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Preface

We would like to present, with great pleasure, the inaugural volume-10, Issue-7, July 2024, 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.

Environmental Research:

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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(Managing Editor)

Dr. Bhagawan Bharali
(Chief Editor)

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Agricultural Sciences	
Soil Science	Plant Science
Animal Science	Agricultural Economics
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Sustainable Natural Resource Utilisation	Management of the Environment
Agricultural Management Practices	Agricultural Technology
Natural Resources	Basic Horticulture
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Breeding	plant fertilization

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Evaluation of Bioagents for their Efficacy in Management of Root-knot Nematode Infesting Mulberry

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Abstract— *Mulberry is integral to sericulture, with its foliage being crucial for silk quality. The root-knot nematode, Meloidogyne incognita, significantly impacts mulberry by causing considerable leaf yield losses and degrading leaf quality. This study evaluated the efficacy of various bioagents for the eco-friendly management of RKN. The bioagents tested were Purpureocillium lilacinum, Trichoderma harzianum, Trichoderma viride, Pochonia clamydosporia, and Pseudomonas fluorescens, alongside control treatments including carbofuran 3G and neem cake. Results demonstrated that T. viride markedly reduced the nematode population in both soil and roots, achieving a nematode reduction of 79.82% in soil and 85.21% in roots at 120 days post-treatment. These reductions were comparable to those obtained with the chemical standard carbofuran 3G. The application of T. viride, in conjunction with farmyard manure, emerged as a highly effective strategy, offering a sustainable alternative to chemical nematicides. This approach not only controls RKN populations but also enhances soil health, thereby supporting sustainable sericulture practices. These findings underscore the potential of bioagents in fostering environmentally sustainable and economically viable sericulture*.

Keywords— Bioagents, Mulberry, Population, Root-knot nematode, Rhizosphere.

I. INTRODUCTION

The perennial plant mulberry (*Morus alba* L.) is highly adaptable to varied climatic conditions ranging from temperate to tropics and thrives well under different soils. Foliage is the major economic part of mulberry that ultimately decides the quality of raw silk since the silkworm feeds on mulberry leaf alone to derive its nutrients for growth and productivity. The quantity of quality leaf produced per unit area has a direct bearing on cocoon production and raw silk quality.

Several factors contribute in obtaining a successful cocoon crop, among them mulberry leaf alone contributes to around 38.20 per cent which is followed by microclimate in the rearing house (37.00%), silkworm rearing techniques (9.30%) and the breed (4.20%), which signifies the role of quality foliage in cocoon production. Apart from soil parameters, the biotic and abiotic stress factors greatly affect the quality of mulberry leaf. The nutritive values get degraded due to diverse biotic stresses *viz*., diseases (pathogens) and pests (insect/ non-insect) and the mulberry plants attract these pests and diseases due to its perennial, fast-growing and lush green characteristics (Miyashita, 1986). The biotic stressors affect both above and below ground parts of the mulberry plant, the symptoms of which can be easily traced through the foliage.

A markedly higher population of fungi and nematodes could be observed in the mulberry rhizosphere (Nandi *et al.*, 2004). Around forty-two species of nematodes belonging to 24 genera were associated with mulberry from almost all countries, where sericulture is being practiced (Swamy and Govindu, 1965). Among them, the nematodes belonging to five genera *viz.*, *Meloidogyne*, *Rotylenchulus*, *Helicotylenchus*, *Hoplolaimus* and *Xiphinema* were reported from India. The root-knot nematode

(RKN), *Meloidogyne incognita* species alone is known to cause 20-50 per cent mulberry leaf yield loss apart from deteriorated quality (Arunakumar *et al.*, 2018).

The infestation of *M. incognita* (Kofoid and White) Chitwood on mulberry was first reported in India by Narayan *et al*. (1966). The infestation is more commonly noticed in sandy to loamy soils and under irrigated conditions. The RKNs are parasites of underground roots, which is difficult to recognize and hence the damage symptoms very often go unnoticed (Sengupta and Govindaiah, 1991). The affected plants show stunted growth, marginal necrosis and yellowing of leaves. The characteristic knots or galls appear on the roots and affect the utilization of water and nutrients resulting in poor plant growth (Govindaiah *et al.*, 1991).

The RKNs have three life stages – egg, larva with four juvenile stages (J_1, J_2, J_3, J_4) and adult of which, the J_2 infects the host plants (Biligrami and Dube, 1976). The female larva enters into roots, harbours in the sub-epidermal layer and starts feeding on the parenchymatous cells causing hypertrophy and hyperplasia that induce characteristic knots. The larvae undergo four moults in the roots and develop into mature oval or spherical egg-laying females. Each female lays 200-300 ellipsoidal eggs covered with a gelatinous substance. The eggs hatch and larvae are liberated into the soil under favourable conditions. The life cycle is completed in 30-40 days and 2-3 such cycles are noticed per annum. A temperature of 15-30˚C and soil moisture of 40-60 per cent are more favourable for the growth and development of RKNs (Padma *et al.*, 2008). The size and number of galls induced by RKNs keep on increasing as the generations are repeated in the root tissues. Apart from damaging the parenchyma tissue, the cracks and holes in the galls invite secondary root infections. Thus, the root-knot infected plants show symptoms of both nutrient deficiency and other root diseases like root rot (Babu *et al.*, 1996).

The studies reveal that the infestation of RKNs not only affects the growth and development of the crop but also affects the physiology ultimately resulting in inferior quality of foliage. Further, since mulberry leaf is the sole source of nutrition for silkworm, *B. mori*, the cocoon crop and quality of raw silk are severely affected causing huge economic loss to the farmer. Hence, effective management of RKNs is imminent for sustained productivity in sericulture. Though synthetic nematicides are available for the management of RKNs, environmental concerns, mammalian toxicity and longer safety periods limit their utility in sericulture. Alternately, the use of bioagents antagonistic to the nematodes serves the purpose of nematode management apart from improving soil health, which is an apt strategy to pace with the increasing environmental concerns.

With this background, an experiment was planned to identify suitable bioagents for eco-friendly management of RKNs infesting mulberry.

II. MATERIALS AND METHODS

2.1 Experiment site details:

The experiment was carried out in the RKN infested mulberry garden in Kalyapura Village, Shidlaghatta Taluk, Chikkaballapura District i.e., in the Eastern Dry Zone (Zone-5) of Karnataka, India at 13°14'20"N latitude and 77°52'17"E longitude, at an altitude of 904m above mean sea level.

The mulberry plantation selected for isolation of nematodes had red sandy loam type of soil with six years old V1 variety plants, planted at the spacing of 90×90cm; bottom pruning (Kolar method) was followed; field was irrigated in two-days interval with drip irrigation facility *i.e.*, based on soil moisture conditions; organic manures and inorganic fertilizers were applied in accordance with the recommended package of practice. Except for the management of RKN, the selected field was well maintained.

2.2 Bioagents:

The following bioagents were selected based on the reviews and were used for the management of RKN in mulberry. The selected bioagents were,

a) *Purpureocillium lilacinum*

b) *Trichoderma harzianum*

c) *Trichoderma viride*

d) *Pochonia clamydosporia*

e) *Pseudomonas fluorescens*

Along with the five bioagents, Nemahari (bio-nematicide developed by CSRTI, Mysore), neem cake, carbofuran 3G and control (untreated check) are included in the treatments for comparison of the efficacy.

2.3 Treatment details:

TABLE 1
TREATMENT DETAILS

Treatments		Recommendation	Reference
T_1	*Purpureocillium lilacinum*	5 kg/ha (with 5 tons FYM)	Saxena *et al.,* 2021
T_2	*Trichoderma harzianum*		
T_3	*Trichoderma viride*		
T_4	*Pochonia clamydosporia*		
T_5	*Pseudomonas fluorescens*		
T_6	Nemahari	40 kg/ha (with 400 kg FYM)	Nishita and Prateeshkumar, 2015
T_7	Neem cake	2000 kg/ha/yr	Dandin and Giridhar, 2014
T_8	Carbofuran 3G (Standard check)	40 kg/ha/yr	Dandin and Giridhar, 2014
T_9	Control (Untreated check)	-	-

The treatments were incorporated near the root zone of the mulberry within a week after pruning by calculating the dosage per plant as per the recommendations.

2.4 Observations recorded:

In the soil, the initial (before imposing the treatment), intermediary (30, 60 and 90 days after treatment imposition - DAT) and final (120 DAT) nematode population were estimated using combined Cobb sieving and decanting method followed by Modified Baermann's funnel method whereas, in mulberry roots, the number of galls and number of egg masses per root system was counted based on visual observations while the initial, intermediary (*i.e.*, first shoot harvest - 60 DAT) and final (*i.e.*, second shoot harvest - 120 DAT) nematode population were estimated using root incubation method (Ayoub, 1977).

The soil and root samples of the infested garden were collected from the rhizosphere soil of each replication of every treatment using a spade and shovel from the root zone of mulberry. Later, the samples each weighing 200 g of soil and 5 g of roots were collected in a polythene bag. The collected samples were preserved under refrigerated conditions and then analysed for the nematode population before imposing the treatments. The same procedure was repeated to collect the soil and root samples for intermediary and final estimations.

2.4.1 Estimation of root-knot nematode population in soil:

The soil sample of 200 cc was washed thoroughly and processed through combined "Cobb's sieving and decantation method followed by Modified Baermann's funnel method" (Ayoub, 1977) as given below:

a) 200 cc of soil was taken in a 1000 ml beaker and a sufficient quantity of water was added to make soil solution

b) This was stirred thoroughly and allowed to stand for heavier particles to settle down

c) Then the soil solution was passed through a set of sieves of 100, 250, 325 and 400 mesh sizes, respectively

d) Residue from 325 and 400 mesh sieves was collected and poured over a tissue paper spread on a wire gauge and placed on Baermann's funnel

e) Level of water in the Baermann's funnel was maintained to keep the tissue paper wet and left undisturbed for 48 hours

f) After incubation for 48 hours, the volume of suspension was made to 200 ml, out of which 10 ml was pipetted out and used for counting the presence of root-knot nematodes using a stereo-zoom binocular microscope

g) The nematode population from this was finally estimated for 200 cc of soil

2.4.2 Estimation of root-knot nematode population in mulberry roots:

The RKN population in 5 g of roots was estimated using the root incubation method (Ayoub, 1977) as follows:

a) Root samples were washed with water

b) The washed roots were cut into bits of 2.5 cm and then sliced longitudinally

c) The cut bits were then placed over tissue paper spread on the wire gauge and then kept on the Petri plate

d) Water level was maintained in the Petri plate and was kept undisturbed for 48 hours

e) Later, the suspension in the Petri plate was collected and observed for nematodes using a stereo-binocular microscope

f) The nematodes counted were finally estimated for 5 g of roots

III. RESULTS AND DISCUSSION

3.1 Nematode population in the rhizosphere soil:

The observation on the effect of different bioagents on the population of root-knot nematode per 200 cc soil was recorded once before the imposition of treatments (initial), intermediary (30, 60 and 90 days after treatment imposition - DAT) and final (120 DAT). The recorded observations are presented in Table 2 and Fig. 1.

