), and phenotypic coefficient of variation (PCV) were calculated as per the formula proposed by Burton (1952). Categorization of the range of variation was done as proposed by Sivasubramanian and Madhavamenon (1973). Heritability in broad sense [$h^2(b)$] was calculated by the formula given by Lush (1940) and heritability estimates were categorized as suggested by Johnson et al. (1955b). The genetic advance was estimated by the formula given by Johnson et al. (1955a) and the range of genetic advance as per cent of mean was classified according to Johnson et al. (1955b).

III. RESULTS AND DISCUSSION

3.1 Mean Performance of the Pearl Millet Genotypes

The mean, range, and top 10 genotypes are presented in Table 1.

3.1.1 Grain Yield per Plant (g)

Among the 100 genotypes, highest grain yield per plant was recorded by SBS 888 (53.9 g) and lowest by API 2001 (18.5 g) with a general mean value of 29.59 g. The genotypes SBS 888 followed by API 2054 and API 2052 recorded high grain yield.

3.1.2 Iron Content (ppm)

Iron content among the 100 genotypes ranged from 24.1 ppm (API 1087) to 223.5 ppm (API 1012) with a general mean of 86.94 ppm. Iron content was observed to be high in API 1012 followed by API 1039 and API 1018. Hence, these can be utilized in development of biofortified pearl millet varieties. The mean values of 42 genotypes were found to be significantly higher than the general mean value. A total of 52 genotypes outperformed the superior check, SBS 888 (66.8 ppm).

3.1.3 Zinc Content (ppm)

Maximum zinc content was recorded in API 1039 (80.3 ppm) and minimum in API 2018 (10.4 ppm). The general mean value for zinc content was 80.3 ppm. Among the 100 genotypes, API 1039 followed by API 1018 and API 1111 recorded highest zinc content which can be further exploited in breeding programmes. Twenty-eight genotypes registered significantly higher zinc content than the general mean value while 65 genotypes showed more zinc content than the superior check, ABV 04 (18.9 ppm).

3.1.4 Protein Content (%)

Mean values of protein content in grain ranged from 5.4% (API 2035) to 15.0% (API 1106) with a general mean of 9.09%. The genotypes API 1106 followed by API 1045 and API 2012 displayed highest protein content. Forty-nine genotypes registered significantly more protein content than the general mean value. Seventeen genotypes recorded more mean protein content than the best check, ABV 04 (10.3%).

3.1.5 Harvest Index (%)

Among the 100 genotypes, harvest index varied between 24.3% (API 2001) and 56.2% (SBS 888) with a general mean value of 40.19%. The superior performance was exhibited by SBS 888 followed API 2007 and API 1058. Thirty-five genotypes showed significantly higher harvest index compared to the general mean value (40.19%). None of the genotypes recorded higher mean value for harvest index than the best check, SBS 888 (56.2%).

3.1.6 Relative Water Content (%)

Among the 100 genotypes, API 1073 (62.5%) registered the lowest relative water content while API 1007 (89.6%) recorded the highest. The general mean for relative water content was 76.12%. The genotypes API 1007, API 1045, and API 1011 exhibited superior performance for the trait. Thirty-three genotypes were found to be significantly superior to the general mean value. Thirty-four genotypes outperformed the best check, ABV 04 (79.0%).

3.1.7 SPAD Chlorophyll Meter Reading at 60 DAS

The mean values of SPAD chlorophyll meter readings at 60 days after sowing (DAS) ranged from 50.5 (API 1029) to 67.2 (API 1084) with a mean of 58.92. Higher SCMR readings were observed in API 1084 followed by API 2056 and API 1083. Two genotypes recorded SCMR readings significantly exceeding the general mean. Nine genotypes recorded higher SCMR readings compared to the superior check, SBS 888 (62.7).

TABLE 1
MEAN PERFORMANCE, RANGE, AND TOP PERFORMING GENOTYPES FOR GRAIN YIELD, NUTRITIONAL, AND PHYSIOLOGICAL TRAITS IN PEARL MILLET

Trait	Range	General Mean	Top Performing Genotypes
Grain Yield (g/plant)	18.5 – 53.9	29.59	SBS 888, API 2054, API 2052
Iron Content (ppm)	24.1 – 223.5	86.94	API 1012, API 1039, API 1018
Zinc Content (ppm)	10.4 – 80.3	80.3	API 1039, API 1018, API 1111
Protein Content (%)	5.4 – 15.0	9.09	API 1106, API 1045, API 2012
Harvest Index (%)	24.3 – 56.2	40.19	SBS 888, API 2007, API 1058
Relative Water Content (%)	62.5 – 89.6	76.12	API 1007, API 1045, API 1011
SPAD Chlorophyll Reading	50.5 – 67.2	58.92	API 1084, API 2056, API 1083

3.2 Genetic Variability Parameters

In the present study, the differences between the phenotypic coefficient of variation and genotypic coefficient of variation were low for all the traits, indicating the less effect of environment on the expression of the traits.

The traits viz., zinc content (GCV = 54.03%; PCV = 54.07%) followed by iron content (GCV = 50.96%; PCV = 50.98%) showed higher estimates of coefficients of variation demonstrating the presence of enormous amount of innate variability among the genotypes that remained unaffected by environmental factors. Hence, a simple selection for these traits would be effective for further improvement. Similar findings were reported by previous workers for zinc content by Anuradha et al. (2018), Subbalakshmi et al. (2018a), Priyanka et al. (2019), and Jaiswal et al. (2025); and for iron content by Anuradha et al. (2018), Subbalakshmi et al. (2018a), Priyanka et al. (2019), Andhale et al. (2024), Thomas et al. (2018), Goswami et al. (2023), and Jaiswal et al. (2025).

Moderate estimates of coefficient of variation were recorded for grain yield per plant (GCV = 18.31%; PCV = 18.76%) followed by protein content (GCV = 17.14%; PCV = 17.19%) and harvest index (GCV = 15.59%; PCV = 15.88%). This suggested that there was enough variation among the genotypes under study for making selections to enhance these traits. These results resonated with Thomas et al. (2018), Priyanka et al. (2019), Swamynatham et al. (2019), Kedarnath et al. (2021), Yadav et al. (2022), Jain et al. (2023), and Kumar et al. (2023) for grain yield per plant; Thomas et al. (2018) and Goswami et al. (2023) for protein content; and Priyanka et al. (2019), Kedarnath et al. (2021), Yadav et al. (2022), and Goswami et al. (2023) for harvest index.

Lower estimates of coefficient of variation were noticed for SPAD chlorophyll meter reading (GCV = 3.94%; PCV = 6.40%) and relative water content (GCV = 7.46%; PCV = 7.73%) demonstrating a limited range of variability for these traits constraining the potential for selection. Lower estimates of coefficient of variation were reported previously for relative water content by Singh et al. (2018) and for SPAD chlorophyll meter readings by Naik et al. (2022).

3.3 Heritability in Broad Sense

Broad sense heritability (h^2b) is a measure of how much genetic variance contributes to the whole phenotypic variance of a variable. Estimates of heritability combined with the coefficient of variation would provide the clearest picture of the amount of advance that can be anticipated from selection. Higher estimates of heritability were recorded for iron content (99.95%) followed by zinc content (99.86%), protein content (99.41%), harvest index (96.35%), grain yield per plant (95.18%), and relative water content (93.02%). Higher heritability values imply that a larger genetic component may be responsible under a range of environmental circumstances. Early generation selection based on per se performance can be useful for these traits. These results are in accordance with the findings of Anuradha et al. (2018), Subbalakshmi et al. (2018a), and Andhale et al. (2024) for yield related and nutritional traits; Nehra et al. (2017), Sumathi and Revathi (2017), Rasitha et al. (2019), Rajpoot et al. (2023), and Singh et al. (2023) for yield related traits. SPAD chlorophyll meter reading (37.78%) recorded moderate heritability, and similar results were reported by Priyanka et al. (2019) and Kumar et al. (2023).

3.4 Genetic Advance

Heritability estimates by themselves do not offer dependable insights into the gene mechanisms influencing the expression of a specific trait and do not indicate the potential genetic improvement that could arise from selecting the top individuals. Johnson et al. (1955a) noted that combining heritability estimates with genetic advance provides greater utility than relying solely on heritability estimates for forecasting the response to selection. The higher estimates of genetic advance were observed for iron content (91.26) followed by zinc content (29.44) while harvest index (12.70) followed by relative water content (11.28) and grain yield per plant (10.89) recorded moderate genetic advance. This indicates that these traits are under the control of additive genes and for the improvement of these traits by selection will be rewarding. The traits viz; protein content (3.20) and SPAD chlorophyll meter reading (2.94) expressed low genetic advance implying that these traits are governed by non-additive gene action.

3.5 Genetic Advance as Per Cent of Mean

The higher estimates of genetic advance as percent of mean were recorded for iron content (111.23) followed by zinc content (104.96), grain yield per plant (36.79), protein content (35.21), and harvest index (31.51), while moderate estimates of genetic advance as percent of mean were displayed by relative water content (14.82). Low genetic advance as percent of mean was exhibited by SPAD chlorophyll meter reading (4.99).

TABLE 2
GENETIC VARIABILITY PARAMETERS FOR GRAIN YIELD, NUTRITIONAL, AND PHYSIOLOGICAL TRAITS IN PEARL MILLET

rait	Mean	Range	GCV (%)	PCV (%)	h^2b (%)	GA	GA as % of Mean
Grain Yield (g/plant)	29.6	18.5 – 53.9	18.31	18.76	95.18	10.9	36.79
Iron Content (ppm)	86.9	24.1 – 223.5	50.96	50.98	99.95	91.3	111.23
Zinc Content (ppm)	80.3	10.4 – 80.3	54.03	54.07	99.86	29.4	104.96
Protein Content (%)	9.09	5.4 – 15.0	17.14	17.19	99.41	3.2	35.21
Harvest Index (%)	40.2	24.3 – 56.2	15.59	15.88	96.35	12.7	31.51
Relative Water Content (%)	76.1	62.5 – 89.6	7.46	7.73	93.02	11.3	14.82
SPAD Chlorophyll Reading	58.9	50.5 – 67.2	3.94	6.4	37.78	2.94	4.99

IV. CONCLUSIONS

High heritability coupled with high genetic advance as percent of mean noted for iron content, zinc content, grain yield per plant, protein content, and harvest index signifies that these traits are predominantly governed by additive genes, and an early and simple selection is advisable. High heritability coupled with moderate genetic advance over percent mean registered for relative water content indicates that this trait is governed by additive genes and might consistently manifest in future generations, resulting in increased effectiveness of the breeding program. Moderate heritability coupled with low genetic advance for SPAD chlorophyll meter reading reveals that this trait is governed by non-additive genes and can be improved by heterosis breeding as simple selection might not be effective.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Andhale, G.R., Shinde, C.S., Bhavsar, V.V., & Barhate, K.K. (2024). Estimation of variability and genetic diversity in different genotypes of pearl millet (*Pennisetum glaucum* L.). *International Journal of Advanced Biochemistry Research*, 8(9), 207-213.

[2] Anuradha, N., Satyavathi, C.T., Bharadwaj, C., Sankar, M., Singh, S.P., & Pathy, T.L. (2018). Pearl millet genetic variability for grain yield and micronutrients in the arid zone of India. *Journal of Pharmacognosy and Phytochemistry*, 7(1), 875-878.

[3] Burton, G.W. (1952). Quantitative inheritance in grasses. *Proceedings of Sixth International Grassland Congress*, 1, 277-283.

[4] Donald, C.M. (1962). In search of yield. *Journal of the Australian Institute of Agricultural Science*, 28, 171-178.

[5] Goswami, P.A., Patel, H.S., & Patel, P.R. (2023). Study of genetic variability, heritability and genetic advance for yield and its component traits in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Pharma Innovation*, 12, 4305-4308.

[6] Jain, S.K., Deewan, D.K.D., Prakash, O., & Sharma, L.D. (2023). Character associations and path coefficient analysis for grain yield and yield contributing traits in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Annals of Arid Zone*, 62(2), 127-133.

[7] Jaiswal, A., Kumhar, B.L., Kharbas, A.S., Choudhary, K., Gocher, K., Nayak, P.K., & Yadav, T.V. (2025). Analysis of variability parameters in restorer lines of pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *Plant Archives*, 25(1), 523-527.

[8] Johnson, H.W., Robinson, H.F., & Comstock, R.E. (1955a). Estimate of genetic and environmental variability in soybean. *Agronomy Journal*, 47, 314-318.

[9] Johnson, H.W., Robinson, H.F., & Comstock, R.E. (1955b). Genotypic and phenotypic correlation in soybean and their implications in selection. *Agronomy Journal*, 47, 477-483.

[10] Lush, J.L. (1940). Intra-sire correlation and regression of offspring on dam as a method of estimating heritability of characters. *Proceedings of American Society of Animal Production*, 33, 292-301.

[11] Naik, B.S.K. (2022). *Genetic analysis of grain yield, morpho-physiological and nutritional traits in CGMS based hybrids of pearl millet* (*Pennisetum glaucum* (L.) R. Br.). Ph.D. Thesis. Acharya N. G. Ranga Agricultural University, Guntur.

[12] Panse, V.G., & Sukhatme, P.V. (1961). *Statistical methods for agricultural workers* (2nd ed.). ICAR, New Delhi.

[13] Priyanka, V., Shanthi, P., Reddy, D.M., & Reddy, B.R. (2019). Genetic variability studies on yield, physiological and nutritional traits in pearl millet [*Pennisetum glaucum* (L.) R. Br.]. *International Journal of Current Microbiology and Applied Sciences*, 8(6), 1234-1245.

[14] Singh, J., & Chhabra, A.K. (2018). Genetic variability and character association in advance inbred lines of pearl millet under optimal and drought condition. *Ekin Journal of Crop Breeding and Genetics*, 4(2), 45-51.

[15] Sivasubramanian, S., & Madhavamenon, P. (1973). Combining ability in rice. *Madras Agricultural Journal*, 60, 419-421.

[16] Swamynatham, S. (2019). *Genetic divergence studies in pearl millet* (*Pennisetum glaucum* (L.) R. Br.). M.Sc. (Ag.) Thesis. Acharya N.G. Ranga Agricultural University, Guntur.

[17] Tandon, H.L.S. (1999). *Methods of Analysis of Soils, Plants, Waters and Fertilisers*. Fertiliser Development and Consultation Organisation, New Delhi.

[18] Thomas, A.M., Babu, C., & Iyanar, K. (2018). Genetic variability and association studies in pearl millet for green fodder yield and quality traits. *Electronic Journal of Plant Breeding*, 9(3), 1263-1271.

[19] Varshney, R.K., Shi, C., Thudi, M., Mariac, C., Wallace, J., Qi, P., Zhang, H., Zhao, Y., Wang, X., Rathore, A., & Srivastava, R.K. (2017). Pearl millet genome sequence provides a resource to improve agronomic traits in arid environments. *Nature Biotechnology*, 35, 969-976.

[20] Weatherley, P.E. (1950). Studies in the water relations of the cotton plant. I. The field measurement of water deficits in leaves. *New Phytologist*, 49, 81-87.

[21] Yadav, M.K., Sanadya, S.K., Kumar, A., Kumar, A., Kumar, R., & Gupta, P.C. (2022). Genetic variability parameters and inter-relationship among yield and its attributes in pearl millet (*Pennisetum glaucum*) hybrids. *Biological Forum–An International Journal*, 14(2), 662-666.

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The Effect of Giving Dragon Fruit Peel and Papaya Seed Extracts through Drinking Water on the Percentage Commercial Carcass of Native Chicken

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Abstract— *The prohibition on the use of Antibiotic Growth Promoters (AGP) has encouraged farmers to seek alternative feed additives, such as dragon fruit peel and papaya seeds. Dragon fruit peel contains various antioxidants, including vitamin C, flavonoids, tannins, alkaloids, steroids, and saponins. Papaya seeds contain phytochemical compounds such as saponins, tannins, and flavonoids, which have potential antibacterial properties. This study aimed to determine the effect of administering aqueous extracts of dragon fruit peel, papaya seeds, and their combination through drinking water on the commercial carcass cuts of native chickens. This study used a Completely Randomized Design (CRD) with four treatments and five replications, where each replication consisted of three native chickens. The treatments applied were drinking water without dragon fruit peel and papaya seed aqueous extract (P0), drinking water with 4% dragon fruit peel aqueous extract (P1), drinking water with 4% papaya seed aqueous extract (P2), and drinking water with 2% dragon fruit peel aqueous extract combined with 2% papaya seed aqueous extract (P3). The observed variables included carcass weight and commercial carcass cuts. The results showed that the administration of dragon fruit peel and papaya seed aqueous extracts in drinking water did not have a significant effect (P > 0.05) on carcass weight or commercial carcass cuts of native chickens. It can be concluded that the administration of 4% dragon fruit peel aqueous extract, 4% papaya seed aqueous extract, and the combination of 2% dragon fruit peel aqueous extract and 2% papaya seed aqueous extract was not able to increase the commercial carcass cuts of 10-week-old native chickens.*

Keywords— Native chicken, Dragon fruit peel, Papaya seed, Commercial carcass, Aqueous extract, Feed additive, Natural growth promoter.

I. INTRODUCTION

Increasing public awareness of the importance of protein in the body has encouraged people to seek animal-based protein sources to meet their nutritional needs. One of the most popular sources of animal protein is chicken meat. Chicken meat contains high nutritional value and plays an important role in fulfilling nutritional requirements, particularly as a source of animal protein. Native chickens are among the poultry types that are highly preferred by consumers.

One of the indicators of successful native chicken production is an increase in carcass weight. According to Ulupi et al. (2018), the carcass is the part of the chicken's body that has high economic value. Commercial carcass cuts consist of the breast, thighs, back, and wings. In native chicken production, several challenges frequently affect carcass yield, including suboptimal growth performance and declining health status. To overcome these problems, farmers have commonly used Antibiotic Growth Promoters (AGPs) to stimulate growth, improve feed efficiency, enhance production performance, and maintain animal health. However, the use of AGPs may result in antibiotic residues in chicken meat, which can pose health risks to consumers (Sinurat et al., 2003). Consequently, the Indonesian government issued the Regulation of the Minister of Agriculture of the Republic of Indonesia Number 14 of 2017, which prohibits the use of antibiotics as growth promoters in livestock production. Therefore, natural feed additives are needed as alternatives to prevent antibiotic residues in native chicken meat, such as dragon fruit peel and papaya seeds.

Dragon fruit peel (*Hylocereus polyrhizus*) has potential as a feed additive because it contains nutrients with antibacterial properties that may improve nutrient absorption efficiency (Mustika et al., 2014). Dragon fruit peel contains various antioxidant compounds, including vitamin C, flavonoids, tannins, alkaloids, steroids, and saponins (Noor et al., 2016). It also contains anthocyanins, which not only function as antioxidants but may also improve the appearance and performance of broiler chickens (Maheri et al., 2022). Papaya seeds (*Carica papaya* L.) are another natural ingredient that can be used as a feed additive due to their antibacterial properties. Papaya seeds contain phytochemical compounds such as saponins, tannins, and flavonoids, which have potential as natural antioxidants (Yanti, 2017). Sukadana et al. (2008) reported that triterpenoid isolates extracted from papaya seeds exhibited antibacterial activity against *Escherichia coli* and *Staphylococcus aureus*, thereby supporting digestive processes in chickens.

The objective of this study was to determine the effect of administering aqueous extracts of dragon fruit peel, papaya seeds, and their combination through drinking water on the percentage of commercial carcass cuts in native chickens.

II. MATERIALS AND METHODS

2.1 Place and Time of the Research

This research was conducted at the Farm of the Faculty of Animal Science, Udayana University, located at Jalan Raya Sesetan Gang Markisa No. 6, Sesetan Village, South Denpasar District, Denpasar City, Bali. The study was carried out in August 2025.

2.2 Native Chickens

The native chickens used in this study were unsexed and aged six weeks. A total of 60 native chickens were selected from 75 available native chickens for the experiment.

2.3 Cages and Equipment

The study utilized colony type cages made of bamboo, with dimensions of 90 cm in length, 70 cm in width, and 45 cm in height. The cages were equipped with bamboo slatted floors. A total of 20 cage units were used, with each cage housing three native chickens. Each cage was provided with a feeder and a drinker made of plastic bowls specifically designed for poultry. Additional equipment used in the study included buckets for mixing dragon fruit peel aqueous extract and papaya seed aqueous extract with drinking water, measuring cylinders for measuring water volume, a blender for preparing the dragon fruit peel and papaya seed aqueous extracts, strainers for filtering the extracts, and stationery for recording research data throughout the experimental period.

2.4 Ration and Drinking Water

The study used a commercial feed, CP 511 Bravo, produced by PT. Charoen Pokphand Indonesia Tbk. Feed and drinking water were provided *ad libitum*, and the remaining feed and water were measured on the following day. The drinking water used in this study was sourced from a well. The nutrient composition of the commercial CP 511 Bravo feed is presented in Table 1.

TABLE 1
NUTRIENT COMPOSITION OF COMMERCIAL CP 511 BRAVO FEED

Nutrient	Amount
Moisture (%)	Max 14.00
Crude Protein (%)	Min 20.00
Crude Fat (%)	Min 5.00
Crude Fiber (%)	Max 5.00
Ash (%)	Max 8.00
Calcium (%)	0.80 – 1.10
Phosphorus (with phytase enzyme) (%)	Min 0.50
Lysine (%)	Min 1.20
Methionine (%)	Min 0.45
Methionine + Cystine (%)	Min 0.80
Tryptophan (%)	Min 0.19
Threonine (%)	Min 0.75

Source: PT. Charoen Pokphand Indonesia Tbk

2.5 Dragon Fruit Peel and Papaya Seed Aqueous Extracts

The preparation of dragon fruit peel and papaya seed aqueous extracts began by collecting dragon fruit peels and papaya seeds that had been separated from their respective fruits. Both materials were thoroughly cleaned. The dragon fruit peels were then cut into small pieces to facilitate the blending process. Subsequently, the dragon fruit peels were blended with water at a ratio of 1:1, meaning 1 kg of dragon fruit peel was mixed with 1 L of water. Similarly, papaya seeds were blended with water at the same ratio of 1:1. After each material was blended until a homogeneous mixture was obtained, the extracts were filtered. The resulting dragon fruit peel and papaya seed aqueous extracts were then administered to the chickens according to the respective treatment groups.

2.6 Research Design

This study employed a Completely Randomized Design (CRD) consisting of four treatments and five replicates, resulting in a total of 20 experimental units. Each experimental unit consisted of three native chickens. The treatments were as follows:

- **P0:** Drinking water without dragon fruit peel or papaya seed aqueous extract (control)
- **P1:** Drinking water supplemented with 4% dragon fruit peel aqueous extract
- **P2:** Drinking water supplemented with 4% papaya seed aqueous extract
- **P3:** Drinking water supplemented with 2% dragon fruit peel aqueous extract and 2% papaya seed aqueous extract

2.7 Randomization

Before the experiment commenced, 75 native chickens were weighed to obtain a homogeneous body weight distribution. A total of 60 chickens with an average body weight of 219.35 g and a standard deviation of ± 0.45 g were selected. The chickens were then randomly assigned to 20 cage units, with each cage unit containing three randomly allocated native chickens.

2.8 Research Preparation

One week prior to the start of the experiment, the cages and equipment were prepared, and cage sanitation was carried out using an antiseptic solution diluted at a ratio of 1:5 (1 mL of antiseptic mixed with 5 L of water) as a disinfectant. On the first day of the experiment, the chickens were weighed to determine their initial body weight and were marked with colored leg bands to facilitate identification and data recording.

2.9 Administration of Dragon Fruit Peel and Papaya Seed Aqueous Extracts

For treatment P0, chickens received drinking water without the addition of dragon fruit peel or papaya seed aqueous extracts. For treatment P1, a 4% concentration of dragon fruit peel aqueous extract was added to the drinking water, consisting of 960 mL of water and 40 mL of dragon fruit peel aqueous extract. For treatment P2, a 4% concentration of papaya seed aqueous extract was added to the drinking water, consisting of 960 mL of water and 40 mL of papaya seed aqueous extract. For treatment P3, drinking water contained a combination of 2% dragon fruit peel aqueous extract and 2% papaya seed aqueous extract, consisting of 960 mL of water, 20 mL of dragon fruit peel aqueous extract, and 20 mL of papaya seed aqueous extract. Drinking water was provided *ad libitum*, meaning it was continuously available throughout the day, and the remaining water was measured the following day.

2.10 Slaughtering of Native Chickens

Prior to slaughtering, the chickens were weighed to determine their final body weight and then fasted for 12 hours while still being provided with drinking water without treatment. Slaughtering was performed according to the procedure described by the USDA (United States Department of Agriculture, 1997), by severing the jugular vein and carotid artery located between the skull and the first cervical vertebra. The blood was collected and weighed. After death was confirmed, the chickens were immersed in hot water at a temperature of 65–75°C for 30–60 seconds to facilitate feather removal. Once the feathers had been removed, the chickens were weighed to determine slaughter weight. Subsequently, the internal and external organs were removed, and the carcasses were weighed to determine carcass weight.

2.11 Observed Variables

The variables observed in this study were carcass weight and the percentage of commercial carcass cuts, including breast, thigh, back, and wing percentages. Carcass weight and carcass cut percentages were calculated as follows:

1) **Carcass weight** was obtained by weighing the chicken after slaughter and the removal of blood, feathers, head, neck, internal organs, and feet.

2) $\textbf{Breast percentage} = \frac{\text{(Breast weight (g)}}{\text{Carcass weight (g))}} \times 100$

3) $\textbf{Thigh percentage} = \frac{\text{(Thigh weight (g)}}{\text{Carcass weight (g))}} \times 100$

4) $\textbf{Back percentage} = \frac{\text{(Back weight (g)}}{\text{Carcass weight (g))}} \times 100$

5) Wing $\textbf{percentage} = \frac{\text{(Wing weight (g)}}{\text{Carcass weight (g))}} \times 100$

2.12 Data Analysis

The data obtained were analyzed using analysis of variance (ANOVA). If significant differences among treatments were detected ($P < 0.05$), the means were further compared using Duncan's Multiple Range Test (DMRT) as described by Steel and Torrie (1993).

III. RESULTS AND DISCUSSION

The results of the study on the effect of administering dragon fruit peel and papaya seed aqueous extracts through drinking water on the percentage of commercial carcass cuts of native chickens are presented in Table 2.

TABLE 2
EFFECT OF ADMINISTERING DRAGON FRUIT PEEL AND PAPAYA SEED AQUEOUS EXTRACTS THROUGH DRINKING WATER ON THE PERCENTAGE OF COMMERCIAL CARCASS CUTS OF NATIVE CHICKENS

Variables	Treatment				SEM
	P0	P1	P2	P3	
Carcass Weight (g)	417.40a	423.60a	422.80a	458.20a	12.3
Breast Percentage (%)	26.21a	27.83a	27.02a	26.03a	0.91
Back Percentage (%)	24.73a	23.42a	23.99a	25.40a	0.8
Thigh Percentage (%)	34.32a	34.58a	34.52a	34.14a	0.57
Wing Percentage (%)	14.74a	14.17a	14.47a	14.43a	0.32

Notes:

P0: Drinking water without dragon fruit peel and papaya seed aqueous extracts (control). P1: Drinking water supplemented with 4% dragon fruit peel aqueous extract. P2: Drinking water supplemented with 4% papaya seed aqueous extract. P3: Drinking water supplemented with 2% dragon fruit peel aqueous extract and 2% papaya seed aqueous extract.

SEM = Standard Error of the Treatment Mean

Means followed by the same superscript letter within the same row are not significantly different (P > 0.05).

IV. DISCUSSION

3.1 Carcass Weight

The carcass weight of native chickens receiving dragon fruit peel and papaya seed aqueous extracts through drinking water in all four treatments was not significantly different ($P > 0.05$) (Table 2). The absence of significant differences in carcass weight among treatments indicates that the aqueous extracts of dragon fruit peel and papaya seed were not able to increase carcass weight in native chickens. The bioactive compounds contained in dragon fruit peel and papaya seeds, such as flavonoids, phenolics, saponins, and tannins, function to reduce oxidative stress and maintain digestive tract health. However, in the present study, these compounds were not able to significantly enhance muscle deposition. Furthermore, the dosage levels used in this study were insufficient to significantly improve nutrient utilization efficiency, resulting in no increase in carcass weight. This finding is supported by Peng et al. (2022), who stated that the effectiveness of feed additives is highly influenced by the dosage level used, which affects growth performance and carcass development. In addition, all treatment groups received diets with similar nutrient compositions, resulting in relatively uniform growth performance among the chickens. According to North and

Bell (1990), chicken growth is strongly influenced by the balance of dietary nutrients, particularly protein and energy; therefore, diets with similar nutrient compositions tend to produce comparable production performance.