FIGURE 1: RKN infested mulberry root with root-knots or galls

TABLE 2
EFFECT OF DIFFERENT BIOAGENTS ON THE POPULATION OF RKN IN THE RHIZOSPHERE SOIL OF MULBERRY

Treatments		Initial	Nematode population per 200 g root							
			30 DAT	Per cent decrease over control	60 DAT	Per cent decrease over control	90 DAT	Per cent decrease over control	120 DAT	Per cent decrease over control
T_1	***Purpureocillium lilacinum***	209.25	184.25	23.78	147.75	46.07	115.50	59.58	69.00	76.51
T_2	***Trichoderma harzianum***	210.25	174.25	27.92	136.25	50.27	100.25	64.91	64.00	78.21
T_3	***Trichoderma viride***	209.50	168.25	30.40	127.25	53.55	89.50	68.67	59.25	79.82
T_4	***Pochonia clamydosporia***	209.75	186.50	22.85	155.00	43.43	119.00	58.35	69.50	76.34
T_5	***Pseudomonas fluorescens***	210.75	171.50	29.05	132.50	51.64	97.00	66.05	60.00	79.57
T_6	**Nemahari**	210.50	160.75	33.50	111.75	59.21	81.25	71.56	51.75	82.38
T_7	**Neem cake**	209.25	164.00	32.16	112.25	59.03	84.50	70.42	54.25	81.53
T_8	**Carbofuran 3G (standard check)**	209.00	139.75	42.19	81.25	70.34	54.25	81.01	27.50	90.63
T_9	**Control (untreated check)**	209.75	241.75	0	274.00	0	285.75	0	293.75	0
	F-test	NS	*	-	*	-	*	-	*	-
	SEm ±	-	10.63	-	11.32	-	10.59	-	9.69	-
	CD $_{0.05}$	-	31.03	-	33.05	-	30.93	-	28.30	-

DAT – Days after treatment imposition; NS – Non-significant; * - Significant

The observations revealed that the nematode population (J2 stage) in the rhizosphere soil was consistent in all the treatment plots before the imposition of treatments (initial). The analysis of rhizosphere soil samples 30 DAT revealed a significant per cent reduction of nematode population in all the individual treatments as compared to the untreated check. Among the treatments, the least nematode population of 139.75 (42.19% reduction) was recorded in the standard check, carbofuran 3G. Among the bioagents, the least nematode population of 168.25 (30.40% reduction) was recorded in *T. viride*, which was on par with Nemahari 160.75 (33.50% reduction) followed by neem cake 164.00 (32.16% reduction), *P. fluorescens* 171.50 (29.50% reduction), *T. harzianum* 174.25 (27.92% reduction), *P. lilacinum* 184.25 (23.78% reduction) and *P. clamydosporia* 186.50 (22.85% reduction). The highest nematode population was recorded in the control (241.75).

On 60 DAT, the least nematode population among the bioagents was recorded in *T. viride* 127.25 (53.55% reduction) which was on par with Nemahari 111.75 (59.21% reduction). This was followed by neem cake 112.25 (59.03% reduction), *P. fluorescens* 132.50 (51.64% reduction), *T. harzianum* 136.25 (50.27% reduction), *P. lilacinum* 147.75 (46.07% reduction) and *P. clamydosporia* 155.00 (43.43% reduction). The nematode population increased from 241.75 to 274.00 in the untreated check.

Among the bioagents, the least nematode population of 89.50 (68.67% reduction) was recorded in the case of *T. viride* on 90 DAT which was on par with Nemahari 81.25 (71.56% reduction) followed by neem cake 84.50 (70.42% reduction), *P. fluorescens* 97.00 (66.05% reduction), *T. harzianum* 100.25 (64.91% reduction), *P. lilacinum* 115.50 (59.58% reduction) and *P. clamydosporia* 119.50 (58.35% reduction). The highest nematode population was recorded in check (285.75).

Among the bioagents, the least nematode population at 120 days after treatment imposition was recorded in *T. viride* 59.25 (79.82% reduction) which was on par with Nemahari 51.75 (82.38% reduction) followed by neem cake 54.25 (81.53% reduction), *P. fluorescens* 60.00 (79.57% reduction), *T. harzianum* 64.00 (78.21% reduction), *P. lilacinum* 69.00 (76.51% reduction) and *P. clamydosporia* 69.50 (76.34% reduction). The nematode population increased to 293.75 from 209.75 during the 120 days period in the untreated check. The highest per cent reduction in the nematode population was observed in the standard check, carbofuran 3G (90.63% reduction).

The similar results were obtained with *T. viride* applied @ 30 g/m^2 (2×10^6 cfu/g) in the pot culture experiments (Narasimhamurthy, 2010). The exact mechanism resulting in the reduction of the nematode population was not studied. The reduction of the nematode population might be due to the parasitism of nematode juveniles and the production of nematotoxic metabolites by the antagonistic fungi and bacteria (Popal, 2020). The manurial attributes of Nemahari might have enhanced the plant's immune responses against the root-knot nematodes in the rhizosphere soil of mulberry (Kshirsagar, 2017).

3.2 Nematode population in mulberry roots:

The observation on the effect of different bioagents on the population of root-knot nematode per 5 g root samples was recorded once before the imposition of treatments (initial), intermediary (*i.e.*, first shoot harvest - 60 DAT) and final (*i.e.*, second shoot harvest - 120 DAT). The recorded observations are presented in Table 3.

TABLE 2
EFFECT OF DIFFERENT BIOAGENTS ON THE POPULATION OF RKN IN THE ROOTS OF MULBERRY

Treatments		Nematode population per 5 g root				
		Initial	60 DAT	Per cent decrease over control	120 DAT	Per cent decrease over control
T_1	***Purpureocillium lilacinum***	170.25	115.75	37.34	66.00	64.17
T_2	***Trichoderma harzianum***	169.75	112.75	38.97	64.75	64.85
T_3	***Trichoderma viride***	170.00	92.75	49.79	27.25	85.21
T_4	***Pochonia clamydosporia***	168.50	123.50	33.15	66.75	63.77
T_5	***Pseudomonas fluorescens***	169.00	121.25	34.37	64.00	65.26
T_6	**Nemahari**	170.75	102.25	44.65	35.25	80.86
T_7	**Neem cake**	169.00	104.25	43.57	39.00	78.83
T_8	**Carbofuran 3G (standard check)**	168.75	74.75	59.53	16.50	91.04
T_9	**Control (untreated check)**	169.00	184.75	0	184.25	0
	F-test	NS	*	-	*	-
	SEm ±	-	10.68	-	6.03	-
	CD $_{0.05}$	-	31.19	-	17.61	-

DAT – Days after treatment imposition; NS – Non-significant; * - Significant

In the experimental plot, the nematode population in the mulberry roots was almost invariable before the imposition of treatments (initial). The analysis of root samples after imposition of treatments *i.e.*, 60 DAT revealed a significant per cent reduction of nematode population in all the treatments when compared to the untreated check. Among the treatments, the least nematode population of 74.75 (59.53% reduction) was recorded in the standard check, carbofuran 3G. Among the bioagents, *T. viride* 92.75 (49.79% reduction) recorded the least nematode population on par with Nemahari 102.25 (44.65% reduction) followed by neem cake 104.25 (43.57% reduction), *T. harzianum* 112.75 (38.97% reduction), *P. lilacinum* 115.75 (37.34% reduction), *P. fluorescens* 121.25 (34.37% reduction) and *P. clamydosporia* 123.50 (33.15% reduction). The highest nematode population was recorded in the control (184.75).

The least nematode population at 120 days after treatment imposition among the bioagents was recorded in *T. viride* 27.25 (85.21% reduction) on par with Nemahari 35.25 (80.86% reduction) followed by neem cake 39.00 (78.83% reduction), *P. fluorescens* 64.00 (65.26% reduction), *T. harzianum* 64.75 (64.85% reduction), *P. lilacinum* 66.00 (64.17% reduction) and *P. clamydosporia* 66.75 (63.77% reduction). The nematode population increased from 169.00 to 184.25 during the 120 days period in the untreated check. The highest per cent reduction in nematode population was observed in the standard check, carbofuran 3G (91.04% reduction).

On comparing different bioagents, Ravichandra and Somasekhara (2010) obtained similar results wherein *T. viride* was very effective in reducing the nematode population both in soil and roots compared to other bioagents like *T. harzianum*, *P. fluorescens* and *P. lilacinum*. The production of chitinase enzyme by *Trichoderma* spp. might have caused the premature hatching of nematode eggs and thereby controlled the nematode population (Narasimhamurthy, 2010). The capability of the bioagents in colonising the RKN-infested regions might reduce the feeding sites for the nematodes, thereby reducing the nematode population in the roots.

IV. CONCLUSION

From the results obtained in the present studies, it may be stated that the bio-management of RKN serves to be a better approach when the nematode density is considerably low and it may be suggested for the application of *T. viride* @ 5 kg/ha with 5 tons FYM in the mulberry field along the drip line in the furrows after pruning once every year. This will help in reducing the root-knot nematode population, subsequently improving the growth and yield parameters of mulberry plants.

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The History of Sustainable Farming in India -A Review

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Abstract— *Agriculture has played a significant role in India's history throughout its long and rich cultural heritage. A holistic approach to sustainable farming (agroecology or regenerative agriculture) strives to strike a balance between environmental stewardship, economic viability, and social equality. Organic farming is based on the idea that "The Earth has enough for everyone's need but not for everyone's greed"- Mahatma Gandhi. The origins of sustainable farming can be found in prehistoric civilisations when dependence on natural systems made conventional farming methods naturally sustainable. However, as industrialisation and mechanised agriculture spread, they also brought forth practices that were dangerous for the environment and the welfare of communities. The Indian subcontinent's ancient civilisations, such as the Harappan and Vedic civilisations, were forerunners in developing sustainable farming practices that supported their societies for generations. Communities of the time relied on the land for their livelihoods and understood the need to protect it for future generations. Therefore, agricultural practices were closely tied to sustainability concepts. By examining ancient history, Mughal history, and their relevance in the context of modern sustainable farming in India, this article illuminates the knowledge of our ancestors, and it draws conclusions from both literary works and historical data.*

Keywords— Agriculture, Sustainable farming, Organic Farming, Environment, Social equality.

I. INTRODUCTION

Agriculture has been the fundamental support of Indian civilization for thousands of years, playing a vital part in the socioeconomic and cultural advancement of the area. The Indian subcontinent has experienced a wide variety of farming techniques, from the rich plains of the Indus Valley Civilization to modern agricultural operations [1]. Sustainable farming, which prioritises the enduring well-being and efficiency of the land while preserving natural equilibrium, has always been an integral component of our agricultural legacy [2]. As the difficulties posed by climate change and food security intensify, there is a rising focus on revitalising customary agricultural practices and advocating for sustainable farming techniques in India. By integrating contemporary technology and scientific breakthroughs into these traditional methods, Indian agriculture may sustain its prosperity while safeguarding its profound cultural legacy [3]. Incorporating conventional knowledge with modern advancements guarantees the durability of agricultural techniques and enhances the general welfare of farmers and customers. By adopting sustainable farming practices, India can effectively tackle existing environmental issues and establish a more robust agricultural industry for future generations[4]. In addition, implementing sustainable farming techniques can effectively mitigate the detrimental effects of chemical pesticides and fertilisers on the environment, enhancing ecosystem health and better soil fertility[5]. The transition towards sustainability can also bolster food security by encouraging the cultivation of various crops and decreasing reliance on external resources.

II. METHODS

This review article employs a research design that combines historical and comparative approaches to examine the development of sustainable farming methods in India. The study emphasises the ongoing development and change in sustainable farming approaches by analysing historical and contemporary practices. The research design methodically examines literature, historical texts, and modern case studies. Using a holistic approach, this paper offers significant insights into the factors that influence the adoption and adaptation of sustainable farming techniques in India. Through the examination of both historical context and present-day trends, this study provides a detailed comprehension of the difficulties and possibilities for achieving sustainable agriculture in the country. This comprehensive research provides a more complete understanding of the development of sustainable agriculture in India, revealing both achievements and areas that need to be enhanced. The study enhances the discussion on the future of sustainable farming techniques in the region by connecting the past and the present.

III. SUSTAINABLE FARMING: ROOTS FROM ANCIENT INDIA

The Indus Valley Civilization, which thrived between 4300 and 1300 BCE, is known for its proficient agricultural methods, which included sustainable farming practices. They created complex irrigation systems, including the "Karez" system, that allowed growing food in desert areas of India and Pakistan[6]. The Harappan civilisation also used crop rotation, numerous crops, and vegetative propagation to maintain soil fertility. These environmentally friendly methods enhanced total agricultural output while preserving soil fertility[7]. With these inventions' aid, the Indus Valley inhabitants could sustainably grow various crops, including cotton, wheat, barley, and rice [8]. Vegetative propagation is a way of reproducing plants that do not rely on seeds. Plants were propagated and cultivated using stem cuttings and root divisions[9]. They employed organic matter to replenish the soil and improve its structure, such as animal manure and compost. This method aided in retaining moisture and nutrients, as well as the soil's long-term fertility[10].

The creation of the sacred text, the Rigveda, which sheds light on early Vedic agricultural practices, characterises the Vedic era[11]. The Vedas strongly emphasise the value of ecological balance and sustainable land use[12]. The Rigveda refers to the practice of "Yajna" or fire ceremonies, in which sacrifices were offered to deities, and the ashes were scattered over the ground to serve as organic fertiliser [13]. This cyclic process has the dual goals of preserving agricultural yield and soil fertility[13].

Organic farming is not a new notion; it has its origins in ancient Indian practices. 'Jivamrita,' a Sanskrit phrase, translates to 'nectar for the living.' It is a traditional organic fertiliser made from cow dung, urine, jaggery, pulse flour, and water[14]. Similarly, as a natural insecticide and fertiliser, 'Panchagavya,' a combination of cow dung, urine, milk, curd, and ghee, was utilised. These practices demonstrate the ancient Indian awareness of the symbiotic interaction between humans, animals, and the environment[15]. These practices highlight the ancient Indian understanding of the symbiotic relationship between humans, animals, and the environment[16].

The ancient Indian faith of Jainism, which strongly emphasises nonviolence (ahimsa), has substantially contributed to sustainable agriculture methods[17]. Jains adhere to stringent dietary laws and agricultural practices that put the welfare of all living things first. There is little animal and insect harm associated with their agriculture. Jains use methods like "mulching" and "cover cropping" to increase soil fertility and stop erosion, aligning with sustainable farming techniques[18].

Tamil Sangam literature from the classical era (300 BCE–300 CE) offers essential insights into Tamil agricultural practices in the past[19]. The literature describes various habitats in the 'Kurinji' (mountain), 'Mullai' (forest), 'Marutham' (cropland), 'Neithal' (coastal), and 'Palai' (desert) regions[20]. Agroecology was practised by the ancient Tamils, who modified their farming techniques to the local environment[21]. This sustainable strategy guaranteed the balance between agricultural productivity and biodiversity. The Tamil rulers understood the value of irrigation well. With a wealth of resources, they carried out extremely massive irrigation works. [22].

The ancient Indian medical system known as Ayurveda extends its ideas to farming. The gods' physician, Dhanvantari, is honoured for his contributions to medicine and for developing agricultural methods that adhered to Ayurvedic principles[23]. Ayurvedic agriculture included the cultivation of medicinal plants, crop variety, and herbal pesticides, all promoting the well-being of the land and its cultivators[24].

IV. TRACES OF SUSTAINABLE FARMING IN THE MEDIEVAL ERA

The Chera, Chola, and Pandya empires, known for their remarkable contributions to governance and agriculture, implemented sustainable water management systems. The people of the south grew a wide variety of crops, including jackfruit, coconut, palm, areca, and plantain trees, as well as rice, sugarcane, millets, black pepper, different cereals, coconuts, beans, cotton, and tamarind and sandalwood. Regular ploughing, manuring, weeding, irrigation, and crop protection were used to maintain agriculture in South India. During this time, water storage techniques were developed. One of the oldest water-regulation structures in the world that is still in use is the dam on the river Kaveri called Kallanai, built in the first and second centuries AD [25]. The Grand Anicut, built by the Chola king Karikala around the 2nd century CE, is one of the oldest water-regulation structures in the world. These empires prioritised the construction of irrigation canals and tanks, enabling efficient water distribution for agriculture[26]. The ancient Indian practice of rainwater harvesting also played a crucial role in sustainable water management. The Arthashastra, attributed to Chanakya, provides insights into the management of rural areas and agricultural practices of the time[3]. India's "Golden Age" under the Gupta Empire is frequently referred to because of the country's notable agricultural expansion[27]. Evidence of increased agricultural productivity and an increase in the area under cultivation exists. The Gupta emperors maintained the Mauryas' land revenue system. Typically, taxes were paid in kind, and the state kept granaries for storage [28].

4.1 Mughal Era:

The early-16th through the mid-19th century Mughal Empire has been recognised for its architectural wonders, cultural achievements, and economic prosperity. However, the widespread use of sustainable farming methods throughout this time is a topic that has received less attention. Recognising the value of agriculture as the foundation of their economy, the Mughals adopted several cutting-edge farming practices that were environmentally benign[29].

Agricultural tools and water-lifting equipment were vital for farming techniques during the Mughal era (1526–1756). These included equipment for managing water resources and crop cultivation, such as ploughs, harrows, and irrigation channels. Innovative water-raising technologies were also developed under the Mughal Empire, including a manually driven water lift that aided farmers in more effective field irrigation[30]. The farmers also employed organic fertilisers to augment soil fertility[31]. Animal manure was a predominant organic fertiliser, specifically from cattle and sheep. [29].

The Mughals put in place systems of community-based water management, where residents took part in the upkeep of water sources and distribution systems[32]. This decentralised strategy promoted community responsibility for sustainable resource management and equitable water delivery. The irrigation systems that the Mughal engineers built were excellent. They were well trained in water management and careful water use since they had the Persian-Transoxania traditions, which had their roots in the desert and oasis region, ingrained in their minds[33]. The Mughals helped introduce new crops to India. Exchanging crops around the empire diversified crops and reduced insect and disease damage. This diversification increased the population's nutritional diversity[34].

Mughal policies regulated agricultural markets, which included pricing controls, hoarding prevention, and fair trade. The Mughals sought to safeguard farmers and consumers by building a stable and transparent market, ensuring agricultural sustainability. However, the Zamindari class controlled agriculture and revenue throughout the Mughal dynasty. The Zamindari class inherited land pleasure. Farmers had no right to sell or mortgage the land, which caused them much hardship[31].

V. BRITISH COLONIAL RULE IN INDIA

The early 17th century until the middle of the 20th century witnessed British colonial rule in India, significantly impacting many facets of Indian culture, including agriculture. The British made various improvements to farming practices due to economic considerations. In the past, diversifying cropping, a wide variety of crops, and a sophisticated awareness of seasonal rhythms were all hallmarks of Indian agriculture. Our Indian Farmers used indigenous methods for managing soil fertility and depended on traditional knowledge passed down from generation to generation.

To further their economic interests, the British introduced cash crops like indigo, cotton, and opium. While these crops were profitable for the British, they frequently displaced food crops, decreasing food production. This transition had serious ramifications during famines, as food scarcity became a recurring issue[35]. During the British era, railway development made transporting agricultural products from rural areas to cities and ports easier(D'Souza, 2006). This infrastructure improvement facilitated transportation, decreased post-harvest losses, and opened up new markets for farmers. However, rather than cultivating crops essential for local sustenance, the main emphasis remained on those profitable for export[37].

The irrigation system was essential to British India's agricultural development [38]. The British East India Company used contemporary irrigation technologies such as canal irrigation to increase crop yields and food production [39]. One of the world's most significant and most intricate irrigation projects was the Indus Basin Irrigation System, which was finished in the 1930s. The system enabled the cultivation of numerous crops, including cotton, rice, and wheat, and provided irrigation to more than 6 million acres of land[40]. The British government funded irrigation projects and installed canal systems in some areas of India. These initiatives sought to increase agricultural output by supplying a steady water supply[41]. While some regions benefited, others encountered ecological difficulties due to poorly thought-out irrigation plans, which caused waterlogging and salinity problems[42].

British forest management regulations had a significant impact on agriculture. The British government enacted stringent forest restrictions that limited access to woodlands for farming, livestock, and other conventional uses[43]. Due to the requirement to meet various demands, many communities were compelled to adopt agroforestry as a sustainable substitute[44].

Devastating famines struck India numerous times when the British ruled it. Famines were frequent under British rule in India, which was made worse by policies prioritising cash crops over food crops, railways, taxation system, and export/import policies [45]. The Bengal Famine of 1943, frequently blamed on British policies, claimed millions of lives. This terrible incident revealed the weaknesses in the agriculture system and the requirement for a sustainable strategy[46].

5.1 Swadeshi and Sustainable Farming:

The Swadeshi movement, a vital element of the freedom struggle, advocated using indigenous goods and resources(D.M. Diwakar, 2009). In the agricultural context, this translated into a revival of traditional and sustainable farming practices. Farmers were encouraged to rely on native seed varieties, shunning the dependence on foreign seeds and chemical inputs[48]. Swadeshi began a conscious effort to reclaim agricultural self-sufficiency(D.M. Diwakar, 2009).

5.2 Sustainable Farming: Gandhian Principles:

As part of his strategy for a rural economy that is self-sufficient, Mahatma Gandhi, an iconic leader in the Indian freedom movement, gave a lot of focus to sustainable agriculture. Decentralised and sustainable agriculture was encouraged by his ideology, which was encapsulated in the idea of "Sarvodaya," or the well-being of all [49]. Gandhi envisioned villages as self-sufficient communities that could provide for their needs through sustainable farming and access to natural resources. Agriculture reforms were a crucial part of Gandhi's Constructive Programme, a set of projects designed to create a new social order. Gandhi exhorted farmers through his teachings to adopt practises that preserved the land and improved the socioeconomic standing of rural communities[50]. Gandhi's initiative led to the establishment of model farms, showcasing sustainable and ethical farming practices. Promoting Khadi, a hand-spun and handwoven cloth during the freedom struggle, was inextricably tied with sustainable agriculture. The Khadi movement attempted to give rural people economic independence by emphasising village-based industries such as agriculture[51]. This supported the use of organic farming methods while discouraging the use of expensive inputs, which aligned with sustainability objectives. The Ahimsa principle was also extended to agriculture, with farmers encouraged to cultivate without harming the environment. Avoiding harmful chemicals and treating animals compassionately, crop rotation, and other non-invasive practices were essential to the Ahimsa agricultural concept[52]. Women were vital to sustainable farming during the freedom movement. Women took over farming while men struggled for freedom [51]. Traditional knowledge of seed preservation, natural pest management, and sustainable farming strengthened rural communities[53].