3.2 Breast Percentage

The breast percentage of native chickens receiving dragon fruit peel and papaya seed aqueous extracts through drinking water in all four treatments was also not significantly different (P > 0.05) (Table 2). This result indicates that the bioactive compounds present in dragon fruit peel and papaya seeds, including flavonoids, alkaloids, tannins, saponins, vitamin C, and phenolic compounds, at the dosage levels used in this study were not able to significantly enhance protein deposition and breast muscle development. Although saponins and tannins have the potential to improve digestive tract health through their antibacterial activity, thereby supporting nutrient absorption (Sukadana et al., 2008), the effectiveness of natural feed additives is influenced by factors such as dosage level, duration of administration, and the physiological response of the animals to these bioactive compounds (Mahfudz et al., 2009). The lack of significant differences in breast percentage may also be attributed to the fact that all treatment groups received diets with similar nutrient contents, resulting in relatively uniform growth and muscle tissue deposition. According to Corzo and Kidd (2004), muscle tissue development is highly dependent on the adequacy and balance of nutrients in the diet.

3.3 Back Percentage

The back percentage of native chickens receiving 4% dragon fruit peel aqueous extract, 4% papaya seed aqueous extract, and a combination of 2% dragon fruit peel aqueous extract and 2% papaya seed aqueous extract showed no significant differences (P > 0.05) (Table 2). This result may be attributed to the fact that the back portion of poultry is predominantly composed of bone tissue, which develops as the animal grows and contains a relatively low proportion of muscle tissue. This finding is consistent with Putra et al. (2021), who reported that the back portion is dominated by bone tissue rather than muscle tissue; therefore, its growth is more influenced by skeletal development than by muscle deposition. Bone formation and growth are primarily determined by the adequacy of minerals such as calcium and phosphorus, as well as vitamin D3 in the diet. Since all treatment groups received diets with similar nutrient compositions, bone growth occurred relatively uniformly and consequently did not affect back percentage. The bioactive compounds present in dragon fruit peel and papaya seeds, including flavonoids, alkaloids, tannins, saponins, vitamin C, and phenolic compounds, are known to improve digestive tract health and metabolic efficiency; however, they do not directly influence bone tissue formation. Flavonoids and phenolic compounds mainly function as antioxidants that protect cells from oxidative damage (Arifin and Ibrahim, 2018). Although saponins and tannins may enhance nutrient absorption through their antibacterial properties, the extract dosages used in this study were insufficient to produce a significant effect on the back percentage of native chickens.

3.4 Thigh Percentage

The thigh percentage of native chickens receiving 4% dragon fruit peel aqueous extract, 4% papaya seed aqueous extract, and a combination of 2% dragon fruit peel aqueous extract and 2% papaya seed aqueous extract did not differ significantly (P > 0.05) from that of the control group (Table 2). This finding indicates that the bioactive compounds contained in dragon fruit peel and papaya seeds, such as flavonoids, alkaloids, tannins, saponins, vitamin C, and phenolic compounds, at the dosage levels used in this study were not able to significantly enhance thigh muscle development. These compounds are primarily involved in maintaining digestive tract health and improving metabolic efficiency rather than directly affecting carcass composition (Khalaji et al., 2011). The absence of significant differences in thigh percentage may also be attributed to the fact that all treatment groups received diets with similar nutrient contents, particularly protein and energy, resulting in relatively uniform muscle growth. Harimurti (1990) stated that similar nutrient compositions in the diet will produce relatively similar muscle growth. In addition, thigh percentage is closely related to slaughter weight and carcass weight. According to Pasang (2016), thigh weight is associated with slaughter weight, while Soeparno (2005) reported that carcass components are closely related to both carcass weight and slaughter weight. Therefore, the lack of significant differences in slaughter weight and carcass weight among treatments resulted in similar thigh percentages across all treatment groups.

3.5 Wing Percentage

The wing percentage of native chickens receiving 4% dragon fruit peel aqueous extract, 4% papaya seed aqueous extract, and a combination of 2% dragon fruit peel aqueous extract and 2% papaya seed aqueous extract did not differ significantly (P > 0.05) among treatments (Table 2). This condition may be attributed to the fact that the wing is a carcass component predominantly composed of bone tissue, with a relatively lower proportion of muscle compared to other carcass parts. Londok and Rompis (2018) reported that the wing is one of the carcass components with a smaller percentage than the breast, thigh, and back. This finding is supported by Mait et al. (2019), who stated that the wing consists of a greater proportion of bone and feathers, resulting in a relatively low contribution to meat formation. Bone tissue development occurs earlier than muscle tissue development; therefore, during the early growth phase, available nutrients are primarily utilized for skeletal formation (Ariawan et al., 2016). The absence of significant differences among treatments may also be explained by the fact that the bioactive compounds present in dragon fruit peel and papaya seeds, including flavonoids, alkaloids, tannins, saponins, vitamin C, and phenolic compounds, play a greater role in improving digestive tract health, enhancing antioxidant activity, and increasing nutrient utilization efficiency rather than directly influencing bone tissue growth. During the growth period, a portion of the absorbed protein is also utilized for feather formation and development, resulting in less protein being available for carcass tissue deposition (Adnyana et al., 2014). Therefore, the administration of dragon fruit peel and papaya seed aqueous extracts at the levels used in this study was not sufficient to produce significant changes in the wing percentage of native chickens.

V. CONCLUSION

Based on the results of this study, it can be concluded that the supplementation of dragon fruit peel and papaya seed aqueous extracts through drinking water at the levels of 4% dragon fruit peel aqueous extract, 4% papaya seed aqueous extract, and a combination of 2% dragon fruit peel aqueous extract and 2% papaya seed aqueous extract did not improve slaughter weight, carcass weight, breast percentage, back percentage, thigh percentage, or wing percentage of native chickens.

Future research should consider evaluating higher dosages, longer treatment durations, or alternative administration methods (such as feed incorporation) to determine whether these factors influence the effectiveness of dragon fruit peel and papaya seed aqueous extracts on carcass traits of native chickens.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this research. The materials used in this study, including dragon fruit peel extract and papaya seed extract, were prepared independently by the researchers and were not influenced by any commercial or financial interests.

REFERENCES

[1] Adnyana, I. G. S., Dewi, G. A. M. K., & Wirapartha, M. (2014). *Pengaruh imbangan energi dan protein ransum terhadap karkas ayam kampung betina umur 30 minggu* [Skripsi]. Universitas Udayana.

[2] Ariawan, P. T. B., Siti, N. W., & Sukmawati, N. M. S. (2016). Pengaruh pemberian ransum diferentasi dengan probiotik berbasis sari daun pepaya terhadap potongan karkas komersial ayam kampung. *Jurnal Peternakan Tropika*, *4*(2), 351-365.

[3] Arifin, B., & Ibrahim, S. (2018). Struktur, bioaktivitas dan antioksidan flavonoid. *Jurnal Zarah*, *6*(1), 21-29.

[4] Corzo, A., & Kidd, M. T. (2004). Dietary amino acid density effects on growth and carcass characteristics of broiler chickens. *Poultry Science*, *83*(5), 683-689.

[5] Harimurti, S. (1990). Pengaruh level pemberian energi dan protein pakan terhadap persentase berat karkas dan bagian-bagiannya pada ayam potong. *Agritech: Jurnal Fakultas Teknologi Pertanian UGM*, *10*(1), 11-15.

[6] Khalaji, S., Zaghari, M., Hatami, K., Hedari-Dastjerdi, S., Lotfollahian, H., & Nazarian, H. (2011). Effects of different levels of *Thymus vulgaris* essential oil and virginiamycin on the performance, immunity, and carcass characteristics of broiler chickens. *African Journal of Biotechnology*, *10*(61), 13482-13489.

[7] Londok, J. J. M. R., & Rompis, J. E. G. (2018). Pengaruh pembatasan pakan pada periode starter terhadap potongan komersial 2 strain ayam pedaging. In *Seminar Nasional VII HITPI* (pp. 5-6).

[8] Maheri, N. W. R., Candrawati, D. P. M. A., & Dewi, G. A. M. K. (2022). Penampilan broiler yang diberi jus kulit buah naga melalui air minum. *Jurnal Peternakan Tropika*, *10*(3), 630-644.

[9] Mahfuds, L. D., Maulana, F. L., Atmpmarsono, U., & Sarjana, T. A. (2009). Karkas dan lemak abdominal ayam broiler yang diberi ampas bir dalam ransum. In *Seminar Nasional Kebangkitan Peternakan*. Fakultas Peternakan, Universitas Diponegoro Semarang.

[10] Mait, Y. S., Rompis, J. E. G., Tulung, B., Laihad, J., & Londok, J. J. M. R. (2019). Pengaruh pembatasan pakan dan sumber serat kasar berbeda terhadap bobot hidup, bobot karkas dan potongan komersial karkas ayam broiler strain lohman. *Zootec*, *39*(1), 134-145.

[11] Mustika, C. I., Aldila, I., & Sjofjan, O. W. E. (2014). *Pengaruh penambahan tepung kulit buah naga merah (Hylocereus polyrhyzus) dalam pakan terhadap penampilan produksi burung puyuh (Coturnix coturnix japonica)* [Thesis]. Universitas Brawijaya.

[12] Noor, M. I., Yufita, E., & Zulfalina. (2016). Identifikasi kandungan ekstrak kulit buah naga merah menggunakan fourier transform infrared (ftir) dan fitokimia. *Journal of Aceh Physics Society*, *5*(1), 14-16.

[13] North, M. O., & Bell, D. D. (1990). *Commercial chicken production manual* (4th ed.). The Avi Publishing Company Inc.

[14] Pasang, N. A. (2016). *Persentase karkas, bagian-bagian karkas dan lemak abdominal itik lokal (Anas Sp.) yang diberi tepung kunyit (Curcuma Domestica Val.) dalam pakan* [Skripsi]. Universitas Hasanuddin.

[15] Peng, W., Talpur, M. Z., Zeng, Y., Zie, P., Lie, J., Wang, S., & Zhang, H. (2022). Influence of fermented feed additive on gut morphology, immune status, and microbiota in broilers. *BMC Veterinary Research*, *18*(1), 218.

[16] Putra, I. P. A. Y., Dewi, G. A. M. K., & Wirapartha, M. (2021). Pengaruh pemberian jus kulit buah naga terhadap produksi karkas burung puyuh umur 10 minggu. *Jurnal Peternakan Tropika*, *9*(2), 378-390.

[17] Sinurat, A. P., Purwadaria, T., Togatorop, M. H., & Pasaribu, T. (2003). Pemanfaatan bioaktif tanaman sebagai feed additive pada ternak unggas: Pengaruh pemberian gel lidah buaya atau ekstraknya dalam ransum terhadap penampilan ayam pedaging. *Jurnal Ilmu Ternak dan Veteriner*, *8*, 139-145.

[18] Soeparno. (2005). *Ilmu dan teknologi daging* (4th ed.). Gadjah Mada University Press.

[19] Steel, R. G. D., & Torrie, J. H. (1993). *Prinsip dan prosedur statistika suatu pendekatan biometrik* (M. Syah, Trans.). Gramedia Pustaka Utama.

[20] Sukadana, I., Rahayu, S. S., & Juliarti, N. (2008). Aktivitas antibakteri senyawa golongan triterpenoid dari biji pepaya (*Carica papaya* L.). *Jurnal Kimia*, *2*(1), 15-18.

[21] Ulupi, N., Nuraini, H., Parulian, J., & Kusuma, S. Q. (2018). Karakteristik karkas dan non karkas ayam broiler jantan dan betina pada umur pemotongan 30 hari. *Jurnal Ilmu Produksi Dan Teknologi Hasil Peternakan*, *6*(1), 1-5. https://doi.org/10.29244/jipthp.6.1.1-5

[22] Yanti, E. P. (2017). Efek pemberian ekstrak biji dan ekstrak daun pepaya (*Carica papaya* linn) terhadap kadar kolesterol total dan trigliserida tikus putih jantan galur wistar (*Rattus norvegicus*) yang diberi diet tinggi lemak. *Hang Tuah Medical Journal*, *15*(1), 1-9.

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Predatory Mites of the Genus *Amblyseius* (Acari: Phytoseiidae) Associated with Insect Pests in South Gujarat

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Abstract— *An intensive field investigation was conducted during the year 2024-25 and 2025-26 to study the diversity of predatory mites associated with major agricultural and horticultural insect pests across South Gujarat. The predatory mite family Phytoseiidae emerged as the most dominant and ecologically significant group, represented by a high diversity of species belonging to the genus Amblyseius. During the study period, eight species from genus Amblyseius were identified: Amblyseius channabasavannai, A. largoensis, A. vasiformis, A. multidentatus, A. sacchari, A. gossypii, A. herbicolus and A. longispinosus. These predatory mites were predominantly associated with soft-bodied sucking pests, particularly the whiteflies Bemisia tabaci and Aleurolobus barodensis. The study establishes a critical taxonomic and ecological baseline for deploying these native phytoseiid predators within Integrated Pest Management (IPM) frameworks.*

Keywords— Diversity, Mites, South Gujarat, Predatory mite, **Amblyseius,** ***Phytoseiidae, Biological control, Whitefly,*** **Bemisia tabaci,** ***Taxonomy.***

I. INTRODUCTION

The genus *Amblyseius* Berlese (Family: Phytoseiidae, Subfamily: Amblyseiinae) represents one of the most species-rich, economically vital and globally distributed groups of predatory mites used in biological pest control. Formally established by Italian entomologist Antonio Berlese in 1914, the genus comprises well over 400 recognized species. Morphologically, these microscopic arachnids are characterized by smooth, lightly sclerotized (hardened) dorsal shields, a characteristically vase-shaped or divided ventrianal shield in females and significantly elongated dorsal setae (specifically the s4, Z4 and Z5 pairs), which facilitate spatial sensing during rapid, agile movement. They possess highly adapted chelicerae with multiple specialized teeth designed to pierce the outer cuticle of soft-bodied agricultural pests, including whitefly nymphs, thrips and phytophagous spider mites (Tetranychidae). Ecologically, the vast majority of species within *Amblyseius* are classified as Type III generalist predators under the globally recognized phytoseiid lifestyle classification system developed by McMurtry et al. (2013). Unlike strict specialist predators that starve when their primary prey is depleted, Type III generalists are highly adaptable opportunists. They can effectively subsist, develop and reproduce on a broad spectrum of alternative foods, including plant pollen, honeydew, fungal spores and small non-pest micro-arthropods. This generalist feeding strategy allows *Amblyseius* populations to successfully persist within agri-horticultural ecosystems even during periods of very low target pest densities, making them exceptionally effective at suppressing pest complexes before they can reach economic injury levels. Because of their high reproductive potential, rapid developmental rates and versatile searching behaviour, several key species—such as *Amblyseius swirskii* Athias-Henriot and *Amblyseius largoensis* (Muma)—have been extensively mass-reared and integrated into global Integrated Pest Management programs as frontline, sustainable alternatives to synthetic chemical acaricides in both open-field crops and protected greenhouse environments.

II. MATERIALS AND METHODS

The field sampling and laboratory investigations were carried out at the Department of Entomology, N. M. College of Agriculture, Navsari Agricultural University, Navsari, Gujarat, India, during the research period spanning 2024-2025 and 2025-2026. Random field surveys were executed across 42 localized collection sites distributed over seven distinct districts of South Gujarat: Navsari, Surat, Bharuch, Tapi, Narmada, Valsad and The Dangs. Ecosystems surveyed included key seasonal field crops (rice, sugarcane, cotton, pulses), vegetable fields (chilli, okra, tomato) and perennial fruit orchards (mango, sapota, guava). Live insect pest specimens and their respective infested plant structures were collected directly via active handpicking, specialized insect nets and light/pheromone traps to minimize host dislodgement. Samples were secured in ventilated plastic bottles labelled accordingly and then transferred to the laboratory. To facilitate precise isolation without loss of delicate morphological features, host insects were temporarily inactivated in a refrigerator for 15 minutes. The specimens were individually scrutinized under a high-resolution stereomicroscope. Located mites were carefully segregated utilizing a fine, moistened camel hair brush and preserved in a 70 percent ethanol medium. Weakly sclerotized specimens were mounted directly onto glass slides in Hoyer's medium. The mounted slides were cured in a constant-temperature oven at 30°C for 1 to 2 weeks to ensure tissue clearing and optimal leg extension. Cured slide rings were permanently sealed with commercial nail polish to prevent atmospheric moisture infiltration. The diagnostics and generic categorizations were performed using a Phase-Contrast Research Microscope, following the specialized keys provided by Krantz and Walter (2009) and Chant and McMurtry (2007). All morphometric evaluations are detailed in micrometres.

III. RESULTS AND DISCUSSION

Members of the family Phytoseiidae under the order Mesostigmata constituted the dominant group. Several predatory mite species, namely *Amblyseius multidentatus*, *A. sacchari*, *A. gossypii*, *A. herbicolus*, *A. largoensis*, *A. longispinosus*, *A. channabasavannai*, *A. vasiformis*, *Euseius finlandicus* and *E. ovalis* were frequently associated with whiteflies and other soft-bodied insects occurring on crops. Similar observations were reported by El-Badry (1967), who demonstrated the predatory role of phytoseiid mites against whiteflies. Krantz and Walter (2009) reported that members of Mesostigmata frequently establish phoretic, predatory and parasitic associations with insects and often dominate insect-associated acarofauna due to their ecological versatility. The predominance of phytoseiid mites may be attributed to their ecological adaptability and their tendency to utilize insects either as prey or as temporary carriers for dispersal. Similar associations of phytoseiid mites with whiteflies have been reported by El-Badry (1967), Nomikou et al. (2001) and McMurtry et al. (2013), suggesting that phytoseiid mites are important natural enemies of whiteflies in different agroecosystems.

3.1 Detailed Systematic Account of Genus *Amblyseius* Species

3.1.1 *Amblyseius channabasavannai* Gupta & Daniel, 1978

Superorder: Parasitiformes

Order: Mesostigmata

Suborder: Monogynaspida

Superfamily: Phytoseioidea

Family: Phytoseiidae

Subfamily: Amblyseiinae

Genus: *Amblyseius*

Colour: Transparent white

Measurements: Length: 325-335 µm; Width: 210-215 µm

Description

Adult Female:

Dorsum: Dorsal shield smooth with 18 pairs of setae. Dorsal setae smooth and pointed; j1, j3, s4, Z4 and Z5 longer than all other equally sized setae, Z5 the longest and whip-like. Setae r3 and R1 are placed on the lateral integument.

Venter: Sternal shield with three pairs of sternal setae, st1, st2 and st3. Genital shield with one pair of setae, st5. Ventrianal shield longer than wide, widest at the level of the seta, Zv2. Ventrianal shield with three pairs of preanal setae, Jv1, Zv2 and Jv2. Peritreme extending to j1 anteriorly, stigmata placed at the level of coxa IV. Spermatheca with a tubular cervix and parallel walls.

Gnathosoma: Fixed digit of chelicerae, multidentate and movable digit with four teeth.

Legs: Macrosetae on leg IV are placed on the genu, tibia and basitarsus. Leg chaetotaxy: genu II 2, 2/0, 2/0, 1; tibia II 1, 1/1, 2/1, 1; genu III 1, 2/1, 2/0, 1; tibia III 1, 1/1, 2/1, 1.

Male: Not recovered during sampling.

Materials examined: Adult specimens of *B. tabaci* collected from Borakhadi (21°08'40" N 73°20'15" E) in Dist. Tapi.

Remarks: The specimens examined closely agree with the original description of *A. channabasavannai* given by Chant and McMurtry (2007), who recognized species of the genus *Amblyseius* by their characteristic dorsal chaetotaxy, spermathecal morphology, and leg macrosetae. The species has all the important diagnostic characters. The species was recorded in association with *B. tabaci* infesting chilli during the present study.

3.1.2 Amblyseius largoensis *Muma, 1955*

Colour: Transparent white

Measurements: Length: 370-375 µm; Width: 275-280 µm

Description

Adult Female:

Dorsum: Dorsal shield with 18 pairs of setae, of which j1, j3, s4, Z4, Z5 are longer than the other dorsal setae, j4, j5, j6, z2, z4, z5, r3, J2, Z1, R1, S4, S5, J5 are short and of the same length. Z5 is long and whip-like. The sublateral setae r3 and R1 are present on the lateral integument. Setal pattern 10A: 8B.

Venter: Sternal shield longer than wide and with three pairs of setae, st1, st2 and st3. Sternal seta st4 is located on the integument. Genital shield with one pair of setae, st5. Ventrianal shield with three pairs of preanal setae, Jv1, Jv2 and Zv2 and a pair of semilunar pores. Peritreme extending to the level of j1. Two pairs of metapodal plates are present. The cervix of the spermatheca is tubular with parallel walls.

Gnathosoma: Fixed digit of chelicerae with seven teeth, three posterior and four anterior to pilus dentilis. Movable digit of the chelicera with two teeth.

Legs: Macrosetae on genu, tibia and basitarsus of leg IV. Chaetotaxy of genu II: 2, 2/0, 2/0, 1, tibia II: 1, 1/1, 2/1, 1, genu III: 1, 2/1, 2/0, 1 and tibia III: 1, 1/1, 2/1, 1.

Male: The arrangement of setae on dorsum is very similar to that of the female. Ventrum with 5 pairs of sternal setae on the sternogenital shield.

Materials examined: The adults of *B. tabaci* collected from Vagaldhara (20°34'20"N 72°59'50" E) in Dist. Valsad.

Remarks: The specimen examined resembles *A. largoensis* reported from Florida in all features. This forms the first report of this species associated with *B. tabaci* from Gujarat. The present observations are in agreement with the descriptions provided by Chant and McMurtry (2007), who emphasized dorsal chaetotaxy, spermathecal structure, and leg macrosetae as key diagnostic characters for species of the genus *Amblyseius*. Similarly, Krantz and Walter (2009) reported that members of the family Phytoseiidae are characterized by well-developed predatory adaptations, including specialized chelicerae and distinct ventral shield structures, which were also observed in the present specimens.

3.1.3 *Amblyseius vasiformis* Moraes & Mesa, 1991

Colour: Transparent white

Measurements: Length: 410-420 µm; Width: 270-275 µm

Description

Adult Female:

Dorsum: Dorsal shield smooth with 17 pairs of setae; j1, j3, j4, j5, j6, z2, z4, z5, s4, J2, J5, Z1, Z4, Z5, S2, S4, S5 and lateral integument with two pairs of setae, r3 and R1. Setal pattern 10A:9B. All dorsal setae smooth and simple except Z4 and Z5, which appear slightly light serrated. All setae are short except j1, j3, s4, Z4 and Z5, which look longer and of variable length, Z5 being the longest. Two pairs of setae, r3 and R1, sublateral.

Venter: Sternal shield as long as wide, with three pairs of setae. One pair of sternal setae, st4 on the integument and st5 situated on the genital shield. Peritreme extends to the level of j1. Ventrianal shield vase-shaped, wider towards the anus. Ventrianal shield with three pairs of preanal setae, Jv1, Jv2, Zv2, anal setae and one pair of pores.

Gnathosoma: Chelicera with 14-15 teeth on the fixed digit and 4-5 teeth on the movable digit. The cervix of the spermatheca is funnel-shaped.

Legs: Macrosetae setaceous and seen on all the segments; SgeI, SgeII, SgeIII, SgeIV on the genu of legs I-IV; Sti III and Sti IV on tibia I & IV and StiIV on tarsus IV. Chaetotaxy of genu II: 2, 2/0, 2/0, 1 and genu III: 1, 2/1, 2/1, 1.

Male: Not recovered during sampling.

Materials examined: The adults of *B. tabaci* collected from Borakhadi (21°08'40" N 73°20'15" E) in Dist. Tapi.

Remarks: The specimens examined closely resemble *A. vasiformis* in all diagnostic characters (Moraes and Mesa, 1991). This is the first record of the species in association with *B. tabaci* infesting chilli in Gujarat.

3.1.4 Amblyseius multidentatus *Chant, 1959*

Colour: Transparent white

Measurements: Length: 350-380 µm; Width: 220-250 µm

Description

Adult Female:

Dorsum: Dorsal shield smooth and lightly sclerotized, bearing 17 pairs of dorsal setae. All dorsal setae smooth and pointed. Setae j1, j3, s4, Z4 and Z5 are longer than the remaining dorsal setae, with Z5 the longest and slightly whip-like. Sublateral setae r3 and R1 are present on the lateral integument. Dorsal shield oval and well-developed.

Venter: Sternal shield smooth, with three pairs of sternal setae (st1-st3). Seta st4 is located on the integument and st5 on the genital shield. Ventrianal shield longer than wide and bearing three pairs of preanal setae (Jv1, Jv2 and Zv2). Peritreme extending anteriorly to the level of j1. Spermatheca with a tubular cervix and distinct atrium.

Gnathosoma: Fixed digit of chelicera multidentate, bearing several teeth. Movable digit with three to four teeth. Palps well developed and typical of the genus.

Legs: Leg IV with distinct macrosetae on genu, tibia and basitarsus. Leg chaetotaxy conforms to that typical of *Amblyseius* species. Legs slender and adapted for rapid movement.

Male: Similar to female in dorsal chaetotaxy. Ventral surface with sternogenital shield bearing five pairs of setae.

Materials examined: The adults of *A. barodensis* infesting sugarcane collected from Bedchit (21°04'55" N 73°22'10" E) in Dist. Tapi.

Remarks: The specimens examined closely resemble *A. multidentatus* in all important diagnostic characters, including dorsal chaetotaxy, spermathecal structure and cheliceral dentition. The species is recognized as an important predatory mite associated with various phytophagous mites and small insect pests.

3.1.5 *Amblyseius sacchari* Berlese, 1914

Colour: Transparent white

Measurements: Length: 330-360 µm; Width: 210-240 µm

Description

Adult Female:

Dorsum: Dorsal shield smooth, oval and moderately sclerotized. Shield bearing 17 pairs of dorsal setae. Dorsal setae smooth and pointed. Setae j1, j3, s4, Z4 and Z5 are distinctly longer than the remaining dorsal setae. Seta Z5 longest among all dorsal setae. Sublateral setae r3 and R1 are present on the lateral integument.

Venter: Sternal shield with three pairs of sternal setae (st1-st3). Seta st4 is situated on the integument and seta st5 is located on the genital shield. Ventrianal shield elongate, with three pairs of preanal setae (Jv1, Jv2 and Zv2). Peritreme extending anteriorly to the level of j1. Metapodal plates distinct. Spermatheca with a tubular cervix and clearly differentiated atrium.

Gnathosoma: Fixed digit of chelicera with several teeth, movable digit bearing two to three teeth. Palpal structures are well-developed and characteristic of the genus.

Legs: Macrosetae present on genu, tibia and basitarsus of leg IV. Leg chaetotaxy typical of the genus *Amblyseius*. Legs slender and well adapted for predatory activity.

Male: Similar to female but comparatively smaller. Ventral region with fused sternogenital shield bearing five pairs of setae.

Materials examined: The adults of *A. barodensis* infesting sugarcane collected from Bedchit (21°04'55" N 73°22'10" E) Dist.: Tapi.

Remarks: The specimens examined agree well with the original description of *A. sacchari*. Diagnostic features such as dorsal chaetotaxy, ventrianal shield structure, spermathecal morphology and cheliceral dentition correspond closely with descriptions. The species is commonly encountered as a predatory mite in agricultural ecosystems.

3.1.6 Amblyseius gossypii *Berlese, 1914*

Colour: Transparent white

Measurements: Length: 340-370 µm; Width: 220-245 µm

Description

Adult Female:

Dorsum: Dorsal shield smooth, oval and moderately sclerotized. Shield bearing 17 pairs of dorsal setae. All dorsal setae smooth and pointed. Setae j1, j3, s4, Z4 and Z5 are comparatively longer than the remaining dorsal setae, with Z5 the longest. Sublateral setae r3 and R1 are present on the lateral integument. Dorsal shield without conspicuous ornamentation.

Venter: Sternal shield smooth with three pairs of sternal setae (st1-st3). Seta st4 is situated on the integument, whereas st5 is located on the genital shield. Ventrianal shield longer than wide and bearing three pairs of preanal setae (Jv1, Jv2 and Zv2). Peritreme extending anteriorly to the level of j1. Metapodal plates distinct. Spermatheca with an elongate tubular cervix.

Gnathosoma: Fixed digit of chelicera with several teeth, movable digit with three teeth. Palps well developed and typical of the genus. Pilus dentilis distinct.

Legs: Leg IV with well-developed macrosetae on genu, tibia and basitarsus. Legs slender and adapted for predatory activity. Chaetotaxy conforms to the generic pattern of *Amblyseius*.

Male: Similar to female in dorsal chaetotaxy but comparatively smaller. Ventral surface with sternogenital shield bearing five pairs of setae.

Materials examined: The adults of *B. tabaci* collected from Borakhadi (21°08'40" N 73°20'15" E) in Dist. Tapi.

Remarks: The specimens examined agree closely with the original description of *A. gossypii*. Diagnostic characters, including dorsal chaetotaxy, ventrianal shield structure, spermathecal morphology and cheliceral dentition, correspond with published descriptions. The species is recognized as a predatory mite commonly associated with crops.

3.1.7 *Amblyseius herbicolus* Chant, 1959

Colour: Transparent white

Measurements: Length: 350-390 µm; Width: 225-260 µm

Description

Adult Female:

Dorsum: Dorsal shield smooth and lightly sclerotized, bearing 17 pairs of dorsal setae. Dorsal setae are smooth, slender and pointed. Setae j1, j3, s4, Z4 and Z5 are distinctly longer than other dorsal setae. Seta Z5 longest and slightly whip-like. Sublateral setae r3 and R1 are present on the lateral integument. Setal pattern 10A:9B.

Venter: Sternal shield slightly longer than broad and bearing three pairs of sternal setae. Seta st4 is present on the integument and st5 is situated on the genital shield. Ventrianal shield elongate with three pairs of preanal setae (Jv1, Jv2 and Zv2). Peritreme extending anteriorly to the level of j1. Spermatheca with an elongate tubular cervix and a distinct atrium.

Gnathosoma: Fixed digit of chelicera multidentate with several teeth. Movable digit bearing three teeth. Palps well developed. Pilus dentilis distinct.

Legs: Macrosetae present on genu, tibia and basitarsus of leg IV. Legs slender and well-adapted for rapid movement and predatory behaviour. Chaetotaxy typical of the genus.

Male: Similar to female but smaller. Ventral surface with fused sternogenital shield and five pairs of sternal setae.

Materials examined: The adults of *B. tabaci* collected from Borakhadi (21°08'40" N 73°20'15" E) in Dist. Tapi.

Remarks: The present specimens agree closely with the original description of *A. herbicolus* provided by Chant and McMurtry (2007). Diagnostic characters such as dorsal chaetotaxy, spermathecal morphology, ventrianal shield and cheliceral dentition were consistent with published descriptions. The species is recognized as an important predator of whiteflies, thrips and phytophagous mites and therefore may contribute to the natural biological control of *B. tabaci* in chilli ecosystems.

3.1.8 Amblyseius longispinosus *Evans, 1952*

Colour: Transparent white

Measurements: Length: 360-420 µm; Width: 230-270 µm

Description

Adult Female:

Dorsum: Dorsal shield smooth, oval and lightly sclerotized. Shield bearing 17 pairs of dorsal setae. Dorsal setae smooth and pointed. Setae j1, j3, s4, Z4 and Z5 are conspicuously longer than the remaining dorsal setae. Setae Z4 and Z5 are especially elongated, giving the species its characteristic appearance. Sublateral setae r3 and R1 are present on the lateral integument. Setal pattern 10A:9B.

Venter: Sternal shield smooth with three pairs of sternal setae (st1-st3). Seta st4 is located on the integument, whereas st5 is situated on the genital shield. Ventrianal shield elongate and bearing three pairs of preanal setae (Jv1, Jv2 and Zv2). Peritreme extending anteriorly to the level of j1. Spermatheca with elongate tubular cervix and a differentiated atrium.

Gnathosoma: Fixed digit of chelicera multidentate with several teeth. Movable digit bearing three teeth. Palps well developed and typical of the genus. Pilus dentilis distinct.

Legs: Leg IV with conspicuous macrosetae on genu, tibia and basitarsus. Macrosetae long and slender. Legs adapted for active predation. Leg chaetotaxy conforms to the generic pattern of *Amblyseius*.

Male: Similar to female in general appearance but smaller. Ventral region with sternogenital shield bearing five pairs of setae.

Materials examined: The adults of *Aleurothrixus floccosus* collected from Kandolpada (21°09'15"N 73°28'30" E) in Dist. Tapi.

Remarks: The specimens examined closely resemble *A. longispinosus* in all important morphological characters. The species can be readily distinguished by the presence of long dorsal setae, particularly Z4 and Z5 and by the structure of the spermatheca and ventrianal shield. It is a widely distributed predatory mite and an important natural enemy of phytophagous mites and small insect pests.

TABLE 1
PHYTOSEIID PREDATORS ASSOCIATED WITH INSECTS OF AGRICULTURAL IMPORTANCE

S. No.	Predatory Mite Species	Host Insect Species	Primary Crop Ecosystem	Preferred Body Region	Nature of Interaction
1	*Amblyseius channabasavannai*	*Bemisia tabaci*	Chilli / Vegetables	Entire body surface	Active predatory
2	*Amblyseius largoensis*	*Bemisia tabaci*	Horticultural flora	Entire body surface	Active predatory
3	*Amblyseius vasiformis*	*Bemisia tabaci*	Chilli / Vegetables	Entire body surface	Active predatory
4	*Amblyseius multidentatus*	*Aleurolobus barodensis*	Sugarcane fields	Entire body surface	Active predatory
5	*Amblyseius sacchari*	*Aleurolobus barodensis*	Sugarcane fields	Entire body surface	Active predatory
6	*Amblyseius gossypii*	*Bemisia tabaci*	Chilli / Vegetables	Entire body surface	Active predatory
7	*Amblyseius herbicolus*	*Bemisia tabaci*	Chilli / Vegetables	Entire body surface	Active predatory
8	*Amblyseius longispinosus*	*Aleurothrixus floccosus*	Citrus / Guava / Fruit trees	Entire body surface	Active predatory

IV. CONCLUSION

Eight distinct predatory species within the genus *Amblyseius* (*A. channabasavannai*, *A. largoensis*, *A. vasiformis*, *A. multidentatus*, *A. sacchari*, *A. gossypii*, *A. herbicolus*, and *A. longispinosus*) were identified and taxonomically characterized. These predatory mites demonstrate strong host preferences for economically damaging whitefly species, including *Bemisia tabaci*, *Aleurolobus barodensis* and *Aleurothrixus floccosus*, across diverse cropping systems. The findings establish a critical taxonomic and ecological baseline for integrating these native phytoseiid predators into Integrated Pest Management (IPM) frameworks in South Gujarat. Future research should focus on evaluating the predatory efficiency, mass-rearing potential, and field efficacy of these species for biological control of whiteflies and other soft-bodied pests.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Berlese, A. (1914). Acari nuovi. *Redia*, *10*, 113-150.
[2] Chant, D. A., & McMurtry, J. A. (2007). *Illustrated keys and diagnoses for the genera and subgenera of the Phytoseiidae of the world (Acari: Mesostigmata)*. Indira Publishing House.
[3] El-Badry, E. A. (1967). Three new species of phytoseiid mites preying on the cotton whitefly, *Bemisia tabaci* in the Sudan (Acarina, Phytoseiidae). *The Entomologist*, *100*, 106-111.
[4] Krantz, G. W., & Walter, D. E. (2009). *A manual of acarology* (3rd ed.). Texas Tech University Press.
[5] McMurtry, J. A., De Moraes, G. J., & Sourassou, N. F. (2013). Revision of the lifestyles of phytoseiid mites (Acari: Phytoseiidae) and implications for biological control strategies. *Systematic and Applied Acarology*, *18*(4), 297-320.
[6] Moraes, G. J., & Mesa, N. C. (1991). Mites of the family Phytoseiidae of Colombia, with descriptions of three new species. *International Journal of Acarology*, *17*(2), 117-131.
[7] Nomikou, M., Janssen, A., Schraag, R., & Sabelis, M. W. (2001). Phytoseiid predators as potential biological control agents for *Bemisia tabaci*. *Experimental and Applied Acarology*, *25*, 271-291.

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Milling and Aromatic Quality Traits of Rice (*Oryza sativa* L.) Landraces of Nepal

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Abstract— *Milling and aromatic quality are two of the most economically important post-harvest attributes that determine the market value and consumer acceptance of rice (*Oryza sativa *L.). This study evaluated six milling quality traits and grain aroma in 30 rice landraces along with 3 released check varieties of Nepal. Milling quality was assessed in a completely randomized design (CRD) with three replications following the IRRI Rice Knowledge Bank protocol, while grain aroma was scored using the standard 1.7% KOH sensory method on a 1-4 intensity scale by a panel of evaluators. Analysis of variance revealed significant genotypic differences for all studied milling quality traits. Head rice recovery, the most economically valuable milling trait, ranged from 50.07% (Ramkumar-3) to 75.05% (NGRC02829), with NGRC02829 emerging as the best milling-quality genotype. The KOH aroma test classified the 33 genotypes into four groups: 8 non-aromatic, 21 slightly aromatic, 3 moderately aromatic, and 1 strongly aromatic (Kalo Nuniya, mean score 3.50 ± 0.84), a genotype independently documented as an aromatic Nepalese landrace. A Kruskal-Wallis test confirmed significant genotypic variation in aroma intensity ($H = 66.84$, $df = 32$, $p < 0.001$), corroborated by a complementary one-way ANOVA ($F = 3.10$, $p < 0.001$), although inter-panelist agreement was low (Fleiss' $\kappa = 0.05$), reflecting the well-documented subjectivity of sensory-based aroma scoring. Hierarchical cluster analysis based on the combined milling and aroma trait profile grouped the genotypes into four clusters, separating a superior-milling cluster (headed by NGRC02829) from a poor-milling cluster, and showed that the strongly aromatic landrace Kalo Nuniya did not belong to the best-milling group. Overall, the study identifies landraces with superior milling recovery and distinct aroma expression that represent valuable breeding material for improving the grain quality of Nepalese rice.*

Keywords— Nepalese Rice landraces, Milling quality, Head rice recovery, Grain aroma, KOH test.

I. INTRODUCTION

Rice (*Oryza sativa* L.) is the staple food crop of Nepal, meeting approximately half of the population's daily caloric requirement and occupying a central place in the country's agricultural economy [1], [2]. Nepal is regarded as one of the centers of rice diversity, harboring thousands of indigenous landraces that have evolved under diverse agro-ecological conditions ranging from the lowland Terai to the high-altitude Himalayan valleys [3], [4]. Beyond their adaptive value, these landraces harbor considerable variation in grain quality attributes such as aroma, cooking behavior, texture, and milling characteristics that are increasingly valued by both producers and consumers [5], [6].

Rice quality is a multifaceted trait combining subjective and objective components, of which grain length, breadth, length-breadth ratio, milling recovery, and aroma are among the key physical and sensory parameters that determine market value and consumer preference [7]. Milling quality specifically reflects the ability of the grain to withstand the de-husking and polishing processes without excessive breakage, and is commercially expressed through brown rice recovery, milling recovery, head rice recovery, broken rice percentage, and dockage percentage [8]. Head rice recovery is considered the single most economically important milling trait because intact, unbroken kernels command a substantially higher market price than broken rice [9].

Aroma is likewise a premium grain-quality trait; aromatic rice types such as Basmati and Jasmine command a considerable price premium in both domestic and export markets [10]. Grain aroma in rice is primarily governed by 2-acetyl-1-pyrroline (2-AP), and the loss-of-function *badh2* allele responsible for its accumulation segregates widely among South Asian landraces. Although gas chromatography and molecular markers allow precise aroma quantification, the alkaline (KOH) sensory test remains the most widely used, low-cost, and rapid screening method for aroma detection in breeding programs and germplasm surveys [11].

Despite the wide genetic base of Nepalese rice landraces, scientific information on their milling and aromatic quality remains scarce, which limits their utilization in quality-oriented breeding programs [6], [12]. With Nepal importing substantial quantities of fine and aromatic rice every year, characterizing local landraces for milling and aroma quality is essential to identify superior genetic resources for varietal improvement and import substitution. The present study was therefore undertaken with the objective of evaluating the milling quality traits and grain aroma of 30 Nepalese rice landraces along with 3 released check varieties, in order to identify genotypes of superior milling and aromatic quality that could serve as valuable parental material in future rice breeding programs.

II. MATERIALS AND METHODS

2.1 Plant Materials

Thirty rice landraces along with three released check varieties (Bahuguni Dhan-2, Hardinath-3, and Radha-11) were used in this study (Table 1). The landraces were procured from the National Agriculture Genetic Resources Centre (NAGRC), Khumaltar, Lalitpur, Nepal, through the Department of Genetics and Plant Breeding, Faculty of Agriculture, Agriculture and Forestry University (AFU), Rampur, Chitwan.

TABLE 1
LIST OF THE THIRTY-THREE RICE GENOTYPES USED TO EVALUATE MILLING AND AROMATIC QUALITY TRAITS

S. No.	Genotype	Local Name		S. No.	Genotype	Local Name
1	G-01	Dadharaj Dhan		18	G-18	NGRC05707
2	G-02	NGRC02116		19	G-19	Vutte Dhan
3	G-03	Niranjan Dhan		20	G-20	Seto Guriya Dhan
4	G-04	NGRC02829		21	G-21	Kuthe Dhan
5	G-05	NGRC02851		22	G-22	NGRC01968
6	G-06	NGRC02864		23	G-23	Belkhole Dhan
7	G-07	Lathi Saro Dhan		24	G-24	NGRC01942
8	G-08	NGRC02874		25	G-25	Arbais Dhan
9	G-09	Simtari Dhan		26	G-26	Sano Damauli
10	G-10	Nirwan Dhan		27	G-27	NGRC02057
11	G-11	Lahare Dhan		28	G-28	Ramkumar-2
12	G-12	Madhesi Dhan		29	G-29	Ramkumar-3
13	G-13	Shyam Zeera Dhan		30	G-30	Kalo Nuniya
14	G-14	NGRC02920		31	G-31	Bahuguni Dhan-2
15	G-15	Manamausi		32	G-32	Hardinath-3
16	G-16	Thankote Dhan		33	G-33	Radha-11
17	G-17	NGRC05706				

2.2 Experimental Site and Design

The milling quality experiment was conducted at the Department of Genetics and Plant Breeding, AFU, Rampur, Chitwan (27°38'39.0"N, 84°21'03.5"E; altitude 229.2 m asl) between January and February 2024. The experiment was laid out in a completely randomized design (CRD) with 33 genotypes and three replications. For each genotype, paddy was dried to below 13% moisture content, verified using a digital moisture meter, and a 50 g sample was used for milling quality assessment [13].

2.3 Milling Quality Assessment

Milling quality traits were evaluated following the IRRI Rice Knowledge Bank factsheet protocol. Paddy samples were dehulled using a laboratory huller to obtain brown rice, which was then milled using an abrasive/frictional mill to obtain milled (polished) rice. The following traits were recorded:

Brown rice recovery (%) = (weight of brown rice / weight of paddy sample) × 100

Milling recovery (%) = (weight of milled rice / weight of paddy sample) × 100

Head rice recovery (%) = (weight of head rice / weight of paddy sample) × 100, where head rice is milled rice with grain length ≥ three-quarters of the whole grain length [8]

Broken rice (%) = (weight of broken rice / weight of paddy sample) × 100, broken rice being milled kernels shorter than three-quarters of the whole grain

Dockage in milled rice (%) = (weight of dockage / weight of milled rice) × 100, dockage referring to foreign matter such as straw, stones or unhulled grains

Grain length-width ratio (LWR) = length of grain / width of grain. Genotypes were classified as slender (LWR > 3.0), medium (2.1-3.0), bold (1.1-2.0), or round (< 1.0) following the IRRI Rice Knowledge Bank classification.

2.4 Grain Aromatic Test

Grain aroma was evaluated using the alkaline potassium hydroxide (KOH) sensory test by a six-member sensory panel comprising alumni of the Department of Genetics and Plant Breeding, Agriculture and Forestry University, all of whom had conducted research in rice breeding. Forty grains of each genotype were soaked in 10 mL of 1.7% KOH solution at room temperature in a covered glass Petri plate for about one hour. Samples were scored on a 1-4 intensity scale, where 1, 2, 3, and 4 corresponded to absence of aroma, slight aroma, moderate aroma, and strong aroma, respectively. A panel of evaluators independently scored the aroma of each genotype, following the methodology of Golam et al. [10].

2.5 Statistical Analysis

For milling quality traits, analysis of variance (ANOVA) was performed on the CRD model $y_i = \mu + g_i + e_i$, where μ is the general mean, g_i is the effect of the ith genotype, and e_i is the random error, using the F-test; genotype means were compared using the least significant difference (LSD) test at 5% probability [14]. All analyses were performed in R Studio (R version 4.4.0) using the 'agricolae' package.

For the aroma-scoring data, genotypes were first summarized by their mean panel score, standard deviation, and modal score across evaluators, and classified into non-aromatic, slightly aromatic, moderately aromatic, or strongly aromatic categories based on the rounded mean score. Because the KOH test produces ordinal categorical scores, differences in aroma intensity among the 33 genotypes were primarily tested using the non-parametric Kruskal-Wallis test, appropriate for ordinal data with unequal within-group variances. As a complementary check, and to remain consistent with the CRD-based ANOVA framework used for milling traits, a parametric one-way analysis of variance was also performed on the aroma scores (treating the panel of evaluators as replications). Inter-panelist agreement was assessed using Fleiss' kappa (κ) for multiple raters scoring a categorical (four-level) variable.

To characterize the overall quality profile of the genotypes, an agglomerative hierarchical cluster analysis was additionally performed using the six milling quality traits together with the mean aroma score as clustering variables. All seven variables were standardized (z-score) prior to clustering to remove scale effects, and genotypes were grouped using Ward's minimum-variance linkage method on standardized Euclidean distances. The resulting dendrogram was cut to obtain four genotype clusters, and cluster mean trait profiles were compared descriptively. This multivariate grouping of genotypes based on their combined trait profile is distinct from a correlation or association analysis; as per the objectives of this study, no pairwise correlation was computed between milling and aromatic quality traits. All statistical computations for the aroma and cluster analyses were carried out in Python (SciPy, pandas, scikit-learn).

III. RESULTS

3.1 Milling Quality Traits

Analysis of variance revealed significant genotypic variation for five of the six milling quality traits studied (Table 2). Highly significant ($p < 0.001$) differences among genotypes were observed for head rice recovery, broken rice percentage, dockage percentage, and grain length-width ratio, while milling recovery percentage differed significantly at $p < 0.05$. Brown rice recovery percentage did not differ significantly among genotypes at the tested probability level, although appreciable numerical variation was observed (Table 3).

TABLE 2
MEAN SUM OF SQUARES FROM ANALYSIS OF VARIANCE FOR MILLING QUALITY TRAITS OF 33 RICE GENOTYPES

Trait	Treatment MS (df = 32)	Error MS (df = 66)	Significance
Brown rice recovery (%)	9515	6.073	ns
Milling recovery (%)	10.27	5.78	*
Head rice recovery (%)	150.86	4.59	***
Broken rice (%)	39.7	7.4	***
Dockage in milled rice (%)	0.58	0.008	***
Grain length-width ratio	0.2	0.02	***

ns = non-significant; * significant at $p < 0.05$; *** significant at $p < 0.001$

Brown rice recovery percentage, reflecting the efficiency of de-husking, ranged from 77.81% (Radha-11) to 86.17% (Nirwan Dhan), with a grand mean of 83.22%; Nirwan Dhan, Simtari Dhan, and NGRC05706 recorded the highest values (Table 3). Milling recovery percentage, indicating the overall yield of milled rice from paddy, varied from 71.67% (Radha-11) to 79.26% (Bahuguni Dhan-2 and Hardinath-3), averaging 76.47%.

Head rice recovery percentage, the most economically valuable milling trait, ranged widely from 50.07% in Ramkumar-3 to 75.05% in NGRC02829, with an overall mean of 65.54% (Figure 2). NGRC02829, Bahuguni Dhan-2, and NGRC02874 were the top-performing genotypes, whereas Ramkumar-3, Vutte Dhan, and Dadharaj Dhan showed the lowest head rice recovery, indicating greater kernel fragility during milling in these genotypes. Correspondingly, broken rice percentage was lowest in Bahuguni Dhan-2 (5.23%) and highest in Arbais Dhan (17.05%) and Ramkumar-3 (16.82%), reflecting an inverse relationship in genotype ranking between the two traits. Dockage percentage in milled rice, an indicator of post-milling cleanliness, ranged from 0.66% (Simtari Dhan) to 2.36% (Lathi Saro Dhan), while the grain length-width ratio ranged from 2.91 (Kuthe Dhan) to 3.93 (Hardinath-3). Based on this ratio, 29 of the 33 genotypes (87.9%) were classified as slender-grained, while the remaining four (NGRC02851, Nirwan Dhan, Kuthe Dhan, and Arbais Dhan) were classified as medium-grained (Figure 3; Table 3), indicating a strong predominance of slender grain shape among the studied Nepalese landraces.

TABLE 3
MEAN PERFORMANCE OF 33 RICE GENOTYPES FOR MILLING QUALITY TRAITS

Code	Genotype	BRR (%)	MR (%)	HRR (%)	BRK (%)	DM (%)	LWR	Grain shape
G1	Dadharaj Dhan	81.74	74.77	53.31	15.73	1.59	3.36	Slender
G2	NGRC02116	83.71	78.18	73.35	6.94	1.67	3.5	Slender
G3	Niranjan Dhan	80.86	75.39	63.06	10.92	1.64	3.29	Slender
G4	NGRC02829	84.41	78.31	75.05	5.86	1.55	3.24	Slender
G5	NGRC02851	80.51	74.48	67.91	7.02	1.5	2.96	Medium
G6	NGRC02864	83.85	76.67	58.97	16.45	1.44	3.34	Slender
G7	Lathi Saro Dhan	81.06	75.54	54.47	15.48	2.36	3.09	Slender
G8	NGRC02874	83.23	78.41	74.68	6.26	1.84	3.26	Slender
G9	Simtari Dhan	85.67	79.21	69.8	10	0.66	3.33	Slender
G10	Nirwan Dhan	86.17	77.56	64.09	12.67	0.93	2.98	Medium
G11	Lahare Dhan	81.33	74.55	63.66	11.03	1.21	3.38	Slender
G12	Madhesi Dhan	85.05	75.97	64.33	11.02	1.18	3.46	Slender
G13	Shyam Zeera Dhan	81.02	74.53	67.4	9.27	1.51	3.35	Slender
G14	NGRC02920	84.37	75.55	70.09	10.33	1.74	3.31	Slender
G15	Manamausi	84.75	76.85	70.11	7.39	1.56	3.26	Slender
G16	Thankote Dhan	84.04	77.29	74	7.21	0.72	3.21	Slender
G17	NGRC05706	85.65	78.61	71.07	7.2	2.29	3.65	Slender
G18	NGRC05707	84.03	77.88	68.83	10.56	1.64	3.53	Slender
G19	Vutte Dhan	84.84	72.79	52.71	16.39	1.33	3.2	Slender
G20	Seto Guriya Dhan	83.15	75.81	67.23	9	1.04	3.28	Slender
G21	Kuthe Dhan	83.44	77.32	62.89	12.13	1.15	2.91	Medium
G22	NGRC01968	83.49	75.25	67.31	8.92	0.93	3.36	Slender
G23	Belkhole Dhan	82.26	77.01	68.81	7.34	1.41	3.56	Slender
G24	NGRC01942	83.39	75.47	58.23	15.8	1.48	3.35	Slender
G25	Arbais Dhan	83.06	77.07	53.41	17.05	1.08	2.93	Medium
G26	Sano Damauli	85.29	78.71	65.83	11.56	1.42	3.38	Slender
G27	NGRC02057	82.59	75.61	59.13	14.43	2.08	3.32	Slender
G28	Ramkumar-2	83.01	76.92	73.14	8.84	2.1	3.4	Slender
G29	Ramkumar-3	83.04	76.85	50.07	16.82	1.67	3.54	Slender
G30	Kalo Nuniya	81.67	74.67	69.74	6.69	2.21	3.54	Slender
G31	Bahuguni Dhan-2	83.27	79.26	74.69	5.23	2.32	3.49	Slender
G32	Hardinath-3	84.66	79.26	71.33	7.58	1.37	3.93	Slender
G33	Radha-11	77.81	71.67	64.28	10.47	1.48	3.12	Slender
	SEm±	1.42	1.39	1.24	1.57	0.05	0.08	
	CV (%)	3.11	3.14	3.27	25.68	6.04	4.22	
	LSD (0.05)	4.22	3.92	3.49	4.43	0.15	0.23	
	Grand mean	83.22	76.47	65.54	10.59	1.52	3.33	

BRR = brown rice recovery; MR = milling recovery; HRR = head rice recovery; BRK = broken rice; DM = dockage in milled rice; LWR = grain length-width ratio; SEm = standard error of mean; CV = coefficient of variation; LSD = least significant difference

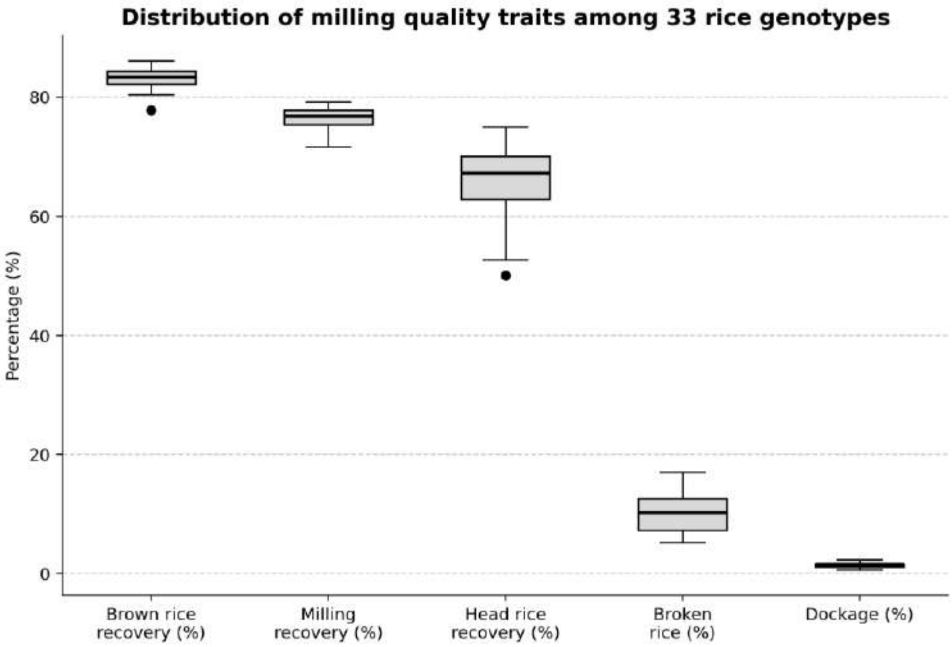

FIGURE 1: Box plots showing the distribution of genotype means for five milling quality traits among 33 rice genotypes, illustrating the relatively wider spread in broken rice and head rice recovery percentages compared to brown/milling rice recovery