VI. SUSTAINABLE FARMING IN MODERN INDIA: POST-INDEPENDENCE

In India's changing agricultural landscape, sustainable farming practices have become paramount. With a growing population and increased environmental concerns, it is more important than ever to strike a balance between productivity and ecological well-being.

6.1 The Green Revolution and Unsustainable Practices:

India went from a food grain deficit to a surplus after the Green Revolution. The Green Revolution had the most significant impact on socioeconomic progress. Over time, agriculture intensified, degrading the delicate agro-ecosystem. High production costs and declining agricultural profits hurt farmers[54]. Overadoption of agricultural technologies by farmers to make the Green Revolution successful has adverse effects on soil fertility, erosion, toxicity, water resources, underground water pollution, salinity, human and livestock diseases, and global warming. Chemical overuse pollutes land, air, water, animal feed and fodder[55]. The Green Revolution of the mid-20th century introduced high-yielding crop types, synthetic fertilisers, and pesticides. This revolution enhanced worldwide food production but degraded the environment, eroded soil, and destroyed biodiversity. Unsustainable irrigation practices stress water resources, threatening modern agriculture's future[56].

6.2 Permaculture:

In the 1970s, Bill Mollison and David Holmgren established a concept known as permaculture, which included a design framework for environmentally responsible agriculture[4]. It emphasises integrating agricultural components into a mutually beneficial and self-sustaining system. Permaculture concepts have seen widespread adoption to establish resilient and varied agricultural ecosystems[57]. Permaculture is a science for small farmers, and India can get a lot out of it since marginal farmers own 67% of farmland. Indian farmers' traditional farming techniques, like ploughing with bullock carts, farmers' seed storage techniques, and using manual stone grinders for fodders, highlight their simplicity and sustainability. However, due to mechanisation and corporate seed control, these are tumbling. Small-scale farming in India is more favourable than in the United States, and the possibility of food self-sufficiency through permaculture is increasing in India. Permaculture emphasises self-sufficient farming practises; however, it is hampered by a lack of willingness to adopt diverse food habits[58].

6.3 Agroforestry:

Agroforestry is widespread in India, particularly in rural regions. It entails incorporating trees into agricultural landscapes to produce a diversified and sustainable environment [59]. Agroforestry benefits in India include increased soil fertility, biodiversity, and ecological resilience[60]. However, it encounters obstacles such as a lack of awareness and ineffective policies. The National Agroforestry Policy of India 2014 is a comprehensive framework for policymaking to enhance agricultural lives by increasing agricultural productivity to combat climate change[61]. Agroforestry techniques, such as growing trees alongside crops, can reduce soil erosion, improve soil fertility, and preserve water. Farmers can increase their income by combining trees and regular crops[62]. As carbon sinks, agroforestry systems can reduce greenhouse gas emissions. By providing a variety of nutrient-dense food sources, crop diversification improves the nutritional security of nearby people. Agroforestry can make agricultural landscapes more climate-change-resistant [63].

VII. SUSTAINABLE FARMING FUTURE AND BEYOND

In recent years, sustainable farming has emerged as a critical response to the adverse environmental impacts provided by conventional agricultural practices. The imperative need to balance food production with environmental protection drives this paradigm change. Sustainable farming practices promise a greener, more resilient agricultural landscape.

7.1 Precision Farming:

Precision farming is a growing trend in India's agricultural sector. It uses cutting-edge technologies such as GPS, drones, and precision irrigation systems to increase crop yields and reduce waste[64]. Many Indian farmers are already using precision farming techniques, and the trend is projected to continue in the future years. The government's emphasis on using remote sensing GIS, ICT, drones, robotics, start-ups, and other technologies and reducing greenhouse gas (GHG) emission intensity has enabled precision agriculture[5].

7.2 Regenerative Agriculture:

Regenerative agriculture seeks to renew ecosystem services and improve food production's environmental, social, and economic components through soil conservation. Traditional farming practices can degrade soil and decrease yield. Regenerative agriculture is promoted as a solution to these problems, focusing on soil health and carbon sequestration [65]. The core principles of regenerative agriculture are to cover the soil, minimise soil disturbance, keep living roots in the soil all year, promote plant diversity, integrate animals, and restrict or eliminate the use of synthetic substances (such as herbicides and fertilisers). The ultimate goals are to revitalise the soil and land while providing environmental, economic, and social advantages to the larger community[66].

7.3 Climate-Smart Agriculture:

Climate-smart agriculture(CSA) assists farmers in adapting to climate change by incorporating climate-resilient practices into their operations[67]. Climate change poses significant threats to agriculture, particularly dryland agriculture. Countries should embrace climate-friendly agricultural development strategies to reduce climate change impact by reducing greenhouse gases while preserving or growing food supply, especially in dryland agriculture[68]. The scope of CSA includes improved water management, crop breeding, conservation agriculture, crop diversification planting, weather index-based insurance, integrated soil fertility management, and other cutting-edge technologies[69].

7.4 Vertical Farming for Urban Sustainability:

Growing crops vertically in a safe indoor environment is known as "vertical farming," and it mostly makes use of hydroponic or aeroponic production systems. Numerous potential advantages of vertical farming include better use of available space, less need for water, faster growing times, less need for pesticides and herbicides, and protection from harsh weather[70]. Although "vertical farming" has been defined in several ways, it typically refers to the multilayered production of plants in carefully regulated indoor settings. Vertical farming has a long history with precedents like the Hanging Gardens of Babylon. Vertical farming seeks to boost long-term food production in the face of climate change. [71].

Vertical farming, an eco-friendly, energy-saving, and promising alternative to conventional farming, will help feed the world's growing population in the future. Vertical farming is gaining popularity worldwide due to its capacity to manage resources and efficiently produce high-quality food[72].

VIII. CONCLUSION

A dynamic and continual process of adaptation and invention is shown throughout the history of sustainable agricultural practices. The Indian subcontinent has developed sustainable agricultural practices since the Harappan Civilization. Sustainable agricultural practices will continue to evolve and play a critical role in preserving the resilience and viability of our agricultural systems as the globe faces increasing problems connected to climate change, population expansion, and environmental degradation. Sustainable farming is a tribute to the timeless wisdom that remains under our guidance as the globe grapples with environmental issues.

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The Rise of Agritourism: An overview of Trends, Impacts and Future Prospects

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Abstract— *Agritourism, the blending of agriculture and tourism, has emerged as a significant global phenomenon in recent years. This review paper aims to provide an overview of the rise of agritourism, analyzing its various dimensions, impacts, and potential for sustainable development. Drawing upon a comprehensive selection of academic literature, industry reports, and case studies, this review synthesizes key findings to shed light on the evolution and significance of this growing trend. The paper begins by outlining the historical context of agritourism, tracing its origins from traditional farm-based activities to the development of organized agritourism enterprises. Subsequently, it explores the drivers behind the surge in agritourism's popularity, including increasing urbanization, consumer interest in authentic experiences, and a growing desire for sustainable and ethical travel. Furthermore, the review delves into the diverse forms of agritourism that have emerged, ranging from farm stays and farmers' markets to educational tours and hands-on experiences in agricultural practices. It also highlights the role of digital platforms and social media in promoting agritourism destinations and fostering a connection between urban tourists and rural agricultural communities. The impacts of agritourism, both positive and negative, are examined in the paper. Positive effects include economic benefits for rural communities, preservation of cultural heritage, and the promotion of agricultural knowledge and understanding among visitors. On the other hand, challenges such as increased environmental footprints, over-tourism, and potential disruption of local traditions are discussed as well. The review also analyzes the regulatory and policy frameworks that have been developed in response to the rise of agritourism. Governments and organizations have sought to strike a balance between promoting rural development and safeguarding the agricultural sector's sustainability and natural resources. Finally, the paper explores the future prospects of agritourism as a sustainable and resilient form of tourism. It discusses opportunities for innovation and diversification, such as incorporating agriculturist principles, integrating technological advancements, and addressing the changing preferences of travelers. In conclusion, the rise of agritourism represents a dynamic and evolving trend with the potential to contribute positively to rural development, sustainable agriculture, and cultural exchange. While challenges exist, careful planning and collaboration between stakeholders can ensure that agritourism continues to thrive as a valuable sector within the broader tourism industry. Further research and strategic initiatives are essential to harness the full potential of agritourism while mitigating its potential negative impacts.*

Keywords— Agritourism, Agriculture, Impact, Rise, Tourism.

I. INTRODUCTION

In recent years, the world has witnessed a remarkable and transformative shift in tourism preferences, as travelers increasingly seek authentic, immersive, and sustainable experiences. In response to this growing demand, a unique form of tourism has been gaining traction worldwide agritourism. The convergence of agriculture and tourism has given rise to a new and dynamic sector that offers travelers the opportunity to connect with rural life, experience farming activities, and gain insights into local agricultural practices.

This review paper aims to provide a comprehensive examination of the rise of agritourism, analyzing its trends, impacts, and potential for future development. As urbanization continues to reshape landscapes and blur the lines between rural and urban areas, agritourism presents itself as a bridge that reconnects people with the land, fosters appreciation for agricultural heritage, and supports sustainable rural economies. The roots of agritourism can be traced back to centuries-old traditions where people would visit farms for agricultural education, festivities, and cultural exchanges. However, the modern surge in agritourism's popularity is a response to changing travel preferences and a heightened desire among tourists to escape the fast-paced urban lifestyle in search of authentic, nature-oriented experiences. From family vacations on working farms to educational field trips showcasing sustainable agricultural practices, agritourism has evolved into a diverse and thriving sector.

Throughout this review, we will explore the drivers behind the rise of agritourism, uncovering the factors that have contributed to its widespread appeal among travelers. Moreover, we will delve into the various forms of agritourism that have emerged, ranging from farm stays and agricultural festivals to culinary tours centered around locally sourced produce. This review will also shed light on the regulatory and policy frameworks that have been developed to support and regulate agritourism activities. Governments and organizations worldwide are grappling with the task of striking a balance between fostering rural development through tourism and safeguarding the delicate balance of the agricultural sector and its natural resources.

1.1 Farming enterprises and techniques in agritourism

- Farm machinery Roadside Stand selling fresh farm goods and crafts Arts & Crafts Demonstrations
- Processing and selling of agricultural products
- Agri-activities demonstrated
- Wool processing; sheep shearing.
- Fishing and/or hunting.
- Local fare
- The riding of horses.
- Agri-tourists are drawn to snow fields and periods of heavy rain.
- A comfortable resting area for guests, perhaps under a large banyan tree.
- Educational excursions for students, officials, and forward-thinking farmers
- Horseback riding, outdoor schools that are mobile in nature and teach agriculture, farm schools to teach a specific skill, snow fields, and a lot of rain all draw in agri-tourists.
- A comfortable resting area for guests, perhaps under a large banyan tree.
- Educational excursions for students, officials, and forward-thinking farmers
- Farm Schools that focus on teaching a specific skill
- Horseback riding;
- Outdoor schools that are nomadic in nature and teach agriculture.
- Agri-tourists are drawn to snow fields and periods of heavy rain.
- A comfortable resting area for guests, perhaps under a large banyan tree.
- Educational outings for students, officials, and forward-thinking farmers
- Farm Schools that focus on teaching a specific skill
- Agriculture is taught at outdoor schools that are nomadic in nature.