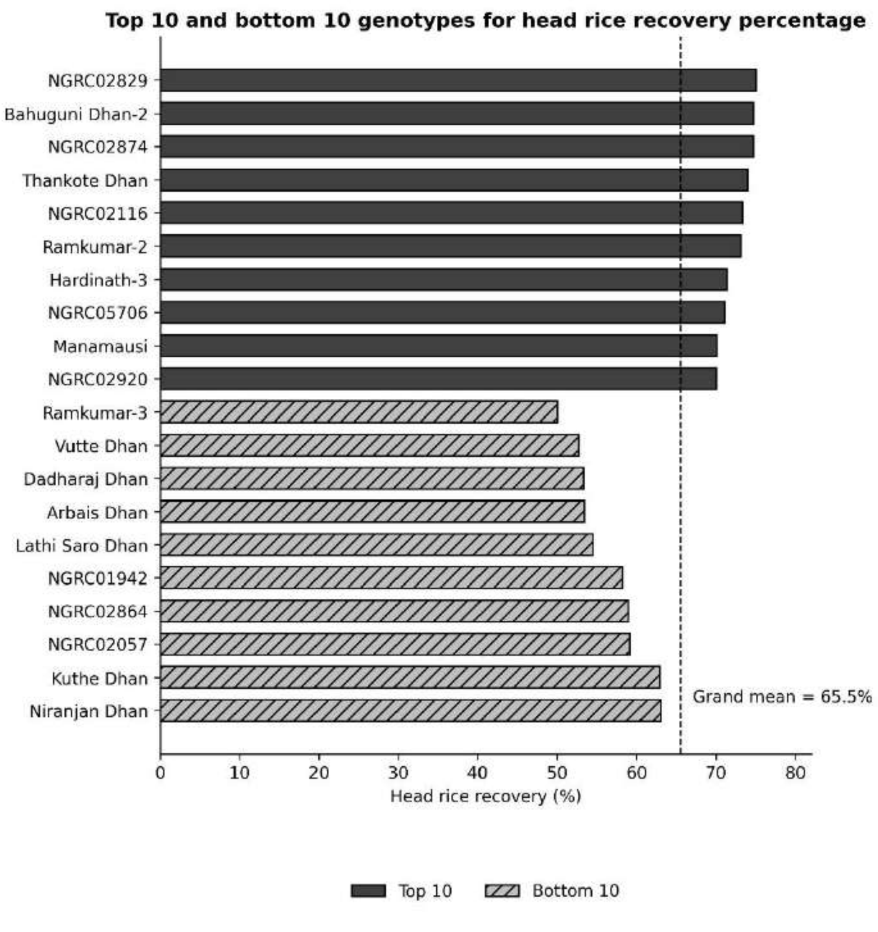

FIGURE 2: The ten highest- and ten lowest- ranked genotypes for head rice recovery percentage, relative to the grand mean (dashed line)

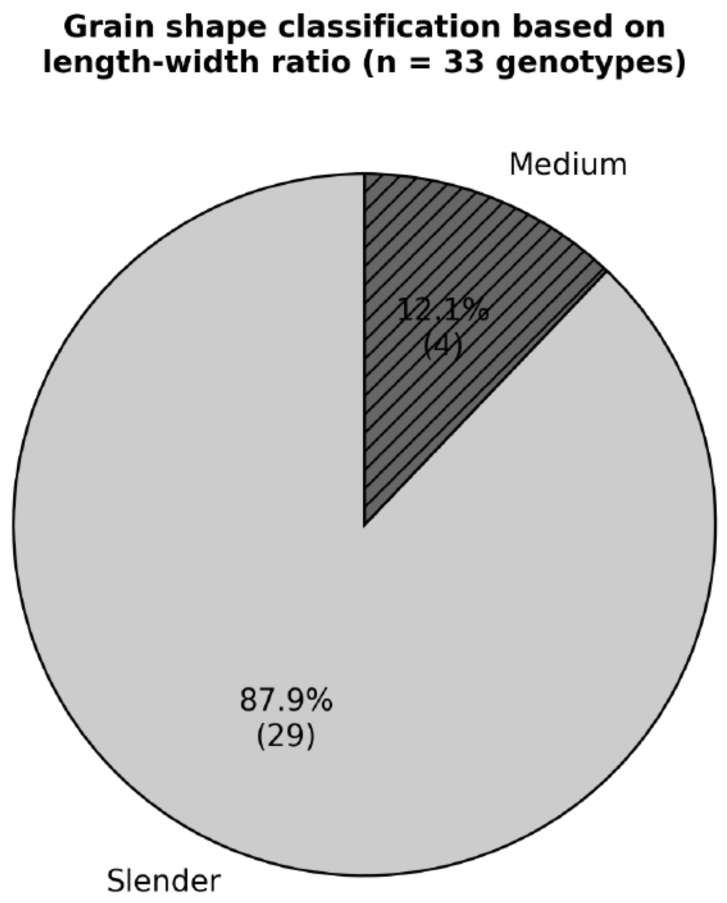

FIGURE 3: Distribution of grain shape classes among the 33 studied genotypes, based on grain length-width ratio

3.2 Grain Aromatic Quality

Aroma scores from the KOH sensory test ranged from 1 to 4 across all genotype-panelist combinations (n = 198 observations). Overall, 40.4% of individual scores indicated absence of aroma (score 1), 33.3% indicated slight aroma (score 2), 19.2% indicated moderate aroma (score 3), and 7.1% indicated strong aroma (score 4). Based on the mean panel score per genotype, the 33 genotypes were classified into four aroma categories (Table 4, Figure 4): 8 genotypes (24.2%) were non-aromatic (Dadharaj Dhan, NGRC02874, Simtari Dhan, Shyam Zeera Dhan, Belkhole Dhan, NGRC02057, Bahuguni Dhan-2, and Radha-11); 21 genotypes (63.6%) were slightly aromatic; 3 genotypes (9.1%), NGRC02864, Sano Damauli, and Ramkumar-3 were moderately aromatic; and a single genotype, Kalo Nuniya, was classified as strongly aromatic with the highest mean score of 3.50 ± 0.84 among all genotypes evaluated.

A Kruskal-Wallis test comparing aroma scores across the 33 genotypes (6 evaluations per genotype) revealed highly significant differences in aroma intensity among genotypes ($H = 66.84$, $df = 32$, $p < 0.001$), confirming substantial genetic variability for this trait in the studied germplasm. The complementary one-way ANOVA, performed by treating the panel of evaluators as replications, corroborated this result (Table 6): the genotype mean square (2.03) was significantly larger than the error mean square (0.65), giving $F = 3.10$ ($p < 0.001$). The low inter-panelist agreement (Fleiss' $\kappa = 0.05$) indicated only slight consistency in the categorical scores assigned by different evaluators to the same genotype—a pattern consistent with the inherent subjectivity of olfactory sensory evaluation reported in previous KOH-based aroma studies.

TABLE 4
MEAN, STANDARD DEVIATION (SD), AND MODAL AROMA SCORE (1-4 SCALE, KOH TEST) OF 33 RICE GENOTYPES SCORED BY A PANEL OF EVALUATORS, AND THEIR RESULTING AROMA CLASSIFICATION

Code	Genotype	Mean score	SD	Modal score	Aroma class
G1	Dadharaj Dhan	1.17	0.41	1	Non-aromatic
G2	NGRC02116	2.5	1.22	3	Slightly aromatic
G3	Niranjan Dhan	2.5	1.05	3	Slightly aromatic
G4	NGRC02829	1.67	0.52	2	Slightly aromatic
G5	NGRC02851	1.83	0.98	1	Slightly aromatic
G6	NGRC02864	2.67	1.21	2	Moderately aromatic
G7	Lathi Saro Dhan	2.33	1.21	1	Slightly aromatic
G8	NGRC02874	1.33	0.52	1	Non-aromatic
G9	Simtari Dhan	1.33	0.52	1	Non-aromatic
G10	Nirwan Dhan	2.33	0.82	3	Slightly aromatic
G11	Lahare Dhan	2	0.89	2	Slightly aromatic
G12	Madhesi Dhan	1.83	0.75	2	Slightly aromatic
G13	Shyam Zeera Dhan	1.33	0.52	1	Non-aromatic
G14	NGRC02920	2	1.26	1	Slightly aromatic
G15	Manamausi	2	0.89	3	Slightly aromatic
G16	Thankote Dhan	2	0.63	2	Slightly aromatic
G17	NGRC05706	1.67	0.82	1	Slightly aromatic
G18	NGRC05707	2	0.89	3	Slightly aromatic
G19	Vutte Dhan	2	1.26	1	Slightly aromatic
G20	Seto Guriya Dhan	1.67	0.52	2	Slightly aromatic
G21	Kuthe Dhan	2.17	0.98	3	Slightly aromatic
G22	NGRC01968	1.67	0.52	2	Slightly aromatic
G23	Belkhole Dhan	1.33	0.52	1	Non-aromatic
G24	NGRC01942	1.67	0.82	1	Slightly aromatic
G25	Arbais Dhan	2	0.63	2	Slightly aromatic
G26	Sano Damauli	3.17	0.75	3	Moderately aromatic
G27	NGRC02057	1.17	0.41	1	Non-aromatic
G28	Ramkumar-2	1.5	0.55	2	Slightly aromatic
G29	Ramkumar-3	3	0.63	3	Moderately aromatic
G30	Kalo Nuniya	3.5	0.84	4	Strongly aromatic
G31	Bahuguni Dhan-2	1.33	0.52	1	Non-aromatic
G32	Hardinath-3	1.83	0.75	2	Slightly aromatic
G33	Radha-11	1.17	0.41	1	Non-aromatic

TABLE 5
SUMMARY DISTRIBUTION OF THE 33 RICE GENOTYPES ACROSS THE FOUR AROMA CLASSES

Aroma class	No. of genotypes	% of total	Representative genotypes
Non-aromatic	8	24.2	Dadharaj Dhan, NGRC02874, Simtari Dhan, Shyam Zeera Dhan, Belkhole Dhan, NGRC02057, Bahuguni Dhan-2, Radha-11
Slightly aromatic	21	63.6	NGRC02116, Niranjan Dhan, NGRC02829, NGRC02851, Lathi Saro Dhan, Nirwan Dhan, Lahare Dhan, Madhesi Dhan, NGRC02920, Manamausi, Thankote Dhan, NGRC05706, NGRC05707, Vutte Dhan, Seto Guriya Dhan, Kuthe Dhan, NGRC01968, NGRC01942, Arbais Dhan, Ramkumar-2, Hardinath-3
Moderately aromatic	3	9.1	NGRC02864, Sano Damauli, Ramkumar-3
Strongly aromatic	1	3	Kalo Nuniya

TABLE 6
ANALYSIS OF VARIANCE OF MEAN AROMA SCORE (1-4 SCALE, KOH TEST) OF 33 RICE GENOTYPES, WITH THE PANEL OF EVALUATORS TREATED AS REPLICATIONS

Source of variation	df	SS	MS	F-value	Significance
Genotype	32	65.01	2.03	3.1	***
Error	165	108	0.65		
Total	197	173.01			

****** significant at p < 0.001****

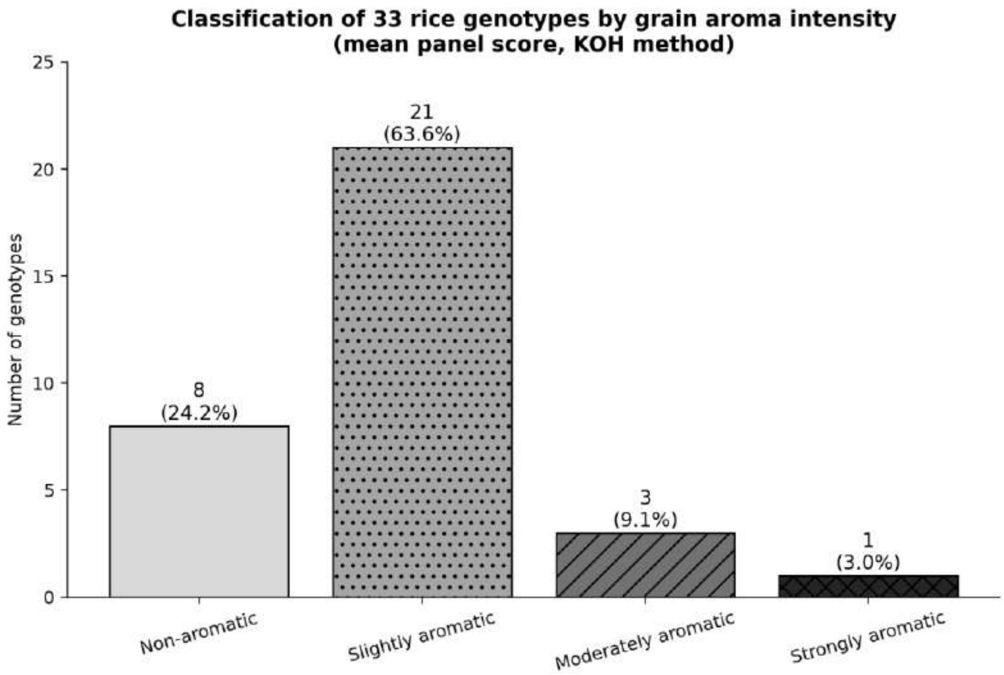

FIGURE 4: Number and percentage of rice genotypes classified into each aroma intensity category based on the mean KOH sensory panel score

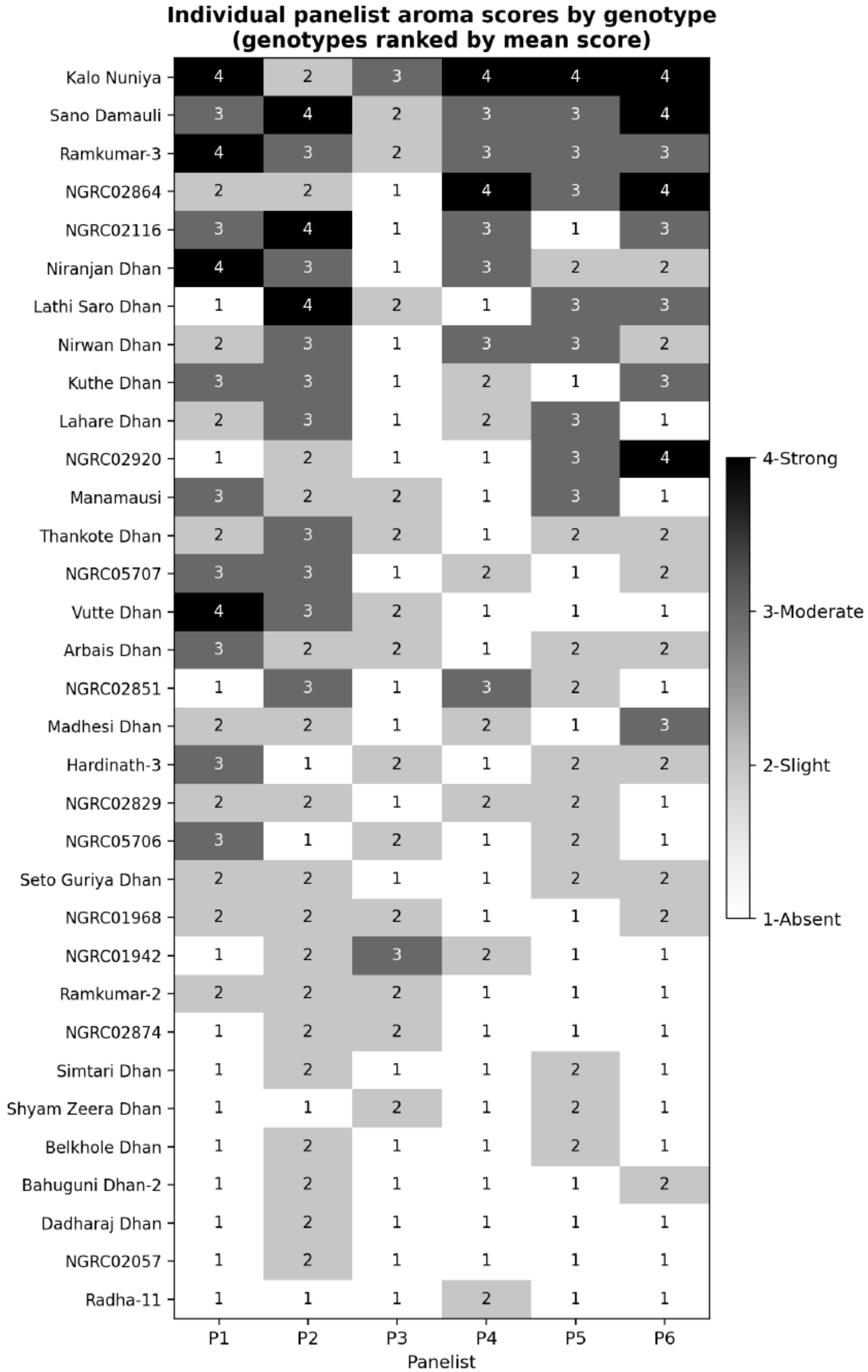

FIGURE 5: Panelist-level (P1-P6) aroma scores for each genotype, ranked from highest to lowest mean aroma score. Darker shading indicates a stronger perceived aroma

3.3 Multivariate Cluster Analysis of Quality Traits

To characterize the overall quality profile of the genotypes independent of any pairwise trait association, hierarchical cluster analysis (Ward's method, standardized Euclidean distance) was performed using all six milling quality traits together with the mean aroma score. The dendrogram (Figure 6) separated the 33 genotypes into four distinct clusters of 12, 9, 6, and 6 genotypes, respectively (Table 7).

Cluster I (n = 12), comprising NGRC02829, Bahuguni Dhan-2, NGRC02874, NGRC05706, Sano Damauli, and related genotypes, was characterized by the highest mean head rice recovery (71.42%) and milling recovery (77.91%) combined with a comparatively high mean aroma score (2.10), representing the genotypes with the best overall milling performance among the panel. Cluster II (n = 9), including Nirwan Dhan, Simtari Dhan, and NGRC02864, showed the highest brown rice recovery (84.21%) and the lowest dockage percentage (1.01%), but only moderate head rice recovery (64.67%). Cluster III (n = 6), comprising Dadharaj Dhan, Vutte Dhan, Lathi Saro Dhan, and Ramkumar-3, had the weakest milling performance, with the lowest head rice recovery (54.65%), the highest broken rice percentage (15.78%), and the lowest mean aroma score (1.58) of all clusters. Cluster IV (n = 6), which notably included the strongly aromatic landrace Kalo Nuniya along with Niranjan Dhan, Lahare Dhan, and Radha-11, was distinguished by the lowest brown rice recovery (80.53%) but an intermediate-to-high mean aroma score (1.92), indicating that some genotypes combine weaker milling strength with greater aroma expression.

This grouping illustrates that milling performance and aroma expression do not necessarily co-occur within the same genotype cluster in this germplasm set, and highlights Cluster I as the most promising group for genotypes combining strong milling recovery with detectable aroma, while confirming Kalo Nuniya (Cluster IV) as a distinct, strongly aromatic outlier despite its comparatively average milling profile.

TABLE 7
MEAN QUALITY-TRAIT PROFILE AND CONSTITUENT GENOTYPES OF THE FOUR CLUSTERS OBTAINED FROM WARD'S HIERARCHICAL CLUSTER ANALYSIS

Cluster	n	BRR (%)	MR (%)	HRR (%)	BRK (%)	DM (%)	LWR	Aroma	Constituent genotypes
I	12	84.05	77.91	71.42	7.92	1.74	3.46	2.1	NGRC02920, Manamausi, NGRC05706, NGRC05707, NGRC02116, Belkhole Dhan, Sano Damauli, Ramkumar-2, Bahuguni Dhan-2, Hardinath-3, NGRC02829, NGRC02874
II	9	84.21	76.91	64.67	11.61	1.01	3.2	1.94	Nirwan Dhan, Madhesi Dhan, Thankote Dhan, Seto Guriya Dhan, Kuthe Dhan, NGRC01968, Arbais Dhan, NGRC02864, Simtari Dhan
III	6	82.78	75.17	54.65	15.78	1.75	3.31	1.58	Dadharaj Dhan, Vutte Dhan, NGRC01942, NGRC02057, Ramkumar-3, Lathi Saro Dhan
IV	6	80.53	74.22	66.01	9.23	1.59	3.27	1.92	Lahare Dhan, Kalo Nuniya, Niranjan Dhan, Radha-11, Shyam Zeera Dhan, NGRC02851

BRR = brown rice recovery; MR = milling recovery; HRR = head rice recovery; BRK = broken rice; DM = dockage in milled rice; LWR = grain length-width ratio; Aroma = mean KOH aroma score

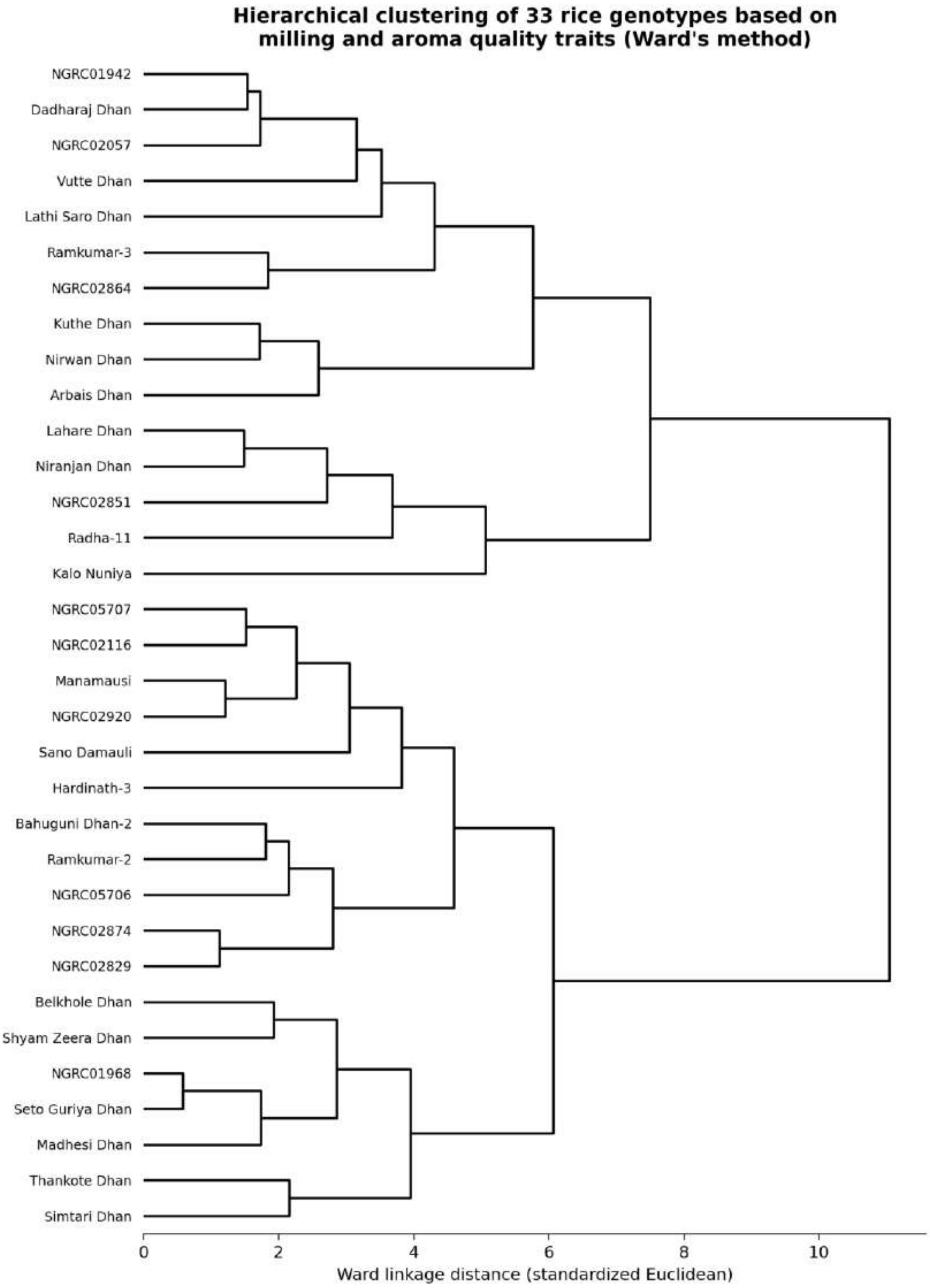

FIGURE 6: Dendrogram from Ward's hierarchical cluster analysis of 33 rice genotypes based on six milling quality traits and mean aroma score (standardized Euclidean distance)

IV. DISCUSSION

4.1 Milling Quality Traits

Milling quality traits are decisive in determining the post-harvest value and marketability of rice, with appearance-related characteristics strongly influencing consumer preference and variety adoption [15], [16]. In the present study, significant genotypic variation in milling recovery, head rice recovery, broken rice, and dockage percentage is consistent with previous reports of considerable diversity in milling characteristics among Nepalese rice landraces [6], [12].

Brown rice recovery, which reflects dehusking efficiency, was highest in Nirwan Dhan, Simtari Dhan, and NGRC05706, values comparable to the range reported for Nepalese landraces by Tiwari et al. [12]. Milling recovery, which is linked not only to yield but also to nutritional attributes such as protein, fat, and ash content that tend to decline with increasing degree of polish [17], was highest in Bahuguni Dhan-2, Hardinath-3, and Simtari Dhan. Thapa et al. [18] suggested that reducing the milling degree from 12% to 4% could increase national rice stock availability by roughly 4%, underscoring the practical relevance of milling recovery for national food security.

Head rice recovery, recognized as the single most economically important milling trait because intact kernels command higher market prices [8], [9], varied more than two-fold across genotypes (50.07-75.05%), highlighting substantial scope for improvement through selection. Landraces NGRC02829 and NGRC02874 combined high head rice recovery with low broken rice percentage, marking them as promising sources for improving grain milling strength. Conversely, Arbais Dhan and Ramkumar-3 exhibited the weakest kernels, evident from their high broken-grain percentages. The predominance of slender grain shape (87.9% of genotypes) observed in this study mirrors the general preference of Nepalese and South Asian consumers for slender, translucent grain types, and aligns with previous characterization of Nepalese landraces [16], [7].

4.2 Grain Aromatic Quality

Grain aroma is among the most prized quality attributes in rice, with aromatic types commanding substantial market premiums [10]. In this study, the KOH sensory test classified the majority of genotypes (87.8%) as either non-aromatic or only slightly aromatic, with a smaller fraction showing moderate to strong aroma expression, a pattern typical of general-purpose landrace collections in which only a minority of accessions carry aromatic quality traits. Notably, Kalo Nuniya, the sole genotype classified as strongly aromatic in this study (mean score 3.50), is independently recognized in Nepalese germplasm records as an aromatic landrace, lending external validity to the panel-based classification used here.

The significant Kruskal-Wallis result ($p < 0.001$) confirms that the studied landraces harbor genuine genetic variability for aroma intensity, consistent with aroma-screening studies conducted on aromatic rice germplasm using the same 1.7% KOH methodology in other tropical environments [10]. At the same time, the low inter-panelist agreement (Fleiss' $\kappa = 0.05$) observed here is a recognized limitation of sensory aroma scoring: aroma perception varies with individual olfactory sensitivity, panelist fatigue, and prior training, and the KOH test itself provides comparatively coarse (binary-to-ordinal) resolution relative to chromatographic quantification of 2-acetyl-1-pyrroline or gene-based markers, both of which have been recommended in combination with sensory panels to improve the reliability of aroma classification in breeding programs. Nevertheless, because of its simplicity, low cost, and reasonable correspondence with grain-tasting evaluation, the KOH test remains a practical first-pass screening tool for large germplasm collections, particularly where molecular facilities are limited, as is often the case for landrace evaluation programs in Nepal.

4.3 Genotype Grouping Based on Combined Quality Profile

The hierarchical clustering of genotypes based on their combined milling and aroma profile provides a multivariate complement to the trait-by-trait comparisons discussed above, without implying any direct statistical association between milling and aroma traits. The separation of a distinct high-milling-performance cluster (Cluster I, including NGRC02829 and Bahuguni Dhan-2) from a distinctly poor-milling cluster (Cluster III, including Ramkumar-3 and Dadharaj Dhan) mirrors the extremes already identified for head rice recovery and broken rice percentage (Table 3), lending consistency to the overall pattern of genotypic variation for milling quality. Notably, Kalo Nuniya, the only strongly aromatic genotype identified in this study, clustered together with genotypes of below-average brown rice recovery (Cluster IV) rather than with the high-milling-quality group, suggesting that, at least within this germplasm set, breeding for combined superior milling and strong aroma expression may require targeted crossing of genotypes drawn from different clusters rather than relying on genotypes that already excel in both traits simultaneously.

V. CONCLUSION

This study demonstrated significant genotypic variation in both milling quality and grain aroma among 30 Nepalese rice landraces and 3 released check varieties. NGRC02829 emerged as a superior landrace for head rice recovery and milling strength, while Nirwan Dhan and Simtari Dhan exhibited the highest brown rice recovery. The KOH aroma test identified Kalo Nuniya as a strongly aromatic landrace, along with Sano Damauli and Ramkumar-3 as moderately aromatic, representing valuable genetic resources for aromatic rice breeding in Nepal. Hierarchical cluster analysis combining all quality traits further grouped the 33 genotypes into four distinct clusters, distinguishing a superior-milling group (Cluster I) from a poor-milling group (Cluster III), and revealed that the strongly aromatic landrace Kalo Nuniya did not co-occur with the best-milling cluster, pointing to the need for targeted crossing to combine both traits.

Recommendations:

1) **For Breeding Programs:** Landraces NGRC02829 and NGRC02874 should be prioritized as parental lines for improving milling quality, while Kalo Nuniya should be used as a donor for aroma.

2) **For Conservation:** The identified superior landraces (NGRC02829, NGRC02874, Kalo Nuniya) should be conserved and multiplied for future use.

3) **For Future Research:** Molecular characterization of aroma genes (e.g., *badh2*) in Kalo Nuniya, Sano Damauli, and Ramkumar-3 is recommended to confirm the sensory aroma classification. Additionally, multi-location trials are needed to assess the stability of milling quality traits across different environments.

Together, these findings highlight promising landraces combining superior milling characteristics and distinct aroma profiles that merit further evaluation and utilization in quality-oriented rice breeding programs aimed at enhancing the competitiveness of Nepalese rice.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] Acharya, S., Ghimire, S., Thapa, R., Bhattarai, P., & Chhetri, B. P. (2024). Evaluation of spring season local and improved rice genotypes on growth, yield, and yield attributing characters in Gorkha district, Nepal. J. La Lifesci, *5*(2), 109-125.

[2] Bao, J. (2018). Rice milling quality. In Handbook of rice: Chemistry and technology (Vol. 2, 4th ed., pp. 339-369). Elsevier, in cooperation with AACC International.

[3] Chen, M. H., & Bergman, C. J. (2005). Influence of grain maturity, milling degree, and milling quality on rice bran phytochemical concentrations. Cereal Chemistry, *82*(1), 4-8.

[4] Dhungel, S., & Acharya, P. (2017). Role of rice in food and nutrition security in Nepal. In Rice science and technology in Nepal (pp. 77-85).

[5] Golam, F., Hui Yin, Y., Masitah, A., Afnierna, N., Majid, N. A., Khalid, N., & Osman, M. (2011). Analysis of aroma and yield components of aromatic rice in Malaysian tropical environment. Australian Journal of Crop Science, *5*(11), 1318-1325.

[6] Gomez, K. A., & Gomez, A. A. (1984). Statistical procedures for agricultural research. John Wiley & Sons.

[7] Hegde, S., Yenagi, N. B., & Kasturiba, B. (2013). Indigenous knowledge of the traditional and qualified ayurveda practitioners on the nutritional significance and use of red rice in medications. Indian Journal of Traditional Knowledge, *12*(3), 506-511.

[8] Joshi, B. K. (2008). Diversity based on coefficient of parentage among rice (Oryza sativa L.) cultivars for mid and high hills of Nepal. Journal of Plant Breeding Group, *1*.

[9] Joshi, B. K. (2015). Rice and wheat gene pools in Nepal (1959-2002). National Agriculture Genetic Resources Center.

[10] Nelson, J. C., Jodari, F., Roughton, A. I., McKenzie, K. M., McClung, A. M., Fjellstrom, R. G., & Scheffler, B. E. (2012). QTL mapping for milling quality in elite western US rice germplasm. Crop Science, *52*(1), 242-252.

[11] Pokhrel, A., Dhakal, A., Sharma, S., & Poudel, A. (2020). Evaluation of physicochemical and cooking characteristics of rice (Oryza sativa L.) landraces of Lamjung and Tanahun districts, Nepal. International Journal of Food Science, *2020*, Article 1589150.

[12] Rai, S., Khadka, D. B., & Pokhrel, B. (2023). Characterization, quality assessment and comparison of selected rice landraces (Anadi, Bhotange, and Kalo Nuniya) of Nepal. Himalayan Journal of Science and Technology, *7*(1), 50-64.

[13] Sharma, S., Pokhrel, A., Dhakal, A., & Paudel, A. (2020). Agro-morphological characterization of rice (Oryza sativa L.) landraces of Lamjung and Tanahun district, Nepal. Annals of Plant Sciences, *9*(2), 3731-3741.

[14] Sood, B. C., & Siddiq, E. A. (1978). A rapid technique for scent determination in rice. Indian Journal of Genetics and Plant Breeding, *38*, 268-271.

[15] Subedi, U., Karki, R., Ojha, P., Mishra, A., Shrestha, M. B., & Dongol, D. M. S. (2018). Degree of milling effect on cold water rice quality. Journal of Nepal Agricultural Research Council, *4*, 7-17.

[16] Thapa, M. J., Shrestha, M. B., Karki, R., & Bhattarai, C. M. (2011). Study on quality and milling recovery of different varieties of rice at varying degree of polishing under Khumaltar condition. Agronomy Journal of Nepal, *2*, 88-92.

[17] Thongbam, P. D., Raychaudhuri, M., Ahmed, T., & Velmurugan, A. (2011). Physicochemical and cooking characteristics of some non-basmati rice varieties of Manipur, India. Rice Science, *18*(3), 175-181.

[18] Tiwari, D. N., Pandey, M. P., Manandhar, H. K., Bhusal, T. N., & Beshir, A. (2025). Exploring diversity in aromatic rice landraces for physio-chemical, cooking and milling quality traits in Nepal. Genetic Resources and Crop Evolution, 1-14.

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Biology of Angoumois Grain Moth, *Sitotroga cerealella* Olivier on Sorghum

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Abstract— *The Angoumois grain moth, Sitotroga cerealella Olivier is one of the most serious pests of sorghum at post-harvest. The experiment was carried out at Biocontrol Laboratory, Department of Entomology, N. M. College of Agriculture, Navsari Agricultural University, Navsari during the period from June to November, 2025 to study the biology of the Angoumois grain moth, Sitotroga cerealella Olivier on sorghum. The study revealed that the incubation period, total larval and pupal period, pre-oviposition, oviposition and post-oviposition period of Angoumois grain moth were 4.42 ± 1.03 days, 26.00 ± 1.89 days, 1.95 ± 0.78 days, 3.03 ± 0.77 and 4.28 ± 1.01 days, respectively. The average hatching percentage of egg was 87.57 ± 4.74%. The average number of eggs laid by a female moth was 100.23 ± 35.87 eggs per female. The average longevity of female moth was 9.35 ± 1.03 days while male moth lived for 7.10 ± 0.77 days. The total life cycle of female and male of* S. cerealella *were 43.17 ± 2.74 days and 38.30 ± 2.41 days, respectively*.

Keywords— ***Sorghum, Biology, Angoumois grain moth,*** **Sitotroga cerealella,** ***Stored grain pest, Life cycle, Fecundity, Post-harvest loss.***

I. INTRODUCTION

Sorghum is a significant cereal crop that is widely cultivated in tropical and subtropical climates worldwide. For millions of people, it is a staple food, especially in Asia and Africa, where it is a vital source of nutrition and energy. Globally, the United States leads in sorghum production with 9,957 MT while India ranks fourth with 4,600 MT (Anonymous, 2025). According to Oganja et al. (2024), it covered over 0.4 lakh hectares in Gujarat and produced 0.5 lakh tonnes annually with a productivity of 1378 kg per ha in 2023-2024. After rice and wheat, sorghum comes in third place in terms of area and production. Nutritionally, sorghum is rich in carbohydrates, protein, fibre, vitamins and minerals and it is gluten-free, making it a valuable food source (Hariprasanna and Patil, 2015).

Storage losses are affected by several factors which can be classified into two main categories: biotic factors (insect pests, rodents and fungi) and abiotic factors (temperature, humidity and rain). Among all the biotic factors, insect pests are considered the most important and cause huge losses in the cereal grains (30% - 40%) (Kumar, 2017). The most important pests affecting grains are found within the order Lepidoptera, *S. cerealella* (Lepidoptera: Gelechiidae) which is a serious pest affecting grains (Boshra, 2007). Infestation of this pest starts in the field itself and immature stages from the field infestation complete their life cycle and emerge as adults in storage (Reed et al., 2002). After entering the grain, the larva feeds internally and subsequently turns around to seal the entry point by spinning a silken web over the opening. Infested grains are typically hollow inside and filled with larval excreta or silken webs with a circular opening left for the emergence of adult moths. Germination is severely affected after infestation (Ahmad et al., 2021).

II. MATERIALS AND METHODS

The experiment on biology of Angoumois grain moth, *Sitotroga cerealella* Olivier was carried out in Biocontrol Laboratory, Department of Entomology, N. M. College of Agriculture, NAU, Navsari during June to November, 2025.

2.1 Disinfestation of Grains

The required quantity of sorghum seeds (variety GJ-102) was collected, thoroughly cleaned and sieved to eliminate foreign materials. The seeds were sterilized in a hot air oven at 55°C for 4 hrs to ensure disinfection. Following sterilization, the seeds were kept at room temperature for 24 hrs to allow equilibration, making them suitable for pest infestation. These sterilized seeds were subsequently used to maintain cultures for experimental purposes.

2.2 Maintenance of Laboratory Culture

Male and female adult moths were collected from infested stored sorghum grain sorted out under a simple microscope by observing their abdominal tergites. In males, the abdomen is thinner, pointed and blackish when viewed from the ventral side whereas in females, the abdomen is bulky and long without any blackish coloration and body size of the male is smaller than female.

Adults of *S. cerealella* were collected from infested grains in storage facilities to establish a laboratory stock culture. Ten pairs of adults were introduced into a glass jar (20 × 15 cm) containing 250 g of sterilized sorghum seeds. The jar was covered with muslin cloth secured by a rubber band to prevent adult moths from escaping and to exclude other insects. The culture was maintained at room temperature (Plate 1).

Newly emerged adults from this stock culture were used for subsequent multiplication and experimentation. To ensure a continuous supply of fresh *S. cerealella* adults, cultures were regularly maintained at predetermined intervals following this rearing protocol. Appropriate care was taken in handling both the insects and seeds throughout the process.

Maintenance of stock culture of *S. cerealella*

Laboratory rearing of *S. cerealella*

PLATE 1: Maintenance of stock culture and laboratory rearing of *S. cerealella* on sorghum

2.3 Collection of Eggs of *S. cerealella*

For the collection of fresh eggs, the freshly emerged adults of *S. cerealella* were collected from laboratory culture and were kept in a cylinder for one day for mating and subsequent egg laying on the glass cylinder. The top of the glass cylinder was covered by muslin cloth. In the consecutive days the eggs laid inside the cylinder were collected with the help of camel hair brush. The eggs were cleaned by removing body parts of moth and fresh eggs were obtained. The collected eggs of *S. cerealella* were kept into a glass tube with labelling and stored in a refrigerator to ensure a continuous supply for future study.

2.4 Egg

For egg period, freshly laid 40 eggs were taken individually in the plastic container from the laboratory culture and observed regularly in the morning for hatching purpose. The incubation period was considered as the period between the date of egg laying and date of egg hatching. The percent egg hatchability of *S. cerealella* was calculated by using the following formula:

$$\text{Egg hatchability (\%)} = \frac{\text{Number of neonate larvae hatched out}}{\text{Total number of eggs}} \times 100 \tag{1}$$

2.5 Larva and Pupa

The morphological characters of larva and pupa were studied by cutting infested grains from the pure culture with the help of a blade. With a view to determining the total larval and pupal period, newly hatched 40 larvae were reared separately on sorghum grains into plastic container (7.5 × 5.5 cm). Total larval and pupal period were recorded.

2.6 Adult

The newly emerged adults were observed for their size, colour and sex differences. To make out the morphological difference in male and female adult, mating pairs of the adults were collected and each of the individuals was examined under microscope carefully. For longevity of male and female, freshly emerged 40 individual adults of each were confined in a transparent plastic container (7.5 × 5.5 cm) and observations were recorded from the period between the emergence of adults to the death of adults. Adults confined in the jar for egg laying were closely observed for their mating behaviour. The female was provided with a male immediately after its emergence and the time from the emergence of the female to starting of mating copulation period, frequency of mating and egg laying behaviour were observed. For sex ratio, all the emerged adults were examined critically to determine male or female on the basis of their morphological characters and the ratio (male: female) was calculated.

2.7 Pre-oviposition, Oviposition and Post-oviposition Period

For oviposition, 40 females were reared separately in each plastic vial (7 × 6 cm) containing 10 g conditioned sorghum grain to observe the pre-oviposition, oviposition and post-oviposition periods. The pre-oviposition period was determined by the newly emerged adult pair. The pre-oviposition period was calculated from the date of emergence of adult female to the date of commencing the egg laying. Oviposition period was calculated from the date of commencing the egg laying to the ceasing of the egg laying by an individual female. The post-oviposition period was calculated from the date of the ceasing of egg laying to the death of adult female.

For fecundity of *S. cerealella*, a number of eggs laid by a single female were collected and counted daily in the morning till the death of the female. The eggs laid by a female were stuck to the base of container and were collected and counted daily with the help of moist fine camel hair brush.

2.8 Life Cycle

With a view to determine the total life cycle of *S. cerealella*, counted numbers of adults were reared separately in a transparent plastic container (7.5 × 5.5 cm) on sorghum grains. The period from date of egg laid to the date of adult emergence was calculated as a life cycle. The total life span of male and female was calculated from the date of egg laid to the death of an adult. Observations on *S. cerealella* were calibrated under the trinocular stereo zoom microscope.

III. RESULTS AND DISCUSSION

3.1 Egg

The eggs of *S. cerealella* were placed on sorghum grains either individually or in clusters. The newly laid eggs were creamy-white, soft and oval to elongated in shape. At the time of hatching, the colour changed to a reddish brown. The length of eggs varied from 0.50 to 0.70 mm with an average of 0.60 ± 0.06 mm, whereas the breadth ranged from 0.28 to 0.32 mm with an average of 0.29 ± 0.01 mm (Table 1). The present study is supported by the results of El-Sherif et al. (2008) who reported that the eggs of *S. cerealella* were placed on maize grains either individually or in clusters of two to sixty and average length and breadth of the egg measured was 0.60 mm and 0.30 mm, respectively.

3.2 Incubation Period, Fecundity and Hatching Percentage

The incubation period varied from 3 to 6 days with an average of 4.42 ± 1.03 days. The adult female of *S. cerealella* laid eggs singly or in batches of 2 to 10 eggs. The egg laying capacity of female moth varied from 48 to 170 eggs per female with an average of 100.23 ± 35.87 eggs per female (Table 2). The hatching rate of eggs varied from 77.19 to 95.29% with an average of 87.57 ± 4.74%. Zote (2023) observed that the incubation period of *S. cerealella* was 3 to 7 days with an average of 4.92 ± 1.37 days on rice. The average incubation period of *S. cerealella* recorded by Basavanjali et al. (2020) was 4.10 ± 0.70 days. According to Akter et al. (2013), the single female moth of *S. cerealella* can produce 42 to 213 eggs with an average of 109 eggs per female. Muthukumar et al. (2017) found that the mean number of eggs laid by *S. cerealella* was 94.76 eggs, ranging from 75.60 to 110.60 eggs. The results are in accordance with Patel (2019) who recorded that the hatching rate of egg varied from 71.79 to 97.14% with an average of 89.30 ± 6.09%. El-Sherif et al. (2008) noted that the hatching percentage ranged from 85 to 100% with a mean of 91%.

3.3 Larva

S. cerealella had four different instars. Similar findings of four instars were also reported by El-Sherif et al. (2008) and Saikia et al. (2014). The freshly hatched larva was yellowish white to yellowish red in colour with light brown head. It had three pairs of thoracic legs and four pairs of prolegs. The colour of the larva gradually turned white within one or two days of feeding. Zote (2023) reported that the newly hatched larva was tiny, elongate and creamy white to yellowish red in colour which gradually turned white within two days of feeding. Second instar larva was creamy white in colour with yellowish brown head and strong mandibles. The head was somewhat narrower than the prothorax. The prolegs were poorly developed and white in colour. Three thoracic and 10 abdominal segments observed and it was less active than the first instar larva. Patel (2019) recorded that second instar larva of *S. cerealella* was white in colour with yellowish brown head and strong mandibles. Third instar larva was morphologically similar to second instar larva but slightly larger in size. The head was yellowish brown in colour and slightly narrower than prothorax. The body of larva was whitish in colour. Zote (2023) observed that the appearance of the third instar larva closely resembled to that of second instar. Fourth instar larva was the same as the third instar larva in morphology but bigger in size. The fully grown larva was dirty white in colour with brownish head. Patel (2019) reported that the fourth instar larva of *S. cerealella* was the same as the third instar larva in morphology but bigger in size.

3.4 Pre-pupa and Pupa

The colour of pre-pupa was milky white to pale yellowish and it was formed inside the sorghum grain. It was smaller in size than full grown larva. The freshly formed pupa was yellowish brown in colour which later changed to dark brown and developed inside the delicate silken cocoon. The pupa was obtect type. Abdomen of developing adult was clearly marked into 10 segments in pupal stage. According to Basavanjali et al. (2020), the pupa of *S. cerealella* was brown in colour, developed inside the silken cocoon.

3.5 Total Larval and Pupal Period

The total larval and pupal period varied from 23 to 29 days with an average of 26.00 ± 1.89 days on sorghum grains. The present study is supported by the results of Demissie et al. (2014) who revealed that the total larval and pupal period of *S. cerealella* was 26.31 ± 0.60 days at 30°C temperature and 28.00 ± 0.97 days at 32°C temperatures. Borzoui et al. (2016) observed that the total larval and pupal period was 26.26 ± 0.24 days on sorghum.

3.6 Adult

The moths were pale golden-yellowish or grey-coloured with greyish brown head and thorax. The fore wing was pale greyish-brown in colour and small black dots was located on it. The hind wing was sharply pointed at the apex with dense fringe of hairs on margin. In terms of morphology, the male and female moths were nearly same to each other except the abdomen which was slender and blackish in male while that of female was broader and greyish white in colour. The female moth is larger than male moth in size. Kumar et al. (2022) described the moth as buff or grey in colour with dark markings on the fore wings, pointed hind wings exposing the abdomen and females larger than males in size on stored maize. The results obtained through the present study are in agreement with the results of earlier workers. The body length of female varied from 3.70 to 4.70 mm with an average of 4.20 ± 0.36 mm and breadth with wing expanded varied from 8.50 to 10.50 mm with an average of 9.59 ± 0.64 mm. Whereas, in case of male the length and breadth with wing expanded varied from 3.20 to 4.10 mm and 7.30 to 8.50

mm with an average 3.69 ± 0.28 mm and 7.79 ± 0.43 mm, respectively. These results are in accordance with Patel (2019), who reported that the length and breadth of female and male were 4.25 and 9.61 mm and 3.82 and 7.70 mm, respectively.

3.7 Pre-oviposition, Oviposition and Post-oviposition Period

The pre-oviposition period of *S. cerealella* varied from 1 to 3 days with an average of 1.95 ± 0.78 days. The oviposition period varied from 2 to 4 days with an average of 3.03 ± 0.77 days and post-oviposition period varied from 3 to 6 days with a mean of 4.28 ± 1.01 days (Table 2). Equivalent observations were also reported by Patel (2019) who recorded that the pre-oviposition, oviposition and post-oviposition period of *S. cerealella* for stored wheat were 1.50 ± 0.69 days, 3.50 ± 0.61 days and 5.25 ± 1.25 days, respectively. According to El-Sherif et al. (2008), the pre-oviposition period, oviposition and post-oviposition period were 2.60 days, 4.10 ± 0.28 days and 4.40 ± 0.26 days, respectively on maize grain.

3.8 Adult Longevity and Total Life Cycle

The longevity of female varied from 8 to 11 days with an average of 9.35 ± 1.03 days while male longevity varied from 6 to 8 days with an average of 7.10 ± 0.77 days. It showed that the female adult lived for longer duration than male adult (Table 2). According to Basavanjali et al. (2020), the average longevity of adult female and male of *S. cerealella* was 8.50 ± 0.85 days and 6.10 ± 1.10 days, respectively. Kumar et al. (2022) observed that the longevity of male adult *S. cerealella* ranged from 5 to 7 days with an average of 5.80 ± 0.01 days while female longevity ranged from 8 to 10 days with an average of 9.10 ± 0.02 days. The results of above workers are more or less similar to the present findings. The total life cycle of female varied from 39 to 48 days with an average 43.17 ± 2.74 days while, in case of male it varied from 35 to 42 days with an average of 38.30 ± 2.41 days. Saikia et al. (2014) studied that the average total life cycle of female was 43.20 and 44.30 days on rice and maize, respectively. While in case of male, the average total life cycle was 37.40 and 43.30 days on rice and maize, respectively. According to Basavanjali et al. (2020), the total life cycle of *S. cerealella* was 35 to 45 days with an average of 41.40 ± 3.54 days. The results of above workers are more or less supported with the present results.

TABLE 1
MORPHOMETRY OF EGGS AND ADULT OF *S. CEREALELLA* ON SORGHUM

Sr. No.	Life stage	Length (mm)		Breadth (mm)	
		Range	Mean ± SD	Range	Mean ± SD
1	Eggs	0.50-0.70	0.60 ± 0.06	0.28-0.32	0.29 ± 0.01
2	Adult Female	3.70-4.70	4.20 ± 0.36	8.50-10.50*	9.59 ± 0.64*
3	Adult Male	3.20-4.10	3.69 ± 0.28	7.30-8.50*	7.79 ± 0.43*

Breadth with wings expanded

TABLE 2
DEVELOPMENT PERIODS OF DIFFERENT LIFE STAGES OF *S. CEREALELLA* ON SORGHUM

Sr. No.	Particulars	Periods	
		Range	Mean ± SD
1	Incubation period (Days)	03-Jun	4.42 ± 1.03
2	Hatching (%)	77.19-95.29	87.57 ± 4.74
3	Larval + Pupal period (Days)	23-29	26.00 ± 1.89
4	Pre-oviposition period (Days)	01-Mar	1.95 ± 0.78
5	Oviposition period (Days)	02-Apr	3.03 ± 0.77
6	Post-oviposition period (Days)	03-Jun	4.28 ± 1.01
7	Adult longevity (Days) Female	08-Nov	9.35 ± 1.03
	Male	06-Aug	7.10 ± 0.77
8	Fecundity (No. of eggs per female)	48-170	100.23 ± 35.87
9	Sex ratio (male: female)	0.81-1.50	1.12 ± 0.23
10	Total life cycle (Days) Female	39-48	43.17 ± 2.74
	Male	35-42	38.30 ± 2.41

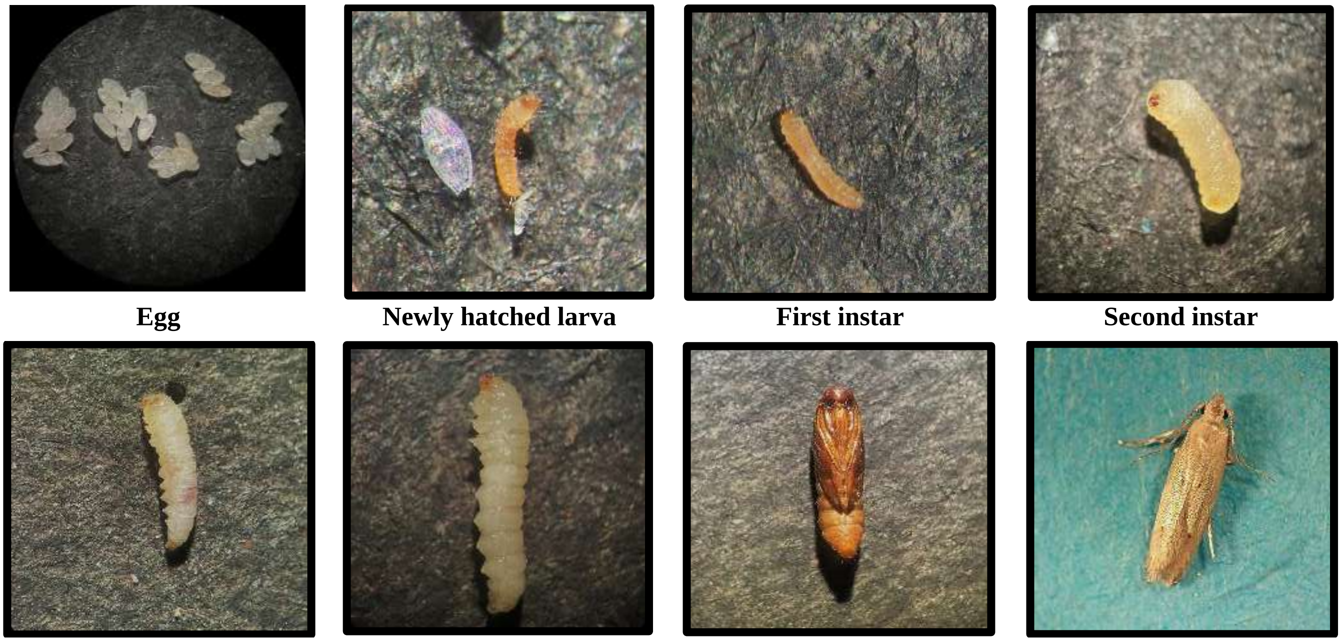

PLATE 2: Development stages of *S. cerealella* on sorghum

IV. CONCLUSION

Sitotroga cerealella exhibits a complete internal feeding life cycle on sorghum grains. It undergoes four larval instars within the grain, progressing through a concealed developmental phase that includes pre-pupal and obtect pupal stages inside a silken cocoon. Overall, it completes its life cycle in approximately 39 to 48 days with females exhibiting a slightly longer developmental duration and higher longevity, highlighting its strong reproductive potential and significant capacity for internal grain damage under storage conditions.

Recommendations:

1) **Monitoring:** Based on the life cycle duration (39-48 days), monitoring programs should be scheduled at regular intervals to detect early infestations.

2) **Management:** The extended larval period inside the grain (23-29 days) indicates that chemical control measures should target adult stages before oviposition.

3) **Storage Practices:** Since infestation starts in the field, harvest should be done promptly and grains should be properly dried (below 13% moisture) to prevent infestation.

4) **Future Research:** Studies on host preference among different sorghum varieties, impact of temperature and humidity on life cycle parameters, and development of eco-friendly management strategies are recommended.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

REFERENCES

[1] Ahmad, R., Hassan, S., Ahmad, S., Nighat, S., Devi, Y. K., Javeed, K., Usmani, S., Ansari, M., Erturk, S., Alkan, M. A., & Hussain, B. (2021). Stored grain pests and current advances for their management. *Postharvest Technology - Recent Advances, New Perspectives and Applications. Journal of Information and Technology*, *100*, 1-37.

[2] Akter, T., Jahan, M., & Bhuiyan, M. S. I. (2013). Biology of the angoumois grain moth, *Sitotroga cerealella* (Oliver) on stored rice grain in laboratory condition. *Journal of the Asiatic Society of Bangladesh Science*, *39*(1), 61-67.

[3] Anonymous. (2025). *USDA. Global scenario of the sorghum*. https://ipad.fas.usda.gov/cropexplorer/cropview/commodityView.aspx

[4] Basavanjali, S. N., Prabhuraj, A., & Basavegowda, S. (2020). Biology of angoumois grain moth, *Sitotroga cerealella* (Olivier) (Gelechiidae: Lepidoptera) on paddy. *Journal of Entomology and Zoology Studies*, *8*(5), 726-729.

[5] Borzoui, E., Naseri, B., & Ganbalani, G. N. (2016). Effects of food quality on biology and physiological traits of *Sitotroga cerealella* (Lepidoptera: Gelechiidae). *Journal of Economic Entomology*, *110*(1), 266-273.

[6] Boshra, S. A. (2007). Effect of high-temperature pre-irradiation on reproduction and mating competitiveness of male, *Sitotroga cerealella* (Olivier) and their F1 progeny. *Journal of Stored Products Research*, *43*(1), 73-78.

[7] Demissie, G., Rajamani, S., & Ameta, O. P. (2014). Effect of temperature and relative humidity on development and survival of angoumois grain moth, *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechiidae) on stored maize. *International Journal of Sciences: Basic and Applied Research*, *15*(2), 9-21.

[8] El-Sherif, S. I., Hashem, M. Y., & Ahmed, S. S. (2008). The life history of the angoumois grain moth, *Sitotroga cerealella* (Olivier) (Lepidoptera: Gelechiidae) on maize (*Zea mays* L.) grains. *Egyptian Journal of Agricultural Sciences*, *59*(4), 333-338.

[9] Hariprasanna, K., & Patil, J. V. (2015). Sorghum: Origin, classification, biology and improvement. In *Sorghum molecular breeding* (pp. 3-20).

[10] Kumar, R. (2017). *Insect pests of stored grain: Biology, behaviour and management strategies*. CRC Press Apple Academic Press.

[11] Kumar, S., Kumar, V., Kumar, A., Sati, K., Raj, P., & Thakur, A. (2022). Studies on biology of *Sitotroga cerealella* Olivier on stored maize. *The Pharma Innovation Journal*, *11*(9), 1422-1425.