1.2 Well-being through agritourism:

1.2.1 Well- being for Farmers

- Agritourism helps farmers by providing an alternative source of income and raising their standard of living.
- The consumer markets would grow, which would lead to a rise in rural employment.
- Farmers would have the opportunity to increase their farming activities.

- Rural young farmers will be taught managerial skills and entrepreneurial behaviors.
- The farm's companies will have the chance to continue operating for a very long time.

1.2.2 Well- being for Communities

- People, especially those who reside in urban areas, will learn about the value of agricultural land.
- The rural economy will be strengthened by creating job possibilities.
- This encourages communication across cultures and regions.
- It is possible to advertise the regional agricultural goods and services.
- It is possible to foster and maintain Indian traditional knowledge.
- Tourism will grow even in remote regions, which will help the local economy grow and generate money through jobs.

1.2.3 Well- being for Tourists/Visitors

- It will offer visitors a chance to interact with nature and learn about the value of the environment in which they live, as well as a firsthand understanding of the many farming tasks carried out on a farm.
- Aids in educating tourists and other visitors about rural living and provides them with knowledge of locally produced agricultural products.

II. REVIEW OF LITERATURE

Ammirato (2014) studied on “The Agritourism as a Means of Sustainable Development for Rural Communities: A Research from the Field” and reported that 51 per cent of respondents said they would boost their investments in agritourism initiatives.

Pinky and Kaur (2014) conducted a study on “Prospects and Problems of Agri-Tourism in Punjab State” and reported that to encourage agritourism entrepreneurs, 93.33 percent of respondents recommended coordination and cooperation between the federal government and state governments, while 80.00 percent said training in various agritourism-related topics should be made available.

Bhavana (2015) incorporated a research on “Agri-Tourism: Potential Socio-Economic Impacts in Kisumu County” and found that agro-tourism has an opportunity for local farmers to increase income and revenue generation for government.

Pal (2016) researched on “Agricultural Tourism- Typology Study & Tourist Perception with Reference to Maharashtra” and. More than 70.00 percent of the urban Indian class has not seen a village, only 15.00 percent of the tourist actually is knowledgeable about the typology of agritourism and almost 32.00 percent tourist never heard of it, while 53.00 percent heard but not sure about the same and also found that 78.00 percent tourists were take part in Agri Tourism activities followed by 63.00 percent enjoying the Village stay.

Srivastava (2016) conducted study on “Agritourism as a Strategy for the Development of Rural Areas Case Study of Dungrajya Village, Southeast Rajasthan, India” said that Farmers used Agritourism business for diversifying farm products and developing new market for generating supplementary income. In many cases, Agritourism also helped farmers‟ children to remain in agricultural activities.

Shembekar, (2017) studied on Consumer Awareness and Preference of Unban Tourism in Nagpur towards Agritoursim” and found that 18.00 percent respondents were not aware about Agritourism. In fact, 86.50 percent people never visited agritourism and also found that 81.00 per cent respondents would like to visit agritourism.

Amaral *et al.*, (2017) researched on “Agricultural Communication Students Perceptions, Knowledge, and Identified Sources of Information about Agritourism” and found that 52.00 percent respondents did not know Agritourism and 48.00 percent indicate about agritourism and also reported that 95.40 percent take information from website, 93.80 percent from Print advertisement and 81.50 percent respondents heard Word-of-mouth about Agritourism.

Haldar (2018) documented the challenges and opportunities of Rural Tourism and reported 86.00 percent of the respondents said that rural tourism will be beneficial for both rural and urban society. This will help in socio-cultural and economic development in rural areas and moreover 75.00 percent of the respondents were interested to know more about the rural Tourism.

Schaller *et al.,* (2018) studied on Agricultural Landscapes, Ecosystem Services and Regional Competitiveness" and reported that the agritourism helps the government to provide the economic benefit to the rural farmers and opportunity to develop the less developed areas

Krishna (2019) conducted research on "Challenges and Strategies for Promotion of Agritourism: A Multi-dimensional Study" and found challenges faced by ATCs in sampling area i.e weak communication skills of staff followed by lack of commercial approach and lack of organised effort like Farmers' organisation in Maharashtra.

Roman and Golnik (2019) did research on Current Status and Conditions for Agritourism Development in the Lombardy Region and found that 45.00 per cent respondents said villages have positive effects of agritourism followed by 32.50 per cent of respondents benefited from agrituorism by selling food products, offering guide and transport services.

Vinuta *et al.,* (2019) studied on of Agri-Tourism with Reference to Coffee Plantations in Kodaguand found that 38.00 percent of the planters and 43.00 percent of the tourist said there are more chances to increase the employment opportunities by Agritourism and 90.00 percent of planters get annual income from crop yield above Rs.15 lakh. And also reported that 43.00 percent of the tourist said increase in employment opportunities as the economic impact.

Krishna *et al.,* (2020) examined the impact of Agritourism as Perceived by Multiple Stakeholders and found that an average number of employment days in Maharashtra and Goa had increased from 149 to 202 man-days/year and 117 to 208 man-days/year viz. after 2016.

Joshi *et al.,* (2020) conducted a study on "Sustainable agri-food supply chain practices: few empirical evidences from a developing economy" and has taken Uttarakhand as the case study, where tourism and agriculture collectively contribute 13.50 percent to the Gross domestic product (GDP)

Arru *et al.,* (2021) analyzed the Economic performance of agritourism of farms located in a less favored area in Italy" and found 46.00 percent share of total GFR (Gross Farm revenue) generated by Agritourism.

III. SCHEME AND POLICIES

3.1 Swadesh Darshan Scheme:

In order to coordinate the growth of the nation's theme-based tourist circuits, a Central Sector Scheme was introduced in 2014–15.

3.1.1 Objectives of Scheme:

- Promote the country's cultural and heritage values in order to provide jobs and a source of income in the targeted regions.
- Improving the circuit's / destinations' attraction to tourists in a sustainable way by building out world-class infrastructure
- To expand employment through the active participation of local communities, it is important to: Make local populations aware of the significance of tourism for them in terms of increased revenue sources, enhanced living standards, and general area development.

3.1.2 Financial Assistance under this scheme:

- The programme is entirely supported at the federal level, and attempts are made to align it with other programmes run by the federal and state governments as well as to take advantage of the voluntary financing that corporations and central public sector organizations make available for CSR activities.
- Under the Swadesh Darshan Scheme, the money would be given to the implementing agency. The funds must be sanctioned rigorously in accordance with the GFRs (General Financial Rules) and the directives periodically published by the Ministry of Finance. All submissions will go through the IFD (Integrated Finance Division) of the Ministry of Tourism.
- Funds wouldn't be released until the implementing agency gave the Ministry a copy of the work orders and a good for construction DPR (Dividend Payout Ratio).

3.2 Maharashtra introduces Agro-tourism policy:

This strategy will make it easier for people to travel, take in the great outdoors, visit farms, and engage in ecotourism, local delicacies made from organic ingredients, and picking seasonal fruits.

3.2.1 Objectives:

Rural development through agrotourism, market access for agricultural products, encouragement of agriculture-related businesses, employment for young women from rural areas, folk art and tradition exhibitions, and a pollution-free, eco-friendly environment are all goals.

3.2.2 Loans benefits:

- You must own a plot of land between two and five acres with living quarters and a meal preparation facility in order to register under the policy.
- Forms are available at the regional deputy director's office of the Maharashtra Tourism Development Corporation or online at www.maharashtratourism.gov.in.
- An agrotourism center must pay a one-time registration fee of 2,500 and a renewal fee of 1,000 every five years to remain registered.

IV. AGRITOURISM PRACTICES: SOME SUCCESS STORIES IN THEIR EVOLUTION

4.1 YATRA-Farm Tourism Venture:

- Name of Agripreneur: Samir Ranjan Bordoloi
- Address: S.S. Botanicals, No.1, Sonarigaon, Tarajan, Jorhat.
- Education: Graduate-Agriculture
- Annual Turnover: 1 Crore
- Mobile: +91-8486029583

Since 2005, Samir has been promoting organic farming and offering consulting services in the north-eastern states. He has been successful in inspiring over 500 farmers to switch to organic farming. He launched a business named "Yatra" in 2010 to increase the revenue of organic farmers. The entire strategy is built on developing model villages, model farms, and agricultural tourism.

After earning his B.Sc. (Agri) degree, Samir started working in the corporate world. But in 2003, he decided to leave his position because he wanted to launch his own business. He took the initiative to start a chemical-free vegetable production method after receiving AC&ABC training for two months, and in the process, he won the support of farmers and the general public. His business is engaged in a number of activities, such as consulting services, organic farming, the supply of agricultural farms with inputs, the manufacturing of vermicompost, agrotourism, and related pursuits. Although his activities are dispersed throughout upper Assam and a few NE states, he is well-known in his field. He has 22 workers working for him and has helped about 500 farms.

4.2 Aryan Farms:

- Prof Mrs. Shubhada Mohan Kulkarni
- In-Charge Director
- KCE's Institute of Management and Research, Behind DIC, Jalgaon, Maharashtra
- Mobile: +91 9423973140

The Mahajan family's dream project, Aaryan Foundation, aims to serve mankind by addressing all facets of human life, including health, medical care, education, agriculture, horticulture, agriforestry, agritourism and others. In Jalgaon, this Noble foundation was founded in 1999. The activity of this foundation began in the medical field since the Mahajan family is committed to helping individuals in the medical field. In the Jalgaon district, Aryan Farms is quickly gaining notoriety. The distance to the city is only 3 KM. It provides a lovely picnic area, which is a fantastic reprieve for the locals from the hustle and bustle of daily life. Aryan Farms is a serene location with 15 hectares of land that is home to large trees, grass, an emu park, a floral park, and a cactus house.

V. DIFFICULTIES IN THE DEVELOPMENT AND PROMOTION OF AGRI TOURISM

- Lack of training in tourism, ignorance of agritourism, ignorance of the concept of agritourism,
- Lack of knowledge of farmers' educational backgrounds
- Lack of orientation in marketing and customer relations
- Inadequate agrotourism marketing plans
- Insufficient risk management approaches
- Adverse climatic conditions; personal difficulties faced by farm families; conflict with primary agricultural output; infrastructure restrictions.

VI. THE ROLE OF AGRICULTURAL EXTENSION SERVICES IN REDUCING AGRITOURISM'S CHALLENGES

- To inform farmers about the significance of value addition, the advantages of agritourism, and the agritourism strategy.
- Production process expertise as well as marketing and promotion training
- Commercialised farming system
- Aid and direct farmers in identifying both agricultural and non-agricultural activities
- To build agritourism businesses on both new and existing farms.
- Help policy makers identify the laws and regulations needed to run the agritourism businesses.
- To inform them on the methods and tools used to advertise and promote agricultural tourism products.

VII. CONCLUSION

Agritourism is becoming more widely recognized as a viable option for boosting rural household incomes, the local economy, and overall national development. Direct marketing is agritourism. Educational initiatives can aid in fostering the shift to this new agriculture, which is also aiding in the growth of agrotourism. In conclusion, the rise of agritourism represents a fascinating confluence of agriculture and tourism, presenting travelers with unique experiences while offering rural communities an avenue for economic development. As we navigate the complexities of balancing tourism growth with environmental and social sustainability, it is imperative to examine the trends, impacts, and future prospects of agritourism. By doing so, we can harness its potential to foster meaningful connections between urban and rural communities while promoting a more sustainable and responsible approach to travel.