[12] Muthukumar, M., Kumar, D. V. S. R., Madhumathi, T., & Ahamed, M. L. (2017). Biology of the angoumois grain moth, *Sitotroga cerealella* (Oliver) on rice varieties. *Indian Journal of Entomology*, *79*(3), 253-256.

[13] Oganja, Y. H., Maheta, H. Y., Kumar, K., & Bharodia, C. R. (2024). Identification of mutation point and trend analysis of area, production and yield of wheat crop in Gujarat, India. *Asian Research Journal of Agriculture*, *17*(4), 150-156.

[14] Patel, H. (2019). *Biology and nonchemical management of angoumois grain moth, Sitotroga cerealella (Olivier) (Lepidoptera: Gelechiidae) in stored wheat* [M.Sc. thesis, Navsari Agricultural University].

[15] Reed, C. R., Ioerger, B. P., Doyungan, S. M., & Trigo-Stockli, D. (2002). Storage of exported US corn and grain sorghum in tropical climates. *Applied Engineering in Agriculture*, *18*(6), 707.

[16] Saikia, J., Goswami, M. M., & Bhattacharyya, B. (2014). Biology and detection technique of angoumois grain moth, *Sitotroga cerealella* Olivier (Lepidoptera: Gelechiidae) on stored rice and maize grains. *Journal of Entomology and Zoology Studies*, *2*(6), 9-11.

[17] Zote, V. (2023). *Bionomics and non-chemical management of angoumois grain moth, Sitotroga cerealella (Olivier) (Gelechiidae: Lepidoptera) on paddy* [Ph.D. thesis, Navsari Agricultural University].

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Effect of Entomopathogens on Angoumois Grain Moth and Seed Viability

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Abstract— *The laboratory experiment on the effect of entomopathogens on the Angoumois grain moth, Sitotroga cerealella* Olivier revealed that the significantly highest percent adult mortal*ity (72.33%) of S. cerealella was recorded in deltamethrin at 0.04 mL/kg after 72 hours of treatment. In case of entomopathogens, the treatment of M. anisopliae 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth @ 20 + 5 g/kg was found to be the next effective treatment having 65.80% adult mortality. The significantly lowest percent adult mortality (38.33%) of S. cerealella was recorded in Metarhizium anisopliae 1.15 WP (1.0 × 10^8 CFU/g) at 10 g/kg after 72 hours of treatment. In case of adult emergence, the significantly lowest adult emergence (2.00) was recorded in deltamethrin at 0.04 mL/kg. The significantly highest seed germination (91.33%) was recorded in treatment of B. bassiana 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg and M. anisopliae 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (91.00%). The significantly lowest seed moisture content (8.24%) was recorded in B. bassiana 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg and it was statistically at par with M. anisopliae 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (8.41%).*

Keywords— Beauveria bassiana, Metarhizium anisopliae, Diatomaceous earth, Sitotroga cerealella, Stored grain pest, Sorghum, Biological control, Seed viability, Entomopathogenic fungi.

I. INTRODUCTION

Sorghum is a significant cereal crop that is widely cultivated in tropical and subtropical climates worldwide. It is essential for industrial applications, fodder and food security. Among all the biotic factors, insect pests are considered the most important and cause huge losses in the cereal grains (30%–40%) (Kumar, 2017). The Angoumois grain moth is a serious primary pest of stored grain in many parts of the world especially on stored wheat and rice (Boshra, 2007). The control of stored-grain insect pests using chemical insecticides and fumigants (methyl bromide and phosphine) is an essential tool for preventing or minimizing insect damage to stored grain. However, the use of synthetic insecticides in stored grain protection resulted in potential hazards for mammals (Mostafalou and Abdollahi, 2013), can be harmful to the natural enemies and insects develop resistance to them (Prakash et al., 1993; Salem et al., 2007). These problems had necessitated the development of new classes of safer insect control agents that would be biodegradable, cheap, readily available and non-toxic to consumers and environmentally friendly. Biological control of stored-product insect pests involves the use of hymenopteran parasitoids, predatory insects and mites as well as insect pathogens such as entomopathogenic fungi, bacteria, viruses, protozoa and nematodes (Moore et al., 2000; Flinn and Scholler, 2012). Among insect pathogens, entomopathogenic fungi represent a promising alternative to chemical insecticides and conventional pesticides. The conidia of these fungi attach to the insect cuticle, germinate and penetrate the integument, ultimately leading to the death of the host. Entomopathogenic fungi are naturally occurring, environmentally safe and exhibit low toxicity to mammals (Cox and Wilking, 1996). The use of diatomaceous earth offers another promising alternative to conventional insecticides. Its particles abrade and inactivate the epicuticular lipids of the insect cuticle leading to internal water loss and eventually death by desiccation (Ebeling, 1971; Korunic, 1998; Mewis and Ulrichs, 2001).

II. MATERIALS AND METHODS

The experiment was carried out under ambient storage condition at Biocontrol Laboratory, Department of Entomology, N. M. College of Agriculture, NAU, Navsari during 2025-2026. The experiment was laid out in completely randomized design with ten treatments including untreated control and three replications. The seeds of sorghum cv. GJ-102 were used for this experiment. To evaluate the different entomopathogens against Angoumois grain moth, *S. cerealella*, 500 g of freshly harvested sorghum seeds with a high percentage of germination and low moisture content (<10%) were taken for each treatment. Each entomopathogen was applied at a respective dose to a previously sterilized bulk of 500 g sorghum seed. Each treatment was mixed thoroughly with sorghum seed by shaking it manually for 5 min in a jar and water used as a carrier for the uniform smearing of insecticide on seeds. The required quantity of deltamethrin was diluted in 2 mL water to treat 500 g of seed for proper coating. After drying in shade, treated seeds were packed in air tight glass jar and kept in a room under ambient temperature, while untreated seeds were taken as control.

Three samples of treated sorghum seed, each of 100 g (one sample for one replication) were drawn from each bulk of treatment. The samples were filled in a plastic jar (25 × 30 cm) individually. Ten pairs of freshly emerged (0-24 hrs old) adults were released in each plastic jar. Then after, the respective containers were tightly closed with the perforated lid and stored in laboratory at room temperature under hygienic conditions. The total number of eggs laid by the Angoumois grain moth, number of adult emergence and percent weight loss were recorded after 15 days and then after 30, 60, 90 and 120 days by drawing a sample of about 100 seeds randomly from each treatment.

TABLE 1
DETAILS OF TREATMENTS

S. No.	Treatment	Dose per kg of seed
1	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	10 g
2	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	20 g
3	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	10 g
4	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	20 g
5	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g
6	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g
7	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g
8	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g
9	Deltamethrin 2.8 EC	0.04 mL
10	Untreated control	–

2.1 Seed Germination

The germination test was carried out on germination papers. A total of 100 seeds from each treatment were randomly selected and spread on circularly cut moist germination paper at uniform distance in Petri plate. The Petri plate covered with the lid carrying the moist filter paper. Little quantity of distilled water was sprinkled on filter paper once a day to keep it moist. The numbers of germinated seeds were counted after 7 days of incubation and percent germination was worked out by counting number of sprouted and non-sprouted seeds.

$$\text{Germination (\%)} = \frac{\text{No. of seed germination}}{\text{Total numbers of seed}} \times 100 \quad (1)$$

2.2 Seed Moisture

First of all, empty metallic crucible was weighed. By taking 100 g of sorghum seeds adjusting with empty metallic crucible. Metallic crucible with sample was placed in oven at 105°C for 24 hrs. The metallic crucible along with sample was weighed and again put it for 2 to 3 hrs till constant weight. After drying, the sample was allowed to cool for some time in oven. Then the metallic crucible was closed and put it in the desiccators for further cooling. After cooling at room temperature, the final weight of metallic crucible with dried sample was noted. This method is given by Bhargava and Raghupathi (1993).

Weight of empty metallic crucible = A

Weight of metallic crucible + sample = B

Weight of sample = (B – A)

Weight of metallic crucible + oven dry sample = C

Weight of moisture content in seed sample = (B – C)

$$\text{Moisture content (\%)} = \frac{(B\text{-}C)}{(B\text{-}A)} \times 100 \quad (2)$$

2.3 Corrected Mortality

The mortality was recorded at 24 hrs intervals up to 3 days. Besides dead, moribund insects were also considered as dead. The percent mortality of the adults was corrected by using a formula suggested by Abbott (1925).

$$P = \frac{(P' - C)}{(100 - C)} \times 100 \quad (3)$$

Where,

P = Percent corrected mortality

P' = Percent mortality in treatment

C = Percent mortality in control

The zero and percent values were replaced by using formula (1/4n) × 100 and (1 – 1/4n) × 100, respectively suggested by Bartlett (1947).

Where, n = Number of adults per treatment

2.4 Adult Emergence

The mean number of adults that emerged from each replication were recorded after 30, 60, 90 and 120 days of treatment.

2.5 Weight Loss

Emerging adults were removed from a sample after 15, 30, 60, 90 and 120 days and the damaged and healthy seeds were weighted separately with electric balance. The weight loss was calculated as per the methodology suggested by Adams and Schulten (1978).

$$\text{Weight loss (\%)} = \frac{(UNu) - (DNd)}{U(Nd + Nu)} \times 100 \quad (4)$$

Where,

U = Weight of undamaged seeds

Nu = Number of undamaged seeds

D = Weight of damaged seeds

Nd = Number of damaged seeds

(A)

(B)

PLATE 1: Experiment setup for effect of entomopathogens (A) and set of seed treatment for seed germination (B)

III. RESULTS AND DISCUSSION

3.1 Adult Mortality

Data recorded after 72 hrs of treatment revealed that the significantly highest percent adult mortality (72.33%) of *S. cerealella* was recorded in the treatment of deltamethrin at 0.04 mL/kg. The treatment of *M. anisopliae* 1.15 WP (1.0×10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg was found to be the next effective treatment having 65.80% adult mortality followed by *B. bassiana* 1.15 WP (1.0×10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (61.80%). Significantly the lowest adult mortality of *S. cerealella* was found in *M. anisopliae* 1.15 WP (1.0×10^8 CFU/g) at 10 g/kg (38.33%).

TABLE 2
EFFECT OF ENTOMOPATHOGENS ON ADULT MORTALITY OF *S. CEREALELLA* IN STORED SORGHUM

Treat. No.	Treatments	Dose per kg of seed	Corrected (%) adult mortality of *S. cerealella* at different period of storage interval		
			24 hrs	48 hrs	72 hrs
T1	*Beauveria bassiana* 1.15 WP (1.0×10^8 CFU/g)	10 g	28.37gh* (32.17)	34.00gh (35.66)	41.17f (39.91)
T2	*Beauveria bassiana* 1.15 WP (1.0×10^8 CFU/g)	20 g	32.00f (34.44)	38.00f (38.05)	44.50e (41.84)
T3	*Metarhizium anisopliae* 1.15 WP (1.0×10^8 CFU/g)	10 g	26.37h (30.88)	32.00h (34.44)	38.33g (38.25)
T4	*Metarhizium anisopliae* 1.15 WP (1.0×10^8 CFU/g)	20 g	30.00fg (33.20)	35.00g (36.27)	42.50ef (40.68)
T5	*Beauveria bassiana* 1.15 WP (1.0×10^8 CFU/g) + Diatomaceous earth	10 + 5 g	40.50d (39.52)	45.50d (42.41)	51.70d (45.97)
T6	*Beauveria bassiana* 1.15 WP (1.0×10^8 CFU/g) + Diatomaceous earth	20 + 5 g	44.50c (41.84)	53.70c (47.12)	61.80c (51.82)
T7	*Metarhizium anisopliae* 1.15 WP (1.0×10^8 CFU/g) + Diatomaceous earth	10 + 5 g	38.00e (38.05)	42.50e (40.68)	49.50d (44.71)
T8	*Metarhizium anisopliae* 1.15 WP (1.0×10^8 CFU/g) + Diatomaceous earth	20 + 5 g	47.50b (43.56)	56.70b (48.85)	65.80b (54.21)
T9	Deltamethrin 2.8 EC	0.04 mL	58.70a (50.01)	66.80a (54.81)	72.33a (60.22)
T10	Untreated control	–	0.00i (0.00)	0.00i (0.00)	0.00h (0.00)
	S. Em. ±		0.49	0.45	0.51
	CD at 5%		1.46	1.32	1.52
	CV (%)		2.49	2.05	2.13

Figures in parentheses are arc sine transformed values while those outsides are original values. Treatment means followed by the same letter(s) are not significantly different according to DNMRT at 5% level of significance.

3.2 Adult Emergence

The data on adult emergence of *S. cerealella* after 30, 60, 90 and 120 DAT are presented in Table 3. Recorded data revealed that all the treatments were found significantly superior in adult emergence over untreated control. More or less corresponding trends of results were also observed for 60, 90 and 120 DAT. In case of 120 DAT, significantly lowest adult emergence (2.00) was recorded in deltamethrin at 0.04 mL/kg. The next significantly effective treatment was *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (5.00) and it was statistically at par with *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (6.00). Significantly highest adult emergence (37.00) was found in untreated control.

TABLE 3
EFFECT OF ENTOMOPATHOGENS ON ADULT EMERGENCE OF *S. CEREALELLA* IN STORED SORGHUM

Treat. No.	Treatments	Dose per kg of seed	Average number of adults emerged after indicated days of treatment			
			30 DAT	60 DAT	90 DAT	120 DAT
T1	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	10 g	9.00f* (3.07)	11.00f (3.38)	13.00g (3.67)	16.00f (4.06)
T2	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	20 g	6.00de (2.54)	7.00de (2.73)	9.00f (3.07)	13.33e (3.71)
T3	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	10 g	7.00e (2.73)	8.00e (2.91)	10.00f (3.23)	14.33ef (3.84)
T4	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	20 g	5.00d (2.33)	6.00d (2.54)	7.00e (2.73)	11.00d (3.38)
T5	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g	3.00c (1.85)	4.00c (2.11)	6.00de (2.54)	10.00d (3.23)
T6	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g	1.33b (1.34)	3.00bc (1.87)	4.00c (2.11)	6.00bc (2.54)
T7	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g	2.33c (1.67)	3.67c (2.01)	4.67cd (2.27)	7.00c (2.73)
T8	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g	1.00b (1.22)	2.00ab (1.58)	2.67b (1.77)	5.00b (2.33)
T9	Deltamethrin 2.8 EC	0.04 mL	0.00a (0.70)	1.33a (1.34)	1.67a (1.46)	2.00a (1.58)
T10	Untreated control	–	17.00g (4.18)	25.67g (5.11)	32.67h (5.75)	37.00g (6.12)
	S. Em. ±		0.09	0.1	0.1	0.11
	CD at 5%		0.27	0.3	0.3	0.31
	CV (%)		7.35	6.86	6.07	5.48

DAT: Days After Treatment. Figures in parentheses are square root transformed values while those outsides are original values. Treatment means followed by the same letter(s) are not significantly different according to DNMRT at 5% level of significance.

3.3 Number of Eggs

The data on effect of entomopathogens on oviposition of *S. cerealella* at different periods of storage intervals are presented in Table 4. Results revealed that significant effect of all the treatments on oviposition were found over untreated control. At 120 DAT, the significantly lowest number of eggs (8.33) was recorded in treatment of deltamethrin at 0.04 mL/kg. The next effective treatment in terms of egg laying (14.67) was *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg followed by *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (20.67). Significantly highest number of eggs laid (67.33) was observed in the untreated control.

TABLE 4
EFFECT OF ENTOMOPATHOGENS ON OVIPOSITION OF *S. CEREALELLA* IN STORED SORGHUM

Treat. No.	Treatments	Dose per kg of seed	Mean number of eggs laid by females after indicated days of treatment				
			15 DAT	30 DAT	60 DAT	90 DAT	120 DAT
T1	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	10 g	14.00f* (3.80)	22.67h (4.81)	27.00g (5.24)	32.00g (5.70)	40.00h (6.36)
T2	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	20 g	5.33d (2.41)	13.33f (3.71)	18.00e (4.30)	24.00f (4.94)	35.00fg (5.95)
T3	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	10 g	8.00e (2.91)	18.00g (4.37)	22.00f (4.74)	25.00f (5.04)	37.00g (6.12)
T4	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	20 g	4.00c (2.11)	11.00e (3.38)	16.67e (4.14)	22.33ef (4.77)	33.33ef (5.81)
T5	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g	3.33c (1.95)	8.00d (2.91)	11.67d (3.48)	19.67e (4.48)	31.67e (5.67)
T6	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g	0.00a (0.70)	1.67b (1.46)	8.00c (2.91)	13.67d (3.76)	20.67c (4.60)
T7	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g	1.00b (1.22)	3.67c (2.03)	9.00c (3.07)	11.00c (3.38)	24.00d (4.94)
T8	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g	0.00a (0.70)	1.33b (1.34)	4.00b (2.11)	6.00b (2.54)	14.67b (3.89)
T9	Deltamethrin 2.8 EC	0.04 mL	0.00a (0.70)	0.00a (0.70)	2.33a (1.67)	3.33a (1.93)	8.33a (2.96)
T10	Untreated control	–	20.33g (4.56)	32.00i (5.70)	43.00h (6.59)	52.33h (7.26)	67.33i (8.23)
	S. Em. ±		0.07	0.09	0.1	0.11	0.08
	CD at 5%		0.2	0.27	0.29	0.33	0.23
	CV (%)		5.64	5.2	4.5	4.48	2.47

DAT: Days After Treatment. Figures in parentheses are square root transformed values while those outsides are original values. Treatment means followed by the same letter(s) are not significantly different according to DNMRT at 5% level of significance.

3.4 Weight Loss

Data on percent weight loss by *S. cerealella* after 15, 30, 60, 90 and 120 DAT are presented in Table 5. In case of 120 DAT, the lowest weight loss (19.80%) was recorded in treatment of deltamethrin at 0.04 mL/kg which was followed by *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (22.30%), *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (25.70%) and *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 10 + 5 g/kg (30.20%). Significantly highest weight loss (48.00%) was recorded in untreated control.

The lowest F1 progeny of *S. cerealella* emerged from diatomaceous earth at 1000 mg/kg + *B. bassiana* at 5 g/kg (37.33) followed by diatomaceous earth at 1000 mg/kg + *M. anisopliae* at 5 g/kg (41.67) was reported by Muthukumar et al. (2016) and these results are in close conformity with present study. Yadav (2024) studied the effect of entomopathogen and inert dust on storage insect pest on wheat and found that the significantly higher adult mortality rate of *S. cerealella* was recorded in treatment of deltamethrin at 0.04 mL/kg seed (60.00%) followed by *B. bassiana* at 20 g/kg seed + diatomaceous earth at 5 g/kg seed (50.00%) after 12 months of storage. Rajasri et al. (2012) studied the efficacy of different indigenous inert materials against stored grain pests of rice and concluded that among the different inert materials, indispron P 406 at 2.5 g/kg and diatomaceous earth at 5 g/kg were found effective against *S. cerealella* up to twelve months of storage period. Thus, the present findings are more or less in conformity with the earlier reports.

TABLE 5
EFFECT OF ENTOMOPATHOGENS ON WEIGHT LOSS AGAINST *S. CEREALELLA* IN STORED SORGHUM

Treat. No.	Treatments	Dose per kg of seed	Percent weight loss at different period of storage interval				
			15 DAT	30 DAT	60 DAT	90 DAT	120 DAT
T1	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	10 g	23.37g* (28.90)	27.00g (31.30)	32.00h (34.45)	37.60h (37.81)	41.20h (39.93)
T2	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	20 g	20.17f (26.67)	23.03f (28.67)	26.00f (30.65)	31.17gh (33.93)	36.70gf (37.28)
T3	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	10 g	22.10g (28.03)	25.33g (30.21)	28.17g (32.05)	32.37g (34.67)	38.00g (38.05)
T4	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	20 g	18.70f (25.62)	20.27e (26.75)	24.70f (29.79)	29.50ef (32.89)	35.60ef (36.63)
T5	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g	15.80e (23.42)	17.27d (24.55)	21.70e (27.76)	27.47e (31.60)	33.37e (35.28)
T6	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g	9.83c (18.27)	12.47c (20.67)	16.27c (23.78)	20.60c (26.98)	25.70c (30.45)
T7	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g	13.60d (21.62)	15.83d (23.43)	18.60d (25.54)	23.17d (28.76)	30.20d (33.33)
T8	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g	6.47b (14.72)	10.50b (18.89)	13.50b (21.54)	17.43b (24.66)	22.30b (28.17)
T9	Deltamethrin 2.8 EC	0.04 mL	4.43a (12.12)	6.60a (14.86)	9.43a (17.88)	14.70a (22.53)	19.80a (26.40)
T10	Untreated control	–	28.50h (32.26)	32.00h (34.44)	37.23i (37.60)	42.33i (40.58)	48.00i (43.85)
	S. Em. ±		0.39	0.41	0.34	0.44	0.46
	CD at 5%		1.15	1.21	1.01	1.31	1.37
	CV (%)		2.9	2.79	2.1	2.44	2.3

DAT: Days After Treatment. Figures in parentheses are arc sine transformed values while those outsides are original values. Treatment means followed by the same letter(s) are not significantly different according to DNMRT at 5% level of significance.

3.5 Seed Germination

The initial germination percentage of sorghum seeds before treatment was 98.00% and after completion of study, the seed germination (%) are presented in Table 6. Results revealed that significantly highest seed germination (91.33%) was recorded in treatment of *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg and it was statistically at par with *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (91.00%), deltamethrin at 0.04 mL/kg (90.00%) and *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 10 + 5 g/kg (89.00%). The next effective treatment in terms of seed germination (%) was *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 10 + 5 g/kg (88.00%) which was followed by *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) at 20 g/kg (87.67%), *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) at 20 g/kg (86.00%), *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) at 10 g/kg (85.00%) and *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) at 10 g/kg (84.00%). The significantly lowest germination percentage (80.00%) was recorded in untreated control.

3.6 Seed Moisture

The initial moisture percentage of sorghum seeds before treatment was 7.25% and after completion of study, the seed moisture (%) are presented in Table 6. Significantly lowest seed moisture content (8.24%) was recorded in *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg and it was statistically at par with *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg (8.41%). The next effective treatment in terms of seed moisture (%) was *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 10 + 5 g/kg (8.56%) and it was at par with the treatment of *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + diatomaceous earth at 10 + 5 g/kg (8.67%) and deltamethrin at 0.04 mL/kg (8.90%). The remaining treatments in ascending chronological order based on seed moisture (%) was *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) at 20 g/kg (9.46%) < *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) at 20 g/kg (9.53%) < *B. bassiana* 1.15 WP (1.0 × 10^8 CFU/g) at 10 g/kg (9.66%) < *M. anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) at 10 g/kg (9.70%). Significantly highest seed moisture content (9.87%) was recorded in untreated control.

Rajasri et al. (2012) studied the efficacy of different indigenous inert materials and reported that the germinability of seed maintained for twelve month which is above certification standards (>80%). These results are in close agreement with the findings of Theertha et al. (2023), who reported that the *M. anisopliae* at 20 g/kg seeds + diatomaceous earth at 5 g/kg seeds had the lowest seed moisture content of 9.64% and highest seed germination 82% after nine months of storage. Anuradha and Bera (2025) also reported that the *M. anisopliae* at 20 g/kg seed + diatomaceous earth at 5 g/kg seeds recording 64.67% germination and 8.33% moisture after twelve months of storage. These results are in close conformity with previous findings, where the significantly lowest moisture content (8.20%) was recorded in treatment of *B. bassiana* at 20 g/kg seed and significantly highest germination percentage (68.67%) was recorded in treatment of *B. bassiana* at 10 g/kg seed + diatomaceous earth at 5 g/kg seed, while significantly highest moisture content (9.06%) was found in the untreated control after 12 months of storage (Anonymous, 2025).

TABLE 6
EFFECT OF ENTOMOPATHOGENS ON SEED VIABILITY IN STORED SORGHUM

Treat. No.	Treatments	Dose per kg of seed	Seed germination (%)	Seed moisture (%)
T1	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	10 g	85.00de* (67.22)	9.66c (18.11)
T2	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g)	20 g	87.67bcd (69.46)	9.46c (17.91)
T3	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	10 g	84.00e (66.42)	9.70c (18.15)
T4	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g)	20 g	86.00cde (68.03)	9.53c (17.98)
T5	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g	89.00abc (70.74)	8.56ab (17.00)
T6	*Beauveria bassiana* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g	91.33a (72.98)	8.24a (16.68)
T7	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	10 + 5 g	88.00bcd (69.74)	8.67ab (17.12)
T8	*Metarhizium anisopliae* 1.15 WP (1.0 × 10^8 CFU/g) + Diatomaceous earth	20 + 5 g	91.00a (72.55)	8.41a (16.84)
T9	Deltamethrin 2.8 EC	0.04 mL	90.00ab (71.57)	8.90b (17.36)
T10	Untreated control	–	80.00f (63.45)	9.87c (18.30)
	S. Em. ±		0.86	0.14
	CD at 5%		2.54	0.43
	CV (%)		2.15	1.42

PLATE 2: Germination performance of sorghum seeds after treatment with entomopathogens and diatomaceous earth

IV. CONCLUSION

The study demonstrated that entomopathogenic fungi, particularly in combination with diatomaceous earth, are effective alternatives to chemical insecticides for managing *Sitotroga cerealella* in stored sorghum. The combination treatments of *M. anisopliae* + diatomaceous earth and *B. bassiana* + diatomaceous earth at 20 + 5 g/kg showed significantly higher adult mortality, reduced adult emergence, lower oviposition, minimized weight loss, and maintained better seed viability compared to individual treatments.

Key Findings:

1) The combination of *M. anisopliae* (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg was the most effective entomopathogenic treatment, achieving 65.80% adult mortality, 91.00% seed germination, and only 8.41% seed moisture content.
2) *B. bassiana* (1.0 × 10^8 CFU/g) + diatomaceous earth at 20 + 5 g/kg was the second most effective treatment, with comparable results.
3) Chemical insecticide (deltamethrin) showed the highest adult mortality (72.33%) but also maintained good seed viability (90.00% germination), indicating its effectiveness as a grain protectant.
4) Deltamethrin is effective but raises concerns about residues, resistance development, and environmental impact. Therefore, entomopathogens combined with diatomaceous earth offer a sustainable alternative for stored grain pest management.

Recommendations:

1) **For Farmers:** The combination of *M. anisopliae* or *B. bassiana* with diatomaceous earth at 20 + 5 g/kg can be recommended as an eco-friendly alternative to chemical insecticides for protecting stored sorghum.
2) **For Seed Viability:** These treatments maintain seed germination above 90% and moisture content below 9%, ensuring seed quality for planting.
3) **For Future Research:** Field-level validation, long-term storage studies, and evaluation of these treatments on different sorghum varieties are recommended.

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CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript.

REFERENCES

[1] Abbott, W. S. (1925). A method of computing the effectiveness of an insecticide. *Journal of Economic Entomology*, *18*(2), 265-267.
[2] Adams, J. M., & Schulten, G. G. M. (1978). Loss caused by insects, mites and micro-organisms in post-harvest grain loss assessment methods. *Journal of Stored Products Research*, *15*, 15-17.
[3] Anonymous. (2025). *Agresco (21st PPSC) report submitted to Navsari Agricultural University, Navsari* (pp. 28-43).
[4] Anuradha, & Bera, A. (2025). Seed treatment with entomopathogens in paddy storage. *Uttar Pradesh Journal of Zoology*, *46*(22), 120-126.
[5] Bartlett, M. S. (1947). The use of transformation. *Biometrics*, *3*(1), 39-52.
[6] Bhargava, B. S., & Raghupathi, H. B. (1993). Analysis for plant materials for macro and micronutrients. In *Methods of analysis of soils, plants, water and fertilizers* (pp. 49-82).
[7] Boshra, S. A. (2007). Effect of high-temperature pre-irradiation on reproduction and mating competitiveness of male, *Sitotroga cerealella* (Olivier) and their F1 progeny. *Journal of Stored Products Research*, *43*(1), 73-78.
[8] Cox, P. D., & Wilking, D. R. (1996). The potential use of biological control of pests in stored grain. *Home Grown Cereals Authority Research Review*, *36*, 53.
[9] Ebeling, W. (1971). Sportive dusts for pest control. *Annual Review of Entomology*, *16*, 123-158.
[10] Flinn, P. W., & Scholler, M. (2012). Biological control: Insect pathogens, parasitoids and predators. *Stored Product Protection*, *156*, 203-212.

[11] Korunic, Z. (1998). Diatomaceous earths, a group of natural insecticides. *Journal of Stored Products Research*, *34*, 87-97.