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Smart Pest Management in Precision Farming: A Comprehensive Review

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Abstract— *Precision agriculture has transformed current agricultural techniques by incorporating cutting-edge technology to maximize resource usage, increase crop output, and reduce insect threats. This article delves into the nexus of precision agriculture and pest management, explaining how precise approaches are designed to address pest concerns effectively and sustainably. Precision agriculture takes a multifaceted approach to pest control, using technology and tactics from throughout the agricultural environment. Remote sensing technologies are essential for early pest identification, sensor technologies for real-time field monitoring, and GPS/GIS applications for accurate mapping and focused control methods. The integration of entomological data is critical in precision pest management because it allows for precise pest identification, behaviour monitoring, and predictive modelling, which helps to successfully forecast and prevent pest outbreaks. Automated insect identification technologies, DNA barcoding, and decision support systems allow for proactive pest control tactics adapted to individual pest species and environmental circumstances. Precision pest management's economic and environmental consequences highlight its importance in contemporary agriculture, with cost-benefit analyses demonstrating increased efficiency and a lower environmental imprint. To encourage wider use and maximum benefits, specific solutions must address implementation challenges such as technology hurdles and farmer acceptance.*

Keywords*— *Automatic insect identification systems, Pest control, Precision agriculture, Remote sensing technology, Sustainable agriculture.

I. INTRODUCTION

Precision agriculture, also known as precision farming or smart farming, is a kind of agricultural management that uses technology, data, and analytics to improve crop productivity and resource efficiency. Precision agriculture is fundamentally about tailoring agricultural operations to individual field circumstances in order to maximize yields, minimize inputs, and reduce environmental consequences (Bhakta *et al*., 2019; Monteiro *et al*., 2021). Pest control is an important part of agricultural production since pests may lower crop output and quality (Dent and Binks, 2020; Stanley *et al*., 2022). Precision agriculture is important in pest control because it gives farmers tools and procedures for successfully monitoring, detecting, and mitigating pest threats. Precision agriculture uses modern technology such as sensors, drones, and data analytics to allow focused pest management tactics while decreasing pesticide usage and environmental hazards (Shaikh *et al*., 2022).

Precision agriculture became apparent in the late twentieth century to meet the rising need for more effective and sustainable agricultural techniques (Bongiovanni and Lowenberg-DeBoer, 2004; Mulla, 2013). Initially, precision agriculture emphasized the use of global positioning systems (GPS) for precise field mapping and navigation. Over time, technological improvements like as remote sensing, data analytics, and automation have broadened the scope of precision agriculture and its pest control applications (Sishodia *et al*., 2020; Roberts *et al*., 2021). Precision agricultural technologies have grown fast in recent years, because to advances in digitalization, communication, and sensor technology (Khanna and Kaur, 2019). Farmers now have access to a diverse set of precision agricultural equipment and systems aimed at improving pest monitoring, early identification, and management procedures. These technologies have transformed pest control procedures by making them more accurate, efficient, and ecologically friendly (Shafi *et al*., 2019; Bolfe *et al*., 2020).

Remote sensing technology, such as satellite imaging and aerial drones, may give significant information on crop health and pest infestations (Zhang *et al*., 2019; Abd El-Ghany *et al*., 2020). High-resolution photos taken from above may detect minute changes in vegetation, enabling farmers to spot pest infestations and take appropriate action (Tsouros *et al*., 2019). Remote sensing offers large-scale agricultural landscape monitoring, allowing for early identification and tailored pest control measures (Weiss *et al*., 2020; Kumar *et al*., 2022). Sensor networks installed in fields capture real-time information on ambient conditions, soil moisture, temperature, and insect activity (Bencini *et al*., 2009). Soil moisture sensors, temperature monitors, and insect traps provide continuous monitoring, enabling farmers to notice changes in pest populations and react quickly (Sciarretta and Calabrese, 2019). Sensor-based monitoring systems provide for proactive pest control tactics, minimizing dependency on reactive measures such blanket pesticide treatments (Sangeetha *et al*., 2024).

Artificial intelligence (AI) approaches are being employed to analyse agricultural data to detect pest outbreak trends (Jose *et al*., 2021). Machine learning algorithms can forecast pest infestations and offer effective management strategies by analysing historical data on pest occurrences, meteorological conditions, and crop health (Domingues *et al*., 2022). AI-powered solutions automate pest identification and decision-making, increasing the efficiency and accuracy of pest control techniques (Javaid *et al*., 2023). Precision agricultural technology have transformed pest management methods by allowing for focused, data-driven approaches to monitoring, identification, and control (Roberts *et al*., 2021; Liang and Shah, 2023). Farmers may maximize pest control tactics while reducing environmental impact and input costs by using remote sensing, sensor networks, machine learning, and decision support systems. In this post, we'll look at how precision farming may drive evolutionary change in contemporary agriculture while also improving pest management skills, providing farmers with novel solutions to pest concerns.

II. KEY COMPONENTS OF PRECISION AGRICULTURE IN PEST MANAGEMENT

Precision agriculture has transformed pest management by combining new technology and data-driven methodologies to monitor, identify, and control pest infestations more accurately and efficiently (Liang and Shah, 2023). In this review, we will take a comprehensive look at the major components of precision agriculture for pest control, such as remote sensing technologies, sensor technologies for field monitoring, and GPS and GIS applications.

2.1 Remote Sensing Technologies:

Remote sensing technologies play a crucial role in pest management by providing valuable insights into crop health, pest infestations, and environmental conditions over large agricultural areas (Abd El-Ghany *et al*., 2020). Two primary remote sensing technologies used in precision agriculture for pest management include

Satellite Imaging for Pest Detection: Satellite imaging enables the detection and monitoring of pest infestations over extensive agricultural landscapes. High-resolution satellite imagery captures detailed images of crops, allowing farmers to identify areas of stress, discoloration, or damage caused by pests. By analysing satellite imagery, farmers can detect pest outbreaks early, assess the extent of infestation, and target management interventions more effectively (Miranda *et al*., 2014; Yang, 2018).

Unmanned Aerial Vehicles (UAVs) in Pest Surveillance: Unmanned aerial vehicles (UAVs), also known as drones, are increasingly used in precision agriculture for pest surveillance and monitoring. Equipped with high-resolution cameras and multispectral sensors, UAVs can capture aerial imagery of crops at various wavelengths, enabling the detection of subtle changes in plant health indicative of pest damage. UAVs provide farmers with real-time aerial views of their fields, allowing for rapid assessment and response to pest infestations (Gao *et al*., 2020; Maslekar *et al*., 2020; Velusamy *et al*., 2021).

2.2 Sensor Technologies for Field Monitoring:

Sensor technologies play a vital role in field monitoring by providing real-time data on soil conditions, climate parameters, and pest activity. These sensors enable farmers to assess pest habitats, monitor environmental conditions, and implement targeted pest management strategies. Two types of sensor technologies commonly used in precision agriculture for pest management include:

Soil Sensors for Pest Habitat Assessment: Soil sensors measure various parameters, such as moisture levels, temperature, and nutrient content, to assess pest habitat suitability and potential breeding grounds. By monitoring soil conditions, farmers can identify areas prone to pest infestations, such as damp or nutrient-rich soils, and take preventive measures to mitigate pest risks. Soil sensors also enable precise irrigation and fertilization, reducing conditions favorable to pests while promoting crop health (Nagendra *et al*., 2013; Zhang *et al*., 2019).

Climate Sensors for Environmental Monitoring: Climate sensors measure environmental parameters, including temperature, humidity, rainfall, and wind speed, to monitor weather conditions conducive to pest activity. By collecting real-time weather data, farmers can anticipate pest outbreaks, track pest migration patterns, and implement timely pest control measures. Climate sensors also help optimize irrigation scheduling and microclimate management, minimizing pest stress on crops and improving overall resilience (Ceccato *et al*., 2014; Ullo and Sinha, 2020).

2.3 GPS and GIS Applications in Precision Agriculture:

Global Positioning System (GPS) and Geographic Information System (GIS) technologies are integral to precision agriculture for spatial data collection, analysis, and decision-making. These technologies enable farmers to map pest infestations, plan targeted interventions, and optimize pest control measures with precision. Two key applications of GPS and GIS in precision agriculture for pest management include:

Geospatial Mapping of Pest Infestations: GPS and GIS technologies allow farmers to create detailed maps of pest infestations and spatial distribution patterns within agricultural fields. By overlaying pest occurrence data with geospatial information, such as soil types, crop varieties, and topography, farmers can identify hotspots of pest activity and prioritize management efforts. Geospatial mapping also facilitates the integration of data from multiple sources, such as satellite imagery, sensor networks, and historical records, for comprehensive pest management strategies (Sabtu *et al*., 2018; Singh *et al*., 2023).

Precision Application of Pest Control Measures: GPS-guided equipment enables precision application of pest control measures, such as pesticides and biological agents, to target specific areas affected by pest infestations. By accurately mapping pest hotspots and tailoring application rates based on spatial variability, farmers can minimize chemical usage, reduce off-target effects, and maximize efficacy in pest control efforts. Precision application technologies also support sustainable pest management practices, mitigating environmental impacts while maintaining crop productivity (Ahmad *et al*., 2018; Tang *et al*., 2023).

III. INTEGRATION OF ENTOMOLOGICAL DATA IN PRECISION AGRICULTURE

Entomological data integration in precision agriculture is critical for developing successful pest control methods. Pests represent considerable hazards to crop yields and agricultural sustainability, thus using modern technology for pest detection, behaviour monitoring, and decision support systems is critical (Oerke *et al*., 2010). In this part, we will look at the important components of integrating entomological data into precision agriculture, such as insect pest detection technology, insect behaviour monitoring, and entomological decision support systems.

3.1 Insect Pest Identification Technologies:

Accurate identification of insect pests is fundamental for implementing targeted pest management practices. Several technologies facilitate rapid and precise identification of insect species:

Automated Insect Recognition Systems: Automated insect recognition systems utilize machine learning algorithms and computer vision techniques to classify and identify insect pests based on their physical characteristics. These systems analyse images captured by cameras or smartphones and compare them with a database of known insect species. By automating the identification process, these systems enable farmers and agricultural professionals to quickly identify pests in the field, facilitating timely interventions (Wang *et al*., 2012; Cardim Ferreira Lima *et al*., 2020).

DNA Barcoding for Pest Species Identification: DNA barcoding involves sequencing a short segment of DNA from a standardized region of the genome to identify species. In entomology, DNA barcoding is used for accurate and reliable identification of insect pests, even at the larval or egg stage. By comparing DNA sequences with reference databases, researchers and pest management professionals can accurately identify insect species, including cryptic or morphologically similar species. DNA barcoding provides a robust tool for taxonomic identification and biodiversity assessment in agricultural ecosystems (Ball and Armstrong, 2014; Jalali *et al*., 2015).

3.2 Monitoring Insect Behaviour:

Understanding insect behaviour is crucial for developing effective pest management strategies. Advanced sensor technologies enable real-time monitoring of insect movement, activity, and habitat preferences:

Sensor-Based Tracking of Insect Movement: Sensor-based tracking systems utilize GPS, RFID (Radio Frequency Identification), or radio telemetry to monitor the movement and dispersal of insect pests within agricultural fields (Bieganowski *et al*., 2021). Tiny transmitters attached to insects emit signals that can be detected by receiver units placed throughout the field. By tracking insect movement patterns and migration routes, farmers can anticipate pest outbreaks, implement targeted control measures, and minimize crop damage (Ju and Son, 2022; Gebauer *et al*., 2024).