[12] Kumar, R. (2017). *Insect pests of stored grain: Biology, behaviour and management strategies*. CRC Press Apple Academic Press.

[13] Mewis, I., & Ulrichs, C. (2001). Action of amorphous diatomaceous earth against different stages of the stored product pests *Tribolium confusum* (Coleoptera: Tenebrionidae), *Tenebrio molitor* (Coleoptera: Tenebrionidae), *Sitophilus granarius* (Coleoptera: Curculionidae) and *Plodia interpunctella* (Lepidoptera: Pyralidae). *Journal of Stored Products Research*, *37*, 153-164.

[14] Moore, D., Lord, J. C., & Smith, S. M. (2000). Pathogens. In *Alternatives to pesticides in stored-product IPM* (pp. 193-227). Springer US.

[15] Mostafalou, S., & Abdollahi, M. (2013). Pesticides and human chronic diseases: Evidences, mechanisms and perspectives. *Toxicology and Applied Pharmacology*, *268*(2), 157-177.

[16] Muthukumar, M., Kumar, D. V. S. R., Madhumathi, T., & Ahamed, L. (2016). Efficacy of diatomaceous earth in combination with certain entomopathogenic fungi against of *Sitotroga cerealella* (Olivier) and *Rhyzopertha dominica* (Fab.) in paddy during storage. *The Andhra Agricultural Journal*, *63*(1), 158-162.

[17] Prakash, A., Rao, J., Gupta, S. P., & Behra, J. (1993). Evaluation of botanical pesticides as grain protectants against rice weevil, *S. oryzae* Linn. *Botanical Pesticides in Integrated Pest Management*, *17*(1), 360-365.

[18] Rajasri, M., Rao, P. S., & Kumari, K. V. S. M. (2012). Inert dusts better alternatives for the management of angoumois grain moth, *Sitotroga cerealella* in stored rice. *International Journal of Science and Research*, *3*(10), 278-283.

[19] Salem, S. A., Abou-Ela, R. G., Matter, M. M., & El-Kholy, M. Y. (2007). Entomocidal effect of *Brassica napus* extracts on two stored pests, *Sitophilus oryzae* (L.) and *Rhyzopertha dominica* (Fab.) (Coleoptera). *Journal of Applied Sciences Research*, *3*(4), 317-322.

[20] Theertha, C. P., Siddaraju, R., Parashivamurthy, C., Naik, M., & Krishna, T. V. (2023). Impact of entomopathogens and inert dust seed treatment on insect pests and seed quality of cowpea (*Vigna unguiculata* L.) during storage. *Mysore Journal of Agricultural Sciences*, *57*(3), 401-410.

[21] Yadav, A. (2024). *Studies on the effect of entomopathogen and inert dust on storage insect pest and seed quality of wheat under ambient condition [wheat (Triticum aestivum L.)]* [M.Sc. thesis, Chandra Shekhar Azad University of Agriculture and Technology].

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Integrated Management of *Tetranychus urticae* Koch in Okra: Current Status, Adoption Challenges and Future Perspectives

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Abstract— *Okra (Abelmoschus esculentus L. Moench) is an important vegetable crop cultivated widely in tropical and subtropical regions, with India contributing the largest share of global production. Among the major arthropod pests affecting okra, the two-spotted spider mite, Tetranychus urticae Koch, causes serious economic losses by reducing plant growth, fruit quality, and marketable yield. Effective management of this pest requires an integrated strategy that combines host plant resistance, biological control, cultural practices, judicious use of acaricides, and timely advisory support to farmers. This review critically examines published research on the biology, host range, damage potential, resistance mechanisms, and management approaches for T. urticae in okra. Particular emphasis is placed on integrated pest management (IPM), the role of agricultural extension services, digital advisory systems, and precision agriculture technologies in promoting sustainable mite management. The review also identifies existing research gaps, including the need for standardized resistance-screening methods, economic threshold levels, resistance monitoring, and climate-resilient management strategies. Strengthening collaboration among researchers, extension agencies, and farming communities will be essential for improving the adoption of scientifically validated practices and ensuring sustainable okra production under changing climatic conditions. The findings presented in this review may assist researchers, extension professionals, and policymakers in designing sustainable mite-management programmes suitable for diverse agro-ecological conditions.*

Keywords— Tetranychus urticae, Okra, Integrated pest management, Agricultural extension, Biological control, Host plant resistance, Sustainable agriculture, Two-spotted spider mite, Abelmoschus esculentus, Acaricide resistance, IPM adoption, Farmer Field School.

I. INTRODUCTION

Okra (*Abelmoschus esculentus* (L.) Moench) is among the most economically important warm-season vegetable crops of South Asia and Africa, valued for its nutritive fruit, short duration and export potential. Global production was estimated at approximately 11.2 million tonnes from about 1.14 million hectares in 2022, with India contributing roughly 70% of world output [11]. This dominant and highly concentrated production share (Figure 1) means that pest constraints affecting Indian okra cultivation carry disproportionate weight for global supply, and that management solutions validated under Indian growing conditions have relevance well beyond the country's own borders. The crop is grown predominantly by small and marginal holders, making its pest-management economics inseparable from questions of smallholder cost, labour and access to advisory support.

Besides its economic value, okra contributes significantly to nutritional security and income generation for resource-poor farming households. Therefore, minimizing production losses caused by spider mites is essential not only for improving productivity but also for enhancing farm profitability and livelihood security.

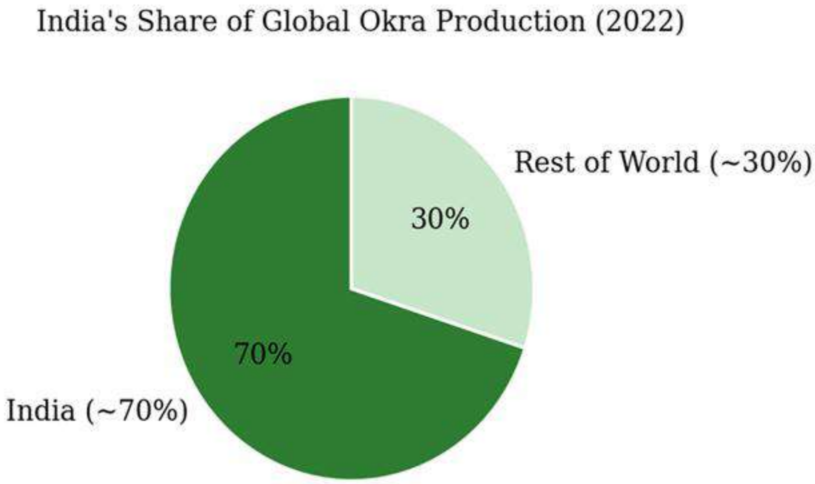


FIGURE 1: India's share of global okra production, 2022 (data: FAO, cited in [11])

Realization of this production potential is persistently constrained by arthropod pests, among which the two-spotted spider mite, *Tetranychus urticae* Koch, ranks as one of the most damaging, with yield losses reported in the range of 7–48% under unmanaged field infestation, and cultivar-wise assessments confirming that susceptible varieties suffer disproportionately greater losses than moderately resistant ones under comparable infestation pressure [30,31]. *T. urticae* is polyphagous and is notorious for the speed with which it evolves acaricide resistance—a trait linked to its short generation time, high fecundity and arrhenotokous reproduction [35]. Repeated, calendar-based chemical spraying, still the default management approach across much of India's vegetable belt, has produced not only resistance but documented resurgence of the pest following certain acaricide applications [21].

This review draws on a doctoral thesis on okra–mite interactions conducted at Banaras Hindu University [32], together with the wider peer-reviewed literature, to synthesize current knowledge of *T. urticae* biology, host-plant resistance and management options in okra, to critically examine the extension and adoption dimension that determines whether laboratory-validated IPM packages reach and are used by farmers, and to outline research gaps and emerging technologies that may reshape mite management over the coming decade.

1.1 Biology, Distribution and Host Range

T. urticae Koch belongs to family Tetranychidae and is commonly termed the two-spotted spider mite for the pair of dark patches visible through the cuticle of feeding females. Its life cycle passes through egg, larva, protonymph, deutonymph and adult stages. Development from larva through deutonymph has been recorded as short as 10 days on a susceptible okra cultivar (Mahyco 10) and as long as 19.8 days on a resistant wild-type accession (Kasturi bhendi), illustrating how host resistance alone can slow developmental rate; fecundity likewise differed sharply by host, at 77.1 eggs/female on the susceptible check versus 41.5 eggs/female on the resistant entry [28]. Feeding occurs through piercing of mesophyll cells, with immature stages generally confined to spongy parenchyma while adults can additionally penetrate palisade tissue [26].

T. urticae has a cosmopolitan distribution across tropical, subtropical and temperate cropping systems worldwide [35]. In India it is reported throughout the major vegetable-growing tracts, with well-documented seasonal build-up in the Gangetic plains, including the Varanasi region where the source thesis work was conducted [12,20,32]. Consistent with its status as one of the most polyphagous arthropod pests known, *T. urticae* has been recorded on vegetables (okra, brinjal, cucumber, tomato, cowpea, bean), fruit crops, cotton and ornamentals, in addition to numerous weed hosts [16,23,25]. Minhajul-Haque et al. [23] recorded the mite on twenty vegetable and twenty-four ornamental species surveyed over a single season in Rajshahi, while Hoque et al. [16] documented differential population build-up on bean, eggplant and okra, with the highest numbers recorded on okra (up to about 174 mites per leaf in August) compared with bean and eggplant in the same survey. This broad host range, together with wind-borne dispersal, complicates area-wide management since untreated alternate hosts continually reseed populations onto the main crop.

The biological characteristics of *T. urticae*, particularly its rapid reproductive capacity and broad host range, enable the pest to establish quickly under favourable environmental conditions. These traits make continuous monitoring essential for timely management.

TABLE 1
REPRESENTATIVE HOST-PLANT CATEGORIES RECORDED FOR *T. URTICAE*, RELEVANT TO OKRA CROPPING SYSTEMS

Host category	Representative species/examples	Source
Vegetables	Okra, brinjal (eggplant), cucumber, tomato, cowpea, bean	[16,23,32]
Fibre crops	Cotton	[25]
Ornamentals	24 ornamental species recorded in a single Rajshahi survey	[23]
Other/weed hosts	Numerous uncultivated field-margin plants	[16,23]

1.2 Economic Importance and Damage Symptoms

Within India's substantial okra production base, *T. urticae* has been identified as one of the most serious pests of the crop, with yield losses of 7–48% reported depending on infestation intensity and cultivar [30,31]. Feeding damage begins as fine chlorotic stippling on the lower leaf surface, progressing to bronzing, leaf curling and premature defoliation under heavy infestation. Quantified in terms of standardized mite-day exposure (a measure combining mite numbers and duration of feeding), net photosynthetic rate in cucumber was reduced by roughly 50% under immature-stage feeding versus roughly 95% under adult-stage feeding at 1,000 mite-days per 6 cm² of leaf area, while total chlorophyll content was reduced by roughly 55% and 80%, and overall leaf greenness by roughly 50% and 80%, for immature versus adult feeding respectively at the same exposure level [26]. Because immature mites feed only through the spongy parenchyma while adults can additionally penetrate palisade tissue, damage severity and visibility increase as a colony matures from newly hatched larvae to a mixed-age adult population, meaning that the same numerical mite count can correspond to quite different levels of realized leaf damage depending on the age structure of the population at the time of scouting [26]—a further argument for threshold systems that account for population structure rather than raw mite counts alone. In okra, infested leaves show measurable depletion of nitrogen, phosphorus, potassium, iron, zinc and copper alongside increases in manganese and phenolic content relative to healthy leaves, with the degree of change varying by cultivar and broadly tracking field susceptibility rankings [32]. Because okra is typically grown on small, fragmented holdings and marketed fresh with a short shelf life, even moderate mite-related quality loss can disproportionately affect the farm-gate returns of resource-poor growers.

1.3 Ecology and Population Dynamics

Field studies in the Varanasi region recorded *T. urticae* incidence on okra beginning around the 9th–10th standard week, with the highest phytophagous mite population per 2.5 cm² leaf area recorded at 47.75 mites in the 21st standard week during one crop season and 45.99 mites in the 18th standard week during the following season—in both cases coinciding with the hot, dry conditions of May—alongside a significant positive correlation with mean temperature, sunshine hours and wind velocity, and a negative correlation with relative humidity and rainfall [20]. A separate doctoral study on the ecology and management of *T. urticae* on okra similarly framed seasonal population build-up as driven primarily by temperature and moisture regime [12]. This temperature-driven pattern is consistent with the wider literature: spider mite populations generally develop and reproduce faster under hot, dry conditions, and warming, drier conditions are broadly expected to intensify outbreak frequency in several *Tetranychus* species [3]. This has direct implications for okra, itself a hot-season crop whose cultivation window overlaps closely with periods of peak mite pressure.

Seasonal monitoring of mite populations can support timely interventions and reduce unnecessary acaricide applications. Integrating weather-based forecasting with field scouting may further improve decision-making under changing climatic conditions.

II. MATERIALS AND METHODS

This study follows a narrative review approach in which published scientific literature and authenticated documentary sources were critically examined, compared, and synthesized to develop a comprehensive understanding of spider mite management in okra.

2.1 Primary Source

The principal source underlying the biology, host-plant resistance, biochemical, and acaricide-efficacy content of this review is a doctoral thesis on the screening of okra varieties against *T. urticae* and its management, submitted to the Department of Entomology & Agricultural Zoology, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi [32]. Data drawn from this thesis include field screening of sixteen okra varieties over two seasons (2013–14 and 2014–15), biochemical estimation of healthy versus mite-infested leaves, and a two-year pooled field evaluation of synthetic, botanical and microbial acaricides, including a dedicated resurgence assessment.

2.2 Literature Search and Selection

Supplementary peer-reviewed literature was identified through targeted searches using combinations of the terms "*Tetranychus urticae*", "okra", "*Abelmoschus esculentus*", "host plant resistance", "acaricide resistance", "integrated pest management adoption", and "agricultural extension". Sources were included only where they could be independently identified and verified (author, year, and outlet); where a specific statistic or claim could not be traced to a verifiable source, it was excluded from the review rather than estimated. This approach necessarily limits the reference base to a curated set of thirty-seven sources rather than an exhaustive bibliometric sample, and the review should be read with that scope in mind.

2.3 Synthesis Approach

Findings from the thesis and the supplementary literature were organized thematically—biology and ecology, host-plant resistance and its biochemical basis, integrated pest management components, farmer adoption barriers, and the role of agricultural extension—and cross-compared to identify points of agreement, disagreement, and gaps in the existing evidence base, which are reported in Section III and summarized as explicit research gaps.

2.4 Scope and Limitations

This review deliberately weights its synthesis toward a single doctoral thesis conducted at one Indian university [32], supplemented by thirty-six independent sources; readers should therefore treat cultivar-resistance rankings, biochemical figures and acaricide-efficacy data reported here as representative of the Varanasi agro-climatic region and the specific trials cited, rather than as universally generalizable across every okra-growing tract. Similarly, the extension analysis in Sections 3.4–3.5 draws on a curated set of institutional and international IPM-adoption sources, but district- or block-level, okra-mite-specific adoption studies were not identified in the literature reviewed and would strengthen future work. Statistics and figures presented throughout are drawn directly from the cited sources; where a specific claim could not be traced to a verifiable source within this curated reference set, it has been omitted or flagged as a gap (Section 3.6) rather than filled with an estimated value. Because several of the technology-related sources in this review (drones, resistance-monitoring genomics) are recent and rapidly evolving fields, their application specifically to *T. urticae* on okra should be read as an identified opportunity rather than an established, field validated practice.

III. RESULTS AND DISCUSSION

3.1 Screening of Resistant Okra Varieties

The source thesis screened sixteen okra varieties under field conditions over two seasons (2013–14 and 2014–15) and categorized them by mean mite population into susceptible, moderately susceptible and moderately resistant groups. HRB-231, Kashi Sathdhari, Pant-A-4, Hisar Naveen and Kashi Lalima were classed as moderately resistant, while Azad Bhindi-1, Varsha Uphar, Punjab Padmini and Panjab-7 were most susceptible [32]. A significant negative correlation was found between mite population and both trichome number ($r = -0.71$) and yield per plant ($r = -0.49$) across both seasons [32].

This trichome-mediated resistance pattern is corroborated by independent work: Manual et al. [22] found Arka Anamika and D-1-87-5 resistant among seven okra lines screened against the related species *T. neocaledonicus* at Pusa, while Roseleen and Ramaraju [29] identified the wild-type accession Kasturi bhendi as consistently the most resistant okra entry against *T. urticae*, with Dharmapuri Local, Parbani Kranti, Pusa Sawani and COBhH1 rated moderately resistant and the commercial cultivar Mahyco 10 remaining susceptible across multiple independent trials [28,29,30]. Guo and Yue [14] provide a broader mechanistic review showing that leaf trichomes affect mite populations both physically—by impeding movement, providing camouflaging shelter, and altering the leaf microenvironment—and chemically, through defense compounds either present in trichomes or induced upon attack, which can also serve as cues that attract predatory mites to infested leaves.

Cultivar rankings are not perfectly comparable across studies, nevertheless, because screening methodology differs. East et al. [8] compared whole-leaf, floating-disc and clip-cage techniques for screening muskmelon resistance to *T. urticae* and found that coefficient-of-variation values were similar for the whole-leaf and floating-disc methods but substantially lower than for the clip-cage method, with resistant melon lines (including accessions labelled BUS, CHI, PI 164343 and PI 17895 in that study) identified consistently across both of the more reliable techniques. This methodological inconsistency is worth flagging as a limitation when comparing okra resistance rankings across research groups that may not have used equivalent screening protocols.

TABLE 2
SELECTED OKRA GENOTYPES AND THEIR REPORTED RESISTANCE RESPONSE TO *TETRANYCHUS* SPP.

Genotype	Reported response	Source
Kasturi bhendi (wild type)	Resistant	[28,29,30]
Dharmapuri Local, Parbani Kranti, Pusa Sawani, COBhH1	Moderately resistant	[29,30]
HRB-231, Kashi Sathdhari, Pant-A-4, Hisar Naveen, Kashi Lalima	Moderately resistant	[32]
Arka Anamika, D-1-87-5	Resistant (vs. *T. neocaledonicus*)	[22]
Mahyco 10	Susceptible	[28,29,30]
Azad Bhindi-1, Varsha Uphar, Punjab Padmini, Panjab-7	Susceptible	[32]

Beyond the trichome and yield correlations reported above, the same two-season thesis dataset found a significant positive correlation between mite population and the number of leaves per branch ($r = 0.46$), a non-significant positive correlation with number of primary branches ($r = 0.17$), and non-significant negative correlations with days to 50% flowering ($r = -0.12$), plant height ($r = -0.42$), number of flowers ($r = -0.21$), fruit length ($r = -0.19$), number of fruits per plant ($r = -0.46$) and fruit diameter ($r = -0.18$) [32]. The pattern—strong, significant associations for trichome number and yield, but weaker or non-significant associations for most other morphological and phenological traits—supports treating trichome density specifically, rather than general plant vigour or architecture, as the primary morphological resistance trait worth prioritising in okra breeding programmes.

TABLE 3
CORRELATION BETWEEN *T. URTICAE* POPULATION AND OKRA PLANT/YIELD TRAITS (POOLED TWO-SEASON FIELD DATA)

Plant/yield trait	Correlation coefficient (r)	Significance
Number of trichomes	−0.71	Significant
Yield per plant	−0.49	Significant
Number of fruits per plant	−0.46	Non-significant
Plant height	−0.42	Non-significant
Number of flowers	−0.21	Non-significant
Fruit length	−0.19	Non-significant
Fruit diameter	−0.18	Non-significant
Number of primary branches	0.17	Non-significant
Days to 50% flowering	−0.12	Non-significant
Number of leaves per branch	0.46	Significant

Source: [32]. Note the divergent behaviour of the two significant traits: higher trichome number is associated with lower mite population (consistent with a protective, antixenotic role), whereas a higher number of leaves per branch is associated with higher mite population, plausibly reflecting the additional feeding surface and microclimate that denser foliage provides.

3.2 Biochemical Basis of Resistance

Biochemical estimation in the thesis showed that mite-infested okra leaves lost nitrogen, phosphorus, potassium, iron, copper and zinc relative to healthy leaves, while manganese content increased [32]. Independent studies on other hosts show a consistent pattern: Ghoshal [13] reported chlorophyll, protein, carbohydrate and several micronutrients depleted in mite-infested Tulsi leaves, with phenol content rising by over 30%; Barman and Ghoshal reported comparable depletion patterns in chilli [5] and coconut [4], with phenol again the one compound that consistently increased with mite feeding. This convergence across unrelated host species indicates that phenolic and tannin accumulation is a general induced-defense response to *Tetranychus* feeding rather than an okra-specific mechanism.

Roseleen and Ramaraju's screening of okra entries against *T. urticae* found that the reduction in leaf moisture content on infestation was greatest (about 15.3%) in the susceptible check and smallest in resistant entries, while resistant wild-type Kasturi bhendi recorded the highest total phenol content of any entry in both healthy (6.23 mg/g) and infested (about 9.50 mg/g) leaves, alongside roughly 20% higher tannin content than mite-free plants of the same entry [29,30]. Infested plants generally recorded lower total protein than mite-free plants, whereas total free amino acids were higher in infested plants than in mite-free ones, and mite feeding was associated with increased peroxidase, polyphenol oxidase and phenylalanine ammonia lyase activity in the resistant entries specifically [29,30]—enzyme markers consistent with an induced, rather than purely constitutive, biochemical defense response.

A more complex picture emerges from Hildebrand et al.'s soybean study [15], in which the cultivars 'Bonus' and 'Williams' were infested with 0, 10 and 200 mites per leaf at the V3, V6 and R2 growth stages: the cultivar showing greater relative resistance ('Williams', which sustained significantly lower mite population increase than 'Bonus') also showed the larger relative loss of leaf chlorophyll (about 55%) and an even larger loss of carotenoid content (about 79%) at the lower mite-infestation level, attributed to a stronger hypersensitive oxidative response. This raises an open question for okra breeding: resistance measured as lower mite numbers does not automatically imply proportionally lower biochemical damage per mite, and the two should be evaluated together rather than resistance being inferred from population counts alone.

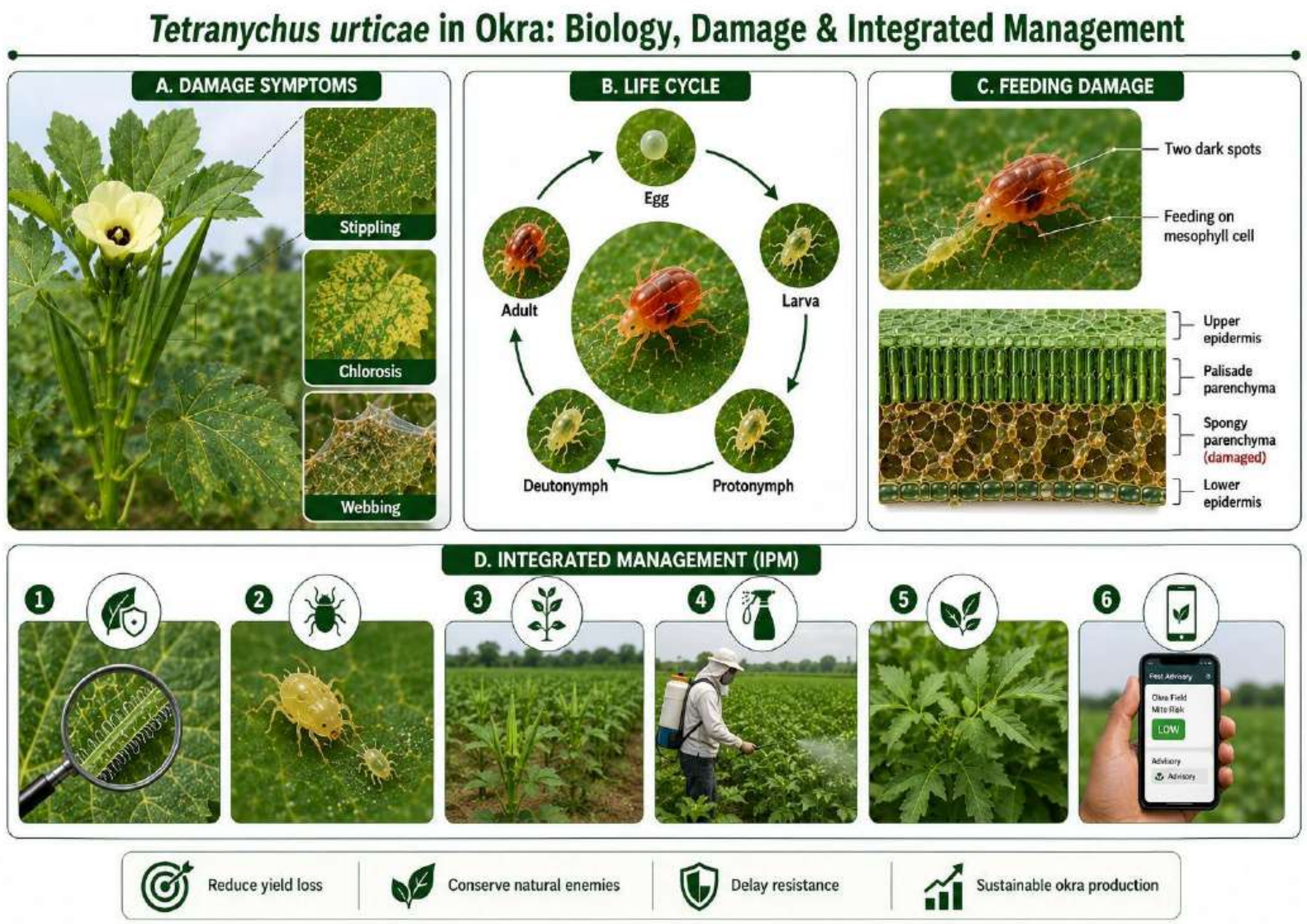
Across the sixteen okra varieties screened in the source thesis, the range of biochemical depletion on mite infestation gives a sense of the variation among genotypes: leaf nitrogen loss ranged from about 1.52% (Azad Bhindi-1) to 1.76% (Panjab-7); phosphorus loss ranged from about 0.16% (Varsha Uphar) to 0.23% (Punjab Padmini); potassium content in infested leaves ranged from about 1.94% (Azad Bhindi-1) to 2.44% (Panjab-7), with the percentage decrease relative to healthy leaves ranging from about 0.44% to 0.72% depending on variety; iron content showed a percentage decrease ranging from about 2.74% (Pusa

Sawani) to 18.60% (HRB-231); zinc content decreased by about 33.5% to 39.5% depending on variety; and copper content decreased by about 24.9% to 37.8% depending on variety, while manganese content increased on infestation across all varieties tested, ranging from about 57.6 to 61.0 mg/kg [32].

TABLE 4
RANGE OF BIOCHEMICAL DEPLETION IN MITE-INFESTED OKRA LEAVES ACROSS SIXTEEN SCREENED VARIETIES

Biochemical parameter	Range across varieties	Direction of change
Nitrogen (N)	1.52% – 1.76%	Depletion
Phosphorus (P)	0.16% – 0.23%	Depletion
Potassium (K), % decrease	0.44% – 0.72%	Depletion
Iron (Fe), % decrease	2.74% – 18.60%	Depletion
Zinc (Zn), % decrease	33.5% – 39.5%	Depletion
Copper (Cu), % decrease	24.9% – 37.8%	Depletion
Manganese (Mn)	57.6 – 61.0 mg/kg	Increase

Source: [32], pooled data from field seasons 2013–14 and 2014–15. The consistent direction of change across all sixteen varieties—depletion of N, P, K, Fe, Zn and Cu alongside a consistent increase in Mn—suggests a shared physiological response to mite feeding across genotypes, even though the magnitude of change (and hence the biochemical "cost" of infestation) differs by variety.



Source: Prepared by the authors based on the published literature cited in this review; icons and layout are illustrative and not reproduced from any single source

3.3 Integrated Pest Management

A quantified economic injury level (EIL) of 1.31–1.52 mites/inch² has been established for *T. urticae* on cucumber under plastic-house conditions, based on a two-season trial in which artificial infestation at rates of 1, 2, 5 and 10 mites/inch² produced yield reductions ranging from about 18% to 54% in the first season and about 20% to 57% in the second, relative to an uninfested control [9]. No analogous, validated threshold specific to *T. urticae* on okra was identified in the reviewed literature—a significant practical gap, since without a threshold, spray decisions on farmers' fields default to calendar schedules rather than population-triggered intervention.