Acoustic Sensors for Insect Activity Monitoring: Acoustic sensors detect and analyze the sounds produced by insect pests, such as feeding, mating, or communication signals. These sensors can be deployed in crop fields to monitor insect activity levels and detect early signs of pest infestations. By analysing acoustic signals using machine learning algorithms, researchers can distinguish between different insect species and assess their population densities. Acoustic monitoring provides a non-invasive and cost-effective method for monitoring insect pests in agricultural ecosystems (Mankin and Hagstrum, 2012; Saleh *et al*., 2018).

3.3 Decision Support Systems for Entomological Data:

Decision support systems (DSS) utilize entomological data to provide farmers with actionable insights and recommendations for pest management. These systems integrate data on insect populations, behaviour, and environmental conditions to optimize pest control strategies:

Modelling Insect Population Dynamics: DSS incorporate mathematical models and simulation techniques to predict insect population dynamics and assess the impact of management interventions. Population models consider factors such as reproduction rates, mortality rates, and environmental conditions to simulate the growth and spread of insect populations over time. By simulating different scenarios and management strategies, DSS help farmers evaluate the efficacy of pest control measures and optimize resource allocation for pest management (Jian *et al*., 2018; Dennis *et al*., 2021).

Predictive Analytics for Pest Outbreaks: Predictive analytics algorithms analyse historical entomological data, environmental variables, and weather forecasts to predict pest outbreaks and assess the risk of infestation. By identifying factors contributing to pest outbreaks, predictive analytics enable farmers to implement preventive measures and early intervention strategies. These may include timely pesticide applications, deployment of biological control agents, or modification of crop planting schedules to minimize pest pressure. Predictive analytics provide farmers with valuable insights into pest dynamics and enable proactive pest management practices (Chen *et al*., 2022; Malloci, 2022; Palani *et al*., 2023).

IV. PRECISION APPLICATION OF PEST CONTROL MEASURES

Precision agriculture has revolutionized pest management strategies by enabling targeted and efficient application of control measures. This approach minimizes environmental impact, reduces input costs, and maximizes efficacy in pest control. Here we will explore the key components of precision application of pest control measures, including variable rate technologies for pesticide application, automated pest control systems, and biological control strategies.

Variable Rate Technologies for Pesticide Application: Variable rate technologies (VRT) offer a sophisticated approach to pesticide application, allowing farmers to adjust application rates based on spatial variations in pest pressure, crop health, and environmental conditions. This precise targeting of pesticides optimizes resource use and minimizes off-target effects. Key VRT systems include:

GPS-guided Sprayers: GPS technology enables precise navigation of spraying equipment within fields, allowing farmers to apply pesticides only where needed. By creating application maps based on field data, such as soil moisture levels, pest infestation patterns, and crop health indicators, GPS-guided sprayers adjust spray nozzles to deliver precise amounts of pesticides, reducing waste and environmental contamination (Huang *et al*., 2008; Khan *et al*., 2018).

Variable Rate Injection Systems: These systems utilize real-time sensor data to adjust pesticide application rates on-the-go. Soil sensors, crop sensors, and weather stations provide input data, which is processed by control algorithms to determine optimal pesticide rates for specific areas within the field. Variable rate injection systems then adjust the flow rate of pesticides accordingly, ensuring uniform coverage and minimizing over-application (Guan *et al*., 2015; Wei *et al*., 2022).

Section Control Technology: Section control technology divides spraying equipment into individual sections that can be turned on or off independently based on GPS-guided field maps. This allows farmers to avoid overlapping spray coverage and prevent double application in areas that have already been treated. Section control technology reduces pesticide waste and ensures efficient use of resources (Suckling *et al*., 2014; Hendrichs *et al*., 2021).

V. AUTOMATED PEST CONTROL SYSTEMS

Automation technologies play a vital role in precision agriculture by enabling autonomous operation of pest control equipment, reducing labour requirements, and improving operational efficiency. Automated pest control systems utilize robotics, artificial intelligence, and sensor technologies to target pests accurately and effectively. Key components of automated pest control systems include:

Robotic Platforms for Precision Spraying: Robotic sprayers equipped with sensors and cameras can navigate through fields autonomously, targeting specific areas with pesticide applications. These robots utilize machine learning algorithms to identify pest-infested areas and adjust spray nozzles to deliver precise amounts of pesticides. Robotic platforms minimize human labour and ensure consistent and accurate pesticide application, reducing environmental impact and optimizing pest control (Scholz *et al*., 2014; Loukatos *et al*., 2021; Meshram *et al*., 2022).

Smart Traps and Lures for Targeted Pest Capture: Smart traps and lures utilize pheromones, attractants, and sensors to lure pests into traps while minimizing non-target captures. These traps can be equipped with cameras and communication modules to monitor pest activity in real-time and alert farmers when pest populations exceed threshold levels. Smart traps and lures enable targeted pest monitoring and control, reducing the need for broad-spectrum pesticides and minimizing ecological disruption (Sciarretta and Calabrese, 2019; Preti *et al*., 2019).

VI. BIOLOGICAL CONTROL STRATEGIES IN PRECISION AGRICULTURE

Biological control strategies harness natural enemies of pests, such as predators, parasitoids, and entomopathogenic organisms, to manage pest populations effectively (Wu *et al*., 2019). In precision agriculture, biological control methods are integrated into pest management strategies to minimize reliance on synthetic pesticides and promote ecological balance. Key biological control strategies include:

Release of Predators and Parasitoids: Natural enemies of pests, such as ladybugs, lacewings, parasitic wasps, and predatory mites, can be released into agricultural fields to control pest populations. These beneficial organisms feed on pest species, reducing their numbers and preventing crop damage. In precision agriculture, the release of predators and parasitoids is targeted to areas with high pest activity, maximizing efficacy while minimizing environmental impact (Zhan *et al*., 2021; Sahin, 2022).

Integration of Entomopathogenic Organisms: Entomopathogenic organisms, such as fungi, bacteria, and nematodes, can be used to control pest populations through biological means. These organisms infect and kill pests without harming non-target organisms, making them ideal for integrated pest management in precision agriculture. By incorporating entomopathogens into soil drenches, foliar sprays, or seed treatments, farmers can effectively suppress pest populations while minimizing chemical inputs and preserving natural ecosystems (Erdoğan *et al*., 2023).

VII. ENVIRONMENTAL IMPACTS OF PRECISION PEST MANAGEMENT

Precision pest management, a key component of precision agriculture, has revolutionized pest control strategies by offering targeted, efficient, and environmentally sustainable approaches to pest management (Katalin *et al*., 2014). In this section we will explore the environmental impacts of precision pest management, reduction in pesticide usage and environmental impact, and the promotion of sustainable agriculture practices enabled by precision technologies.

7.1 Reduction in Pesticide Usage and Environmental Impact:

One of the most significant benefits of precision pest management is the reduction in pesticide usage and environmental impact (Gill and Garg, 2014). Precision agriculture technologies enable targeted application of pesticides, minimizing environmental contamination and promoting ecological sustainability:

Minimized Pesticide Drift: Precision pest management techniques, such as GPS-guided sprayers and variable rate technologies, ensure precise application of pesticides, minimizing drift and off-target effects. By delivering pesticides directly to the intended areas, farmers can reduce pesticide loss to non-target areas, minimizing environmental contamination and preserving ecosystem health (Reimer and Prokopy, 2012; Xun *et al*., 2023).

Reduced Chemical Residue: Precision agriculture allows farmers to apply pesticides at lower rates and with greater precision, reducing chemical residue in soil, water, and food products. By minimizing pesticide residues, precision pest management promotes food safety, protects human health, and reduces the risk of pesticide-related illnesses (Zanin *et al*., 2022).

Preservation of Beneficial Organisms: Precision pest management strategies, such as biological control methods and targeted spraying, help preserve beneficial organisms, such as pollinators, natural enemies of pests, and soil microorganisms. By minimizing pesticide exposure to non-target organisms, precision agriculture promotes biodiversity, ecosystem resilience, and natural pest control services (Bhakta *et al*., 2019).

Water Quality Protection: Precision agriculture techniques, such as sensor-based irrigation and variable rate pesticide application, help reduce pesticide runoff and leaching into water bodies. By optimizing water usage and minimizing chemical inputs, precision pest management protects water quality, aquatic ecosystems, and human health (Douguet and Schembri, 2006).

7.2 Sustainable Agriculture Practices Enabled by Precision Technologies:

Precision pest management plays a crucial role in promoting sustainable agriculture practices by optimizing resource use, reducing environmental impact, and enhancing agricultural resilience:

Conservation of Resources: Precision agriculture technologies, such as soil sensors, climate monitors, and GPS-guided equipment, help farmers optimize resource use by matching inputs to crop requirements. By minimizing waste and maximizing efficiency, precision pest management promotes the conservation of land, water, energy, and nutrients, contributing to long-term agricultural sustainability (Oliver *et al*., 2013).

Soil Health Improvement: Precision pest management practices, such as reduced pesticide usage and conservation tillage, help improve soil health and fertility. By minimizing soil disturbance and chemical inputs, precision agriculture preserves soil structure, enhances microbial activity, and promotes nutrient cycling, resulting in improved soil health and productivity over time (Sophocleous, 2021).

Climate Resilience: Precision agriculture enables farmers to adapt to climate change and extreme weather events by optimizing management practices and reducing vulnerability to environmental stressors. By utilizing real-time data and predictive analytics, precision pest management helps farmers anticipate climate-related risks, such as pest outbreaks and droughts, and implement proactive measures to mitigate their impact (Roy and George, 2020).

Enhanced Food Security: Precision pest management plays a crucial role in ensuring food security by improving crop yields, minimizing post-harvest losses, and reducing reliance on chemical inputs. By optimizing pest control strategies and promoting ecological balance, precision agriculture contributes to the sustainable production of nutritious and safe food for growing populations worldwide (Qureshi *et al*., 2022).

VIII. CHALLENGES IN IMPLEMENTING PRECISION PEST MANAGEMENT

Precision pest management holds immense promise for revolutionizing agricultural practices by offering targeted, efficient, and environmentally sustainable pest control solutions. However, its successful implementation faces various challenges, including technological barriers, data integration issues, and farmer adoption and education (Shah and Razaq, 2020). Here we will delve into these challenges and explore potential strategies to overcome them.

8.1 Technological Barriers:

Complexity of Technologies: Precision pest management relies on advanced technologies such as GPS, remote sensing, and automated pest control systems. Implementing and integrating these technologies into existing agricultural practices can be challenging due to their complexity. Farmers may lack the technical expertise or resources to adopt and utilize these technologies effectively (Bosompem, 2021).

Cost of Implementation: The initial investment required for purchasing precision pest management technologies, such as GPS-guided sprayers or robotic pest control systems, can be prohibitively high for many farmers. Additionally, ongoing maintenance, training, and software updates incur additional costs, posing financial barriers to adoption (Lal, 2015).

Compatibility and Interoperability: Different precision agriculture technologies may use proprietary software or hardware, leading to compatibility issues and interoperability challenges. Integrating disparate technologies into a seamless system for pest management can be complicated, requiring customized solutions and technical expertise (Rossi *et al*., 2023).

8.2 Strategies to Address Technological Barriers:

Research and Development Funding: Governments, research institutions, and industry stakeholders can invest in research and development to improve the affordability, usability, and interoperability of precision pest management technologies.

Technical Assistance and Training: Providing farmers with access to training programs, workshops, and technical support services can help bridge the knowledge gap and build capacity for adopting and utilizing advanced technologies.

Collaborative Partnerships: Industry collaborations and partnerships between technology providers, research organizations, and agricultural extension services can facilitate the development of integrated solutions and standardized platforms for precision pest management.

8.3 Data Integration and Standardization:

Data Complexity and Volume: Precision pest management relies on collecting and analyzing vast amounts of data from various sources, including sensors, satellites, weather stations, and pest monitoring devices. Managing and integrating these diverse data streams pose challenges due to their complexity, volume, and heterogeneity (Méndez-Vázquez *et al*., 2019).

Data Quality and Consistency: Ensuring the quality, accuracy, and consistency of data collected from different sources can be challenging. Variability in sensor accuracy, calibration, and maintenance can lead to discrepancies and errors in data interpretation, affecting the reliability of pest management decisions (Damos, 2015).

Lack of Standardization: The absence of standardized protocols, formats, and data exchange mechanisms complicates data sharing and integration efforts in precision pest management. Different vendors may use proprietary data formats or interfaces, hindering interoperability and collaboration among stakeholders (Li *et al*., 2021).

8.4 Strategies to Address Data Integration and Standardization:

Development of Data Standards: Industry organizations, regulatory agencies, and standardization bodies can develop and promote standardized protocols and data formats for collecting, sharing, and exchanging agricultural data.

Open Data Initiatives: Encouraging open data initiatives and data-sharing platforms can facilitate collaboration and knowledge exchange among stakeholders, enabling interoperability and data integration.

Quality Assurance and Validation: Implementing quality assurance processes, data validation checks, and sensor calibration protocols can help ensure the accuracy, reliability, and consistency of data collected for precision pest management.

Investment in Data Infrastructure: Governments and private sector entities can invest in building data infrastructure, such as cloud-based platforms, data repositories, and analytical tools, to support data management and integration in precision agriculture.

8.5 Farmer Adoption and Education:

Awareness and Education: Many farmers may lack awareness of the potential benefits of precision pest management or may be sceptical about adopting new technologies and practices. Educating farmers about the economic, environmental, and agronomic advantages of precision pest management is crucial for fostering adoption and behaviour change (Murage *et al*., 2015).

Technical Literacy: Farmers need to possess the necessary technical skills and knowledge to effectively utilize precision pest management technologies and interpret the data generated by these systems. However, limited access to training, technical support, and extension services may hinder farmers' ability to adopt and implement these technologies (Daberkow and McBride, 2003).

Risk Aversion: Farmers may be hesitant to adopt precision pest management practices due to concerns about the risks involved, such as potential crop damage from equipment malfunction or the uncertainty of returns on investment. Overcoming risk aversion requires demonstrating the reliability, efficacy, and long-term benefits of precision pest management through pilot projects, case studies, and outreach efforts (Bueno *et al*., 2021).

8.6 Strategies to Address Farmer Adoption and Education:

Extension and Outreach Programs: Agricultural extension services, farmer cooperatives, and industry associations can organize training workshops, field demonstrations, and outreach events to educate farmers about precision pest management technologies and practices.

Demonstration Farms: Establishing demonstration farms or pilot projects where farmers can observe firsthand the benefits of precision pest management can help build confidence and trust in these approaches.

Financial Incentives: Providing financial incentives, grants, or subsidies for adopting precision pest management technologies can offset initial investment costs and encourage early adoption among farmers.

Peer-to-Peer Learning Networks: Facilitating peer-to-peer learning networks and knowledge-sharing platforms where farmers can exchange experiences, best practices, and success stories can foster a supportive community and accelerate adoption of precision pest management practices.

IX. CASE STUDIES ON SUCCESSFUL IMPLEMENTATION OF PRECISION PEST MANAGEMENT

Precision pest management, facilitated by advancements in technology and data-driven approaches, has been increasingly adopted across various crops worldwide. This section presents case studies demonstrating the successful implementation of precision agriculture techniques in pest management, highlighting their efficacy in reducing pest populations, improving crop yields, and enhancing sustainability which is shown in Table 1.

TABLE 1
SUCCESSFUL IMPLEMENTATION OF PRECISION PEST MANAGEMENT

Crops	Feature	Reference
Maize	In the United States, precision agriculture techniques have been widely adopted in maize production to manage pests effectively. Farmers utilize GPS-guided sprayers and variable rate technologies to apply pesticides precisely where needed, based on field maps generated using satellite imagery and soil sensors. By targeting areas with high pest pressure while minimizing pesticide usage in unaffected areas, farmers have achieved significant reductions in pest damage and increased maize yields	Lan *et al*., 2010; Shafi *et al*., 2019
Rice	In Asia, where rice is a staple crop, precision agriculture techniques are being adopted to manage pests such as rice blast disease and stem borers. Remote sensing technologies, coupled with sensor networks, are used to monitor rice fields for signs of pest infestations and disease outbreaks. Farmers receive real-time alerts on their smartphones or computers, allowing them to take timely action, such as adjusting irrigation schedules, applying fungicides, or releasing natural enemies, to control pests and diseases effectively. Precision pest management has helped rice farmers achieve higher yields, reduce crop losses, and improve overall farm profitability	Ali *et al*. 2021; Ramadass and Thiagarajan, 2021
Cotton	Cotton farming in Australia has embraced precision agriculture to combat pests such as cotton bollworm and aphids. Unmanned aerial vehicles (UAVs) equipped with multispectral cameras are used to monitor cotton fields, detecting pest infestations at an early stage. This allows farmers to implement targeted pest control measures, such as spot spraying or releasing beneficial insects, to mitigate pest damage while minimizing chemical inputs. As a result, cotton yields have improved, and pesticide usage has been reduced, leading to economic and environmental benefits	Deguine *et al*., 2009; Reeves and Phillipson, 2017
Soyabean	In Brazil, soybean producers face significant challenges from pests such as soybean rust and soybean aphids. Precision agriculture technologies, including satellite imagery, unmanned aerial vehicles (UAVs), and sensor networks, are utilized to monitor soybean fields and identify pest hotspots. By applying fungicides and insecticides only where needed, based on field mapping and pest scouting data, soybean farmers have reduced pesticide usage while maintaining effective pest control. This targeted approach has resulted in higher soybean yields, reduced production costs, and minimized environmental impact, contributing to the sustainability of soybean farming in Brazil	Iost Filho, 2023

X. FUTURE TRENDS AND INNOVATIONS IN PRECISION AGRICULTURE FOR PEST MANAGEMENT

The field of precision agriculture is undergoing tremendous development, propelled by breakthroughs in technology, data analytics, and automation. Novel methods are being created in the field of pest control to improve accuracy, effectiveness, and long-term viability. This article examines upcoming developments and advancements in precision agriculture for pest control, specifically highlighting progress in sensor technologies, the incorporation of artificial intelligence (AI), and the emergence of possibly groundbreaking technologies.

10.1 Advances in Sensor Technologies:

Sensor technologies play a crucial role in precision agriculture by providing real-time data on soil conditions, weather patterns, crop health, and pest activity. Future trends in sensor technologies for pest management in Table 2:

TABLE 2
ADVANCED SENSOR TECHNOLOGY IN PEST MANAGEMENT

Sensor	Feature	References
Nano-sensors	It offer unprecedented sensitivity and specificity in detecting pest-related signals, such as volatile organic compounds emitted by insects or pathogens. These miniature sensors can be embedded in crops or deployed in the field to monitor pest activity with high precision, enabling early detection and targeted interventions.	Johnson *et al*., 2021
Biosensors	It utilize biological molecules, such as antibodies or enzymes, to detect specific pests or pathogens. These sensors can be integrated into wearable devices or handheld diagnostic tools for rapid and on-site detection of pest infestations. Biosensors offer potential applications in monitoring invasive species, disease outbreaks, and pesticide resistance in real-time	He *et al*., 2023
Remote Sensing	Advancements in remote sensing technologies, such as hyperspectral imaging and LiDAR (Light Detection and Ranging), enable high-resolution mapping of crop health indicators and pest infestations from aerial platforms. Future developments in remote sensing may include miniaturized and low-cost sensors deployed on drones or satellites for continuous monitoring of large agricultural landscapes	Ullo and Sinha, 2021

10.2 Integration of Artificial Intelligence in Precision Pest Management

Artificial intelligence (AI) and machine learning algorithms have the potential to revolutionize pest management by analyzing complex data sets, predicting pest dynamics, and optimizing control strategies. Future trends in AI for precision pest management include:

Predictive Analytics: AI algorithms can analyze historical data on pest populations, environmental conditions, and crop management practices to predict future pest outbreaks with high accuracy. By identifying risk factors and vulnerable areas, predictive analytics enable proactive pest management strategies, such as early intervention and targeted control measures (Demirel and Kumral, 2021; Toscano-Miranda *et al*., 2022).

Autonomous Pest Detection: AI-powered image recognition and pattern recognition algorithms can automatically identify pest species and assess pest damage from images captured by drones or field cameras. Autonomous pest detection systems equipped with AI can rapidly survey large areas, providing real-time insights into pest distribution and severity for timely decision-making (Adetunji *et al*., 2023).

Adaptive Control Strategies: AI algorithms can continuously learn from feedback data, adjusting pest control strategies in real-time based on changing environmental conditions and pest dynamics. Adaptive control systems optimize pesticide application rates, timing, and placement, minimizing pesticide resistance while maximizing efficacy and sustainability in pest management (Dong *et al*., 2020).

10.3 Emerging Technologies and Potential Breakthroughs

Beyond existing sensor technologies and AI applications, several emerging technologies hold promise for revolutionizing precision agriculture and pest management:

Gene Editing and RNA Interference: Advancements in gene editing technologies, such as CRISPR-Cas9, and RNA interference (RNAi) offer novel approaches to pest control by targeting specific genes essential for pest survival and reproduction. Gene-edited crops with enhanced resistance to pests and diseases could reduce reliance on chemical pesticides and mitigate environmental impacts (Adeyinka *et al*., 2020; Singh *et al*., 2022).

Microbial Biocontrol Agents: Research into microbial biocontrol agents, such as bacteria, fungi, and viruses, as alternatives to chemical pesticides is gaining momentum. Engineered microbial strains capable of suppressing pest populations or enhancing plant defences show promise for sustainable pest management in agriculture (Roberts *et al*., 2021).

Internet of Things (IoT) and Edge Computing: The integration of IoT devices, edge computing, and cloud-based platforms enables real-time monitoring and control of agricultural systems. Smart sensors, actuators, and automated decision-making algorithms deployed in the field facilitate precision pest management through data-driven insights and autonomous interventions (Qadri *et al*., 2020).

XI. CONCLUSION

Farmers now have access to the resources and methods necessary to handle pest concerns in an efficient and environmentally responsible manner thanks to the emergence of precision agriculture as a transformational approach to pest control. The purpose of this conclusion is to present a review of the most important results, investigate the possibilities for the future of precision agriculture in entomological pest control, and propose suggestions for further study and application.

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Heat Waves in India: Patterns, Impacts, and Mitigation Strategies

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Abstract— *Heat waves are extreme weather events characterized by prolonged periods of excessively high temperatures, which