TABLE 5
MITE INFESTATION RATE AND CORRESPONDING YIELD REDUCTION IN CUCUMBER, INFORMING THE ECONOMIC INJURY LEVEL (EIL) CONCEPT

Infestation rate (mites/inch²)	Yield reduction, Season 1 (%)	Yield reduction, Season 2 (%)
1	18	20.5
2	28.2	32.2
5	38.9	45.1
10	54	56.6

Source: [9]. No comparable infestation-rate/yield-loss trial for T. urticae on okra was identified, underscoring the research gap noted in Section 3.6.

Because mite populations build up faster under hot, dry conditions, cultural measures that maintain adequate crop humidity and avoid moisture stress can help suppress early-season build-up [3,20]. Among biological agents, the predatory mite *Phytoseiulus persimilis* achieved 68.6–88.2% population reduction at release ratios of 1:5 and 1:10 (predator:prey) against *T. urticae* on eggplant [1]. Beyond Phytoseiid mites, soil-dwelling predatory mites of the genus *Hypoaspis* have shown biocontrol potential against related mite pests, though their predatory efficacy was found to be temperature-dependent and reduced by the presence of alternative prey in laboratory assessment [2]—a caution relevant to any field release programme, since okra fields rarely host a single prey species in isolation.

Compatibility between acaricides and biological control agents varies substantially by product and needs to be assessed alongside raw mite-mortality data. Azadirachtin caused negligible direct mortality to the predatory mites *Neoseiulus californicus* and *Phytoseiulus macropilis* in strawberry, with egg viability in treated plots remaining above 80% (similar to untreated controls), though it still reduced predator fecundity by about half; importantly, azadirachtin's biological persistence in that trial (about 7 days) was considerably shorter than that of abamectin (about 21 days), meaning any negative effect on the predators was also comparatively short-lived [6]. Among acaricides tested against *T. urticae* in citrus orchards, mineral oil, tebufenpyrad and clofentezine were found harmless to the parasitoid *Aphidius colemani*, whereas fenazaquin was moderately harmful to the predatory mite *Neoseiulus californicus* specifically, illustrating that natural-enemy compatibility cannot be assumed to be uniform even among acaricides with similar target-pest efficacy [34]. Selecting acaricides for both efficacy and natural-enemy compatibility is consequently a distinct decision from selecting for mite mortality alone.

In the pooled two-year thesis field trial, botanical formulations gave moderate control—NSKE (5%) reduced mite numbers by 50.8%, azadirachtin (0.03%) by 49.5%, and neem oil (0.03%) by 44.6%—while microbial formulations of *Paecilomyces fumosoroseus* performed comparatively poorly under field conditions (22.4–29.3% reduction) [32]. Independent screening of plant extracts against *T. urticae* found that *Lolium perenne*, *Anthemis vulgaris* and *Chenopodium album* extracts produced considerably higher adult mortality than azadirachtin at the concentrations tested [37], indicating that botanical efficacy varies considerably by plant source and is not yet standardized.

Newer acaricide chemistries substantially outperformed older standards in the thesis trial: clofentazine gave the highest mite reduction (91.6%), followed by cyflumetofen (82.5%), fenpyroximate (77.5%), propargite (72.1%) and dicofol (66.9%) [32]. In a separate laboratory evaluation of acaricides against *T. urticae* on cotton, chlorfenapyr, pyridaben and fenpyroximate were the most effective miticides overall, with chlorfenapyr producing 87–100% mortality in both laboratory and field assessments, while dicofol was the least effective of the compounds tested (32–38% mortality); fenpyroximate additionally recorded the lowest LC50 value (about 5.18 mg/L) among the acaricides evaluated in that study [25], reinforcing the pattern of dicofol's comparatively weak field performance seen in the okra thesis data.

Resistance to acaricides in *T. urticae* arises through a combination of target-site mutations that reduce the sensitivity of the acaricide's binding site and metabolic detoxification via enhanced activity of detoxifying enzyme families, mechanisms that have been documented across numerous acaricide classes and mite populations worldwide [35]. Widely reported dicofol resistance in *T. urticae* populations illustrates how persistent such resistance can be: laboratory-selected resistance of about 23-fold was maintained for a full year even after selection pressure was removed, declining only to about 15.8-fold after two years and 10.7-fold after three years without further dicofol exposure [19]—indicating that resistance, once established in a field population, is not expected to reverse quickly even if the compound is temporarily withdrawn from use. This reinforces the case for rotating modes of action rather than repeated use of a single acaricide class.

TABLE 6
DECLINE IN DICOFOL-RESISTANCE LEVEL OF *TETRANYCHUS URTICAE* OVER TIME WITHOUT FURTHER SELECTION PRESSURE

Time since selection halted	Resistance level (fold, relative to susceptible strain)
1 year	~23.0-fold
2 years	~15.8-fold
3 years	~10.7-fold

Source: [19]. The gradual, incomplete decline illustrated in Table 6 underlines why acaricide-resistance management works best as a preventive rotation strategy rather than a reactive one.

Critically, only dicofol among the compounds tested in the thesis trial triggered pest resurgence in the resurgence-specific assessment, while clofentazine, cyflumetofen, fenpyroximate and propargite did not [32]. This echoes the broader mechanism documented for resurgence in other sucking pests: repeated organophosphate, carbamate or pyrethroid use has been shown to induce resurgence primarily through insecticide-driven changes in host-plant chemistry—particularly nutritional status—following application, sometimes accompanied by increased fecundity, a shortened nymphal period, and an altered sex ratio favouring the pest, whereas neonicotinoids, insect growth regulators and botanicals have generally not induced comparable resurgence in the sucking-pest systems studied [33].

TABLE 7
COMPARATIVE EFFICACY OF SYNTHETIC, BOTANICAL AND MICROBIAL PESTICIDES AGAINST *T. URTICAE* ON OKRA (POOLED TWO-YEAR FIELD DATA)

Treatment	Mean mite reduction (%)	Resurgence observed?
Clofentazine 50 SC	91.6	No
Cyflumetofen 20 SC	82.5	No
Fenpyroximate 5 EC	77.5	No
Propargite 57 EC	72.1	No
Dicofol 18.5 EC	66.9	Yes
NSKE 5%	50.8	—
Azadirachtin 0.03%	49.5	—
Neem oil 0.03%	44.6	—
Paecilomyces fumosoroseus (dust)	29.3	—
Paecilomyces fumosoroseus (EC)	22.4	—

Source: [32], pooled data from field seasons 2013–14 and 2014–15. "—" indicates resurgence was not separately assessed for that treatment in the pooled trial.

The same thesis also examined efficacy separately by mite life stage—egg, nymph, adult male and adult female—under laboratory conditions, releasing each stage onto treated okra leaf surfaces and recording mortality up to 72 hours after treatment [32]. Clofentazine gave the highest mortality at every stage examined (egg 99.9%, nymph 100%, adult male 99.9%, adult female 86.6%), whereas neem oil and azadirachtin were consistently the weakest performers, with neem oil giving only 32.6% egg mortality and 8.25% nymph mortality, and azadirachtin giving only 36.8% adult-male mortality [32]. Adult females were the life stage most tolerant of treatment across almost all products tested, including the most effective compound, suggesting that a single spray timed against egg or nymph populations is likely to leave a partially surviving adult-female cohort capable of resuming oviposition—reinforcing the case for repeat or overlapping applications rather than a single intervention, regardless of which acaricide is chosen.

TABLE 8
LIFE-STAGE-WISE MORTALITY OF *T. URTICAE* UNDER LABORATORY BIOASSAY, 72 HOURS AFTER TREATMENT (SELECTED TREATMENTS)

Treatment	Egg (%)	Nymph (%)	Adult male (%)	Adult female (%)
Clofentazine 50 SC	99.9	100	99.9	86.6
Azadirachtin 0.03%	—	—	36.8	—
Neem oil 0.03%	32.6	8.3	—	38.2

Source: [32]. "—" indicates the treatment was not among the highest/lowest performers reported for that particular life stage in the thesis summary and is omitted here rather than estimated.

TABLE 9
COMPARISON OF MAJOR MANAGEMENT OPTIONS FOR *T. URTICAE* IN OKRA: ADVANTAGES AND LIMITATIONS

Management option	Advantages	Limitations
Host-plant resistance (trichome-rich cultivars)	Chemical-free; persistent across the season	Resistant cultivars not universally available; screening methods inconsistent across studies [8]
Biological control (Phytoseiid predators, *Hypoaspis* spp.)	Self-sustaining once established; compatible with several botanicals	Predator availability limited at village level; sensitive to broad-spectrum sprays [1,2,6,34]
Botanical acaricides (azadirachtin, NSKE, neem oil)	Low mammalian toxicity; safer for natural enemies	Moderate, variable field efficacy (~44–51% reduction) [32]
Microbial acaricides (entomopathogenic fungi)	Environmentally benign; fits organic production	Weakest field performance among options tested (~22–29% reduction) [32]
Selective synthetic acaricides (clofentazine, cyflumetofen, fenpyroximate)	Highest field efficacy (77–92% reduction); no resurgence observed [32]	Cost and availability constraints at farm level [7]
Legacy acaricides (dicofol)	Low unit cost; widely available	Triggers resurgence; documented resistance persisting a year or more [19,32]

3.4 Farmer Adoption Challenges

Even where research demonstrates that IPM packages combining host resistance, biological control and selective acaricides outperform calendar spraying, adoption on Indian okra farms lags. A broad review of global IPM adoption identifies technical complexity, insufficient training investment, weak confidence in decision-support information, and a persistent gap between farmers recognizing IPM's value and actually sustaining its use, as recurring barriers across cropping systems [7]. Several of these barriers apply directly to okra:

- **Knowledge and awareness:** Farmer knowledge of economic thresholds is limited by the absence of a validated threshold for this crop (Section 3.3), and awareness of *T. urticae* as distinct from other okra pests such as jassids and whitefly is often incomplete, since early stippling damage is easily overlooked until populations are already substantial [7].
- **Cost and availability:** Newer, more effective acaricide chemistries and biological control agents are not always accessible to small and marginal farmers at village level, compared with widely stocked legacy compounds such as dicofol, restricting practical choice regardless of awareness [7].
- **Training:** Scouting and threshold-recognition skills are a prerequisite for any monitoring-based alternative to calendar spraying, and one-off input distribution without accompanying training tends not to translate into sustained behaviour change [7].
- **Socio-economic constraints and extension delivery:** Smallholding size and the labour demands of monitoring-based IPM relative to calendar spraying can make even a technically superior package less attractive to resource-constrained households in the short run, while weak confidence in decision-support information points to extension delivery itself, not merely farmer knowledge, as a limiting factor [7]. Because okra is grown predominantly by resource-constrained households, the socio-economic and extension-delivery dimensions of adoption are as consequential as the underlying technical options themselves.

The successful adoption of IPM technologies depends not only on the availability of effective management options but also on continuous farmer education, local demonstrations, and access to reliable advisory services. These factors collectively influence long-term adoption behaviour.

3.5 Role of Agricultural Extension

Because the preceding section shows that adoption barriers are as much institutional as technical, this section reviews the specific mechanisms through which validated okra-mite IPM could realistically reach farmers. The Farmer Field School (FFS) model—participatory, season-long, discovery-based learning conducted directly in farmers' own fields rather than through top-down instruction—was developed as a response to insecticide-induced pest outbreaks and has since been documented across a large number of low- and middle-income countries, with a systematic review estimating some 10–20 million farmer graduates worldwide [36]; the same systematic review notes that while FFS participation is associated with improved farmer knowledge and, in many studies, reduced pesticide use, the certainty of evidence for yield and income outcomes is more mixed across the studies it assessed, underlining that FFS-style extension is a promising but not unconditionally guaranteed route to behaviour change [36]. The approach has been formally promoted as a route "from farmer field school to community IPM" by the FAO's regional office for Asia and the Pacific [10]. Although most documented FFS work centres on rice IPM in Asia, the same participatory logic is directly transferable to vegetable IPM: building farmer capacity to distinguish phytophagous mites from beneficial predatory mites, to recognize early stippling and webbing, and to make spray decisions based on field observation rather than the calendar.

India's Kisan Call Centre (KCC) scheme provides toll-free, multilingual telephone advisory to farmers, with unresolved queries escalated to subject-matter specialists [24], and the complementary mKisan portal delivers SMS- and voice-based advisories drawing on the same institutional network [27]. Neither platform was documented in the reviewed literature as currently carrying okra-mite-specific advisory content, pointing to a content gap rather than a platform-availability gap—the institutional channel already exists and reaches farmers at scale.

Beyond telephone- and SMS-based advisory, precision technologies such as unmanned aerial vehicles equipped with multispectral, thermal or hyperspectral imaging sensors are increasingly recognized as innovative tools for precision pest management, particularly valuable where infestations are patchy or pests are too small to see readily by eye [18]—conditions that describe early-stage *T. urticae* stippling on okra reasonably well. Extending such precision-technology approaches, or the

FFS/KCC/mKisan channels already reaching Indian farmers, to carry okra-mite-specific, threshold-based advisory content represents a concrete, near-term opportunity rather than a distant prospect.

Strengthening collaboration among research organizations, extension agencies, input suppliers, and farmer groups will improve the dissemination of location-specific recommendations and encourage wider adoption of integrated mite management practices.

TABLE 10
EXTENSION APPROACHES RELEVANT TO OKRA–MITE IPM TECHNOLOGY TRANSFER

Approach	Mechanism	Relevance to okra–mite IPM	Source
Farmer Field School (FFS) / community IPM	Season-long, participatory, discovery-based learning in-field	Model for building scouting and threshold-recognition skill; not yet institutionalized for Indian vegetable IPM	[10,36]
Kisan Call Centre (KCC)	Toll-free, multilingual telephone advisory	Could carry okra-mite advisory; no such content documented yet	[24]
mKisan portal	SMS / voice location- and language-specific advisory	Same institutional reach as KCC; content gap for mite-specific advisory	[27]
UAV / precision pest-management technology	Imaging sensors for early, localized pest detection	Suited to patchy, hard-to-scout infestations; not yet applied to okra mite specifically	[18]

TABLE 11
RECENT STUDIES (2020–2025) INFORMING THE TECHNOLOGY AND FUTURE-PERSPECTIVE CONTENT OF THIS REVIEW

Year	Focus	Key relevance to okra–mite IPM	Source
2020	Drone-based precision pest management technology	UAV imaging suited to patchy, hard-to-scout infestations	[18]
2021	Global review of IPM adoption barriers	Frames technical, training and cost barriers relevant to okra IPM adoption	[7]
2024	Water stress, temperature and outbreak potential in spider mites	Confirms warming, drier conditions raise mite outbreak risk, with specialist/generalist species differing in response	[3]
2025	Acaricide resistance monitoring and structural/genomic insights	Molecular basis for resistance-informed acaricide rotation	[17]
2025	Okra production constraints and opportunities, global review	Source of global production and India's production-share statistics used in Section I	[11]

3.6 Research Gaps

Several gaps emerge from this synthesis: (i) no economic injury level or action threshold specific to *T. urticae* on okra has been established, unlike the quantified EIL documented for cucumber [9]; (ii) resistance-screening methodologies vary widely across studies, limiting direct comparability of "resistant" cultivar rankings between research groups [8]; (iii) the relationship between host-plant resistance and induced biochemical defense is not fully reconciled, since some resistant entries show larger relative biochemical shifts than susceptible ones [15]; (iv) extension research on okra-specific IPM adoption in India is sparse compared with the broader IPM-adoption literature [7]; (v) no published work was identified that integrates precision or digital pest-surveillance tools specifically for smallholder okra–mite management, despite the demonstrated general applicability of such tools to comparably patchy pest problems [18]; (vi) the specialist-versus-generalist difference in climate-driven outbreak potential documented for spider mites generally has not been examined specifically for *T. urticae* on okra under Indian field conditions [3]; and (vii) although trichome number and yield per plant show significant, consistent correlations with mite population across the varieties tested, most other morphological and phenological traits show weak or non-significant associations, and the underlying physiological basis for why leaf-density traits (leaves per branch) correlate positively with mite population while trichome density correlates negatively continues to be mechanistically unexplained [32].

3.7 Future Perspectives

Genomic and structural approaches are clarifying acaricide-resistance mechanisms at the molecular level; recent work combining bioassays with mutation screening and structural analysis has mapped resistance-associated mutations—for example in the voltage-gated sodium channel and cytochrome b genes—across *T. urticae* field populations, offering a route toward resistance-informed acaricide rotation rather than trial-and-error spraying [17]. Precision pest-management technologies, including UAV-based multispectral, thermal and hyperspectral imaging already used for early detection of patchy infestations in other cropping systems, represent a plausible extension to okra-mite surveillance, though validated applications specific to *T. urticae* remain to be developed [18].

Climate-resilient IPM will also need to account for the likely intensification of mite pressure under warming, drier conditions: a comparative study of a specialist and a generalist spider mite species found that water-stressed host plants and elevated temperature both increased outbreak potential, though the magnitude of the effect differed between the specialist and generalist species examined, indicating that climate-driven outbreak risk may not be uniform across *Tetranychus* species and host-plant combinations [3]. Future research should also focus on validating digital decision-support systems under farmers' field conditions and evaluating their economic feasibility for smallholder vegetable production systems.

This reinforces the case for breeding trichome-rich, drought-tolerant okra cultivars that combine mite resistance with resilience to the same hot, dry conditions that favour mite population growth. Taken together, resistance-mechanism monitoring, precision surveillance technology, and continued investment in host-plant resistance breeding represent a plausible, though still developing, path toward reducing reliance on synthetic acaricides in okra–mite management over the coming decade.

IV. CONCLUSION

T. urticae remains a persistent constraint on okra productivity, with documented yield losses, well-characterized biology, and a growing though fragmented body of work on varietal resistance, biochemical defense and acaricide efficacy. The doctoral thesis synthesized here indicates that newer acaricide chemistries (clofentazine, cyflumetofen, fenpyroximate) substantially outperform legacy compounds such as dicofol, which additionally triggers resurgence and whose resistance, once established, declines only slowly even after selection pressure is removed [19,32]. Trichome-mediated host resistance offers a complementary, chemical-free line of defense, corroborated across independent screening studies despite methodological differences between them [8,14,22,28,29,30,32].

Yet translation of this research base into farmer practice is constrained less by a shortage of technical options than by adoption barriers—knowledge, cost, training, and socio-economic and extension-delivery constraints documented in the wider IPM literature but under-studied specifically for Indian okra systems [7]. Encouragingly, mechanisms already exist that could carry validated okra-mite IPM to farmers—Farmer Field School-style participatory learning, the Kisan Call Centre and mKisan advisory network, and precision surveillance technologies [10,18,24,27,36]—such that closing the gap between research and practice is substantially a content and validation challenge: populating these existing channels with okra-mite-specific, threshold-based advisory material, while continuing to invest in resistance-mechanism monitoring and trichome-based breeding for a warmer, drier future [3,17].

The findings synthesized in this review emphasize that future progress in spider mite management will depend on integrating biological knowledge with practical extension strategies. Strengthening collaboration among researchers, extension professionals, policymakers, and farmers will facilitate wider adoption of integrated pest management practices and improve the long-term sustainability of okra production systems.

Overall, sustainable management of *T. urticae* will require an integrated approach that combines scientific innovation, farmer participation, and effective extension support. Continued investment in research, capacity building, and climate-smart pest management strategies will be essential for maintaining profitable and environmentally sustainable okra production.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this review.

REFERENCES

[1] Abou-Zaid, A. M. M., Bakr, E. M., Yassin, S. A., & Hameed, N. A. A. (2012). Abundance of three sap-sucking pests on three eggplant cultivars with utilization of *Phytoseiulus persimilis* Athias-Henriot against *Tetranychus urticae* Koch. *Acarines*, *6*, 49-53.

[2] Ali, W., George, D. R., Shiel, R. S., Sparagano, O. A. E., & Guy, J. H. (2012). Laboratory screening of potential predators of the poultry red mite (*Dermanyssus gallinae*) and assessment of *Hypoaspis miles* performance under varying biotic and abiotic conditions. *Veterinary Parasitology*, *187*, 341-344.

[3] Barnes, C. L., Wickwar, D., Yost, M., Creech, E., & Ramirez, R. A. (2024). The effects of water stress, temperature, and plant traits on the outbreak potential of a specialist and generalist spider mite species (Acari: Tetranychidae). *Journal of Applied Entomology*, *148*(1), 13-25.

[4] Barman, S., & Ghoshal, S. (2009). Effect of mite feeding in relation to depletion of organic, mineral and inorganic compounds in coconut (*Cocos nucifera*). *Environment and Ecology*, *27*(4A), 1746-1748.

[5] Barman, S., & Ghoshal, S. (2011). Biochemical changes in relation to infestation of *Tetranychus ludeni* Zacher on chilli (*Capsicum frutescens*). *Environment and Ecology*, *29*(2A), 881-884.

[6] Bernardi, D., Botton, M., Cunha, U. S., Bernardi, O., Malausa, T., & Garcia, M. S. (2013). Effects of azadirachtin on *Tetranychus urticae* (Acari: Tetranychidae) and its compatibility with predatory mites (Acari: Phytoseiidae) on strawberry. *Pest Management Science*, *69*, 75-80.

[7] Deguine, J.-P., et al. (2021). Integrated pest management: Good intentions, hard realities. *Agronomy for Sustainable Development*, *41*, Article 38.

[8] East, D. A., Edelson, J. V., & Harris, M. K. (1992). Evaluation of screening methods and search for resistance in muskmelon (*Cucumis melo* L.) to the two-spotted spider mite, *Tetranychus urticae* Koch. *Crop Protection*, *11*, 39-44.

[9] El-Adawy, A. M., & El-Esnawy, B. A. (2005). Economic injury level for the two-spotted spider mite, *Tetranychus urticae* Koch, on cucumber under plastic house conditions. *Egyptian Journal of Agricultural Research*, *83*(3), 1217-1223.

[10] Food and Agriculture Organization of the United Nations. (n.d.). *From farmer field school to community IPM*. FAO Regional Office for Asia and the Pacific.

[11] Frontiers in Sustainable Food Systems. (2025). Constraints and opportunities on okra (*Abelmoschus esculentus*) production in Ethiopia: A review.

[12] Geroh, M. (2007). *Ecology and management of Tetranychus urticae Koch on okra (Abelmoschus esculentus L.)* [Doctoral dissertation, CCS Haryana Agricultural University].

[13] Ghoshal, S. (2013). Population dynamics and biochemical fluctuations in relation to the infestation of *Tetranychus neocaledonicus* André on the leaves of *Ocimum sanctum*. *International Journal of Life Science, Biotechnology and Pharma Research*, *2*(3), 225-231.

[14] Guo, Z. X., & Yue, H. X. (2009). Effects of trichomes of plant surface on mites and its enlightenment on biological control of pest mites. *Chinese Bulletin of Entomology*, *46*(2), 210-215.

[15] Hildebrand, D. F., Rodriguez, J. G., Brown, G. C., & Volden, C. S. (1986). Twospotted spider mite (Acari: Tetranychidae) infestations on soybeans: Effect on composition and growth of susceptible and resistant cultivars. *Journal of Economic Entomology*, *79*(4), 915-921.

[16] Hoque, M. F., Khalequzzaman, M., & Wahedul Islam. (2010). Population dynamics of *Tetranychus urticae* Koch and *Phytoseiulus persimilis* Athias-Henriot on three host plants. *Pakistan Entomologist*, *32*(1), 6-11.

[17] Insects. (2025). Acaricide resistance monitoring and structural insights for precision *Tetranychus urticae* management. *Insects*, *16*(5), Article 440.

[18] Journal of Economic Entomology. (2020). Drones: Innovative technology for use in precision pest management. *Journal of Economic Entomology*, *113*(1), 1-25.

[19] Kim, G. H., Song, C., Chang, B. Y., Park, N. J., & Cho, K. Y. (1995). Stability of dicofol resistance of the two-spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae). *Korean Journal of Applied Entomology*, *34*(1), 61-64.

[20] Kumar, D., Raghuraman, M., Singh, R. N., Santeswari, & Singh, J. (2014). Effect of environmental factors on the population of spider mite *Tetranychus urticae* Koch on okra in Varanasi region. *The Ecoscan*, *6*(Special Issue), 231-235.

[21] Kumar, S., Prasad, S., & Singh, R. N. (2002). Resurgence of two-spotted mite, *Tetranychus urticae* Koch (Acarina: Tetranychidae) due to acaricides and botanicals on okra. *Annals of Plant Protection Sciences*, *10*(2), 239-242.

[22] Manual, S. K., Sah, S. B., & Gupta, S. C. (2007). Field screening of some okra cultivars against red spider mite *Tetranychus neocaledonicus* André. *Journal of Applied Zoological Research*, *18*(1), 59-61.

[23] Minhajul-Haque, Tamanna-Islam, Najmoon-Naher, & Haque, M. M. (2011). Seasonal abundance of spider mite *Tetranychus urticae* Koch on vegetable and ornamental plants in Rajshahi. *University Journal of Zoology*, *30*, 37-40.

[24] Ministry of Agriculture & Farmers Welfare. (n.d.). *About Kisan Call Centre (KCC)*. mKisan Portal.

[25] Muhammad Amjad, Bashir, M. H., Gogi, M. D., Muhammad Aslam, Khuram Zia, Khan, M. A., & Ali, L. (2012). Evaluation of some acaricides against the two-spotted spider mite, *Tetranychus urticae* Koch (Acari: Tetranychidae) on cotton under laboratory and field conditions. *Pakistan Entomologist*, *34*(2), 125-129.

[26] Park, Y. L., & Lee, J. H. (2002). Leaf damage and tissue damage of cucumber caused by the two-spotted spider mite (Acari: Tetranychidae). *Journal of Economic Entomology*, *95*(5), 952-957.

[27] Press Information Bureau. (n.d.). *mKisan Portal*. Ministry of Agriculture & Farmers Welfare, Government of India.

[28] Roseleen, S. S. J., & Ramaraju, K. (2011). Effect of okra entries on biology of two-spotted spider mite *Tetranychus urticae* (Koch). *Annals of Plant Protection Sciences*, *19*(1), 67-70.

[29] Roseleen, S. S. J., & Ramaraju, K. (2012). Resistance of okra against two-spotted spider mite *Tetranychus urticae* Koch. *Annals of Plant Protection Sciences*, *20*(1), 126-129.

[30] Roseleen, S. S. J., Ramaraju, K., Verma, A. K., Bhardwaj, S. P., & Gupta, P. R. (2010). Host-plant resistance in okra against the two-spotted spider mite *Tetranychus urticae* Koch. *Pest Management and Economic Zoology*, *18*(1-2), 179-187.

[31] Sharma, S. S., Kalra, V. K., Dhankhar, B. S., & Kaushik, H. D. (2001). Assessment of yield losses caused by mite *Tetranychus urticae* Koch on different varieties/cultivars of okra. *Haryana Journal of Horticultural Sciences*, *30*(1-2), 128-130.

[32] Singh, S. K. (2017). *Screening of okra varieties against two-spotted spider mite (Tetranychus urticae Koch) and its management* [Doctoral dissertation, Banaras Hindu University].

[33] Suri, K. S., & Singh, G. (2009). Chemical induction of resurgence in sucking insect pests of rice. *Journal of Insect Science*, *22*(3), 213-226.

[34] Urbaneja, A., Pascual-Ruiz, S., & Pina, T. (2008). Efficacy of five selected acaricides against *Tetranychus urticae* (Acari: Tetranychidae) and their side effects on relevant natural enemies occurring in citrus orchards. *Pest Management Science*, *64*(8), 834-842.

[35] Van Leeuwen, T., Vontas, J., Tsagkarakou, A., Dermauw, W., & Tirry, L. (2010). Acaricide resistance mechanisms in the two-spotted spider mite *Tetranychus urticae* and other important Acari: A review. *Pesticide Biochemistry and Physiology*.

[36] Waddington, H., Snilstveit, B., Garcia Hombrados, J., Vojtkova, M., Anderson, J., & White, H. (2012). Farmer field schools for improving farming practices and farmer outcomes in low- and middle-income countries: A systematic review. *Campbell Systematic Reviews*.

[37] Yanar, D., Kadoglu, I., & Gokce, A. (2011). Acaricidal effects of different plant part extracts on the two-spotted spider mite (*Tetranychus urticae* Koch). *African Journal of Biotechnology*, *10*(55), 11745-11750.

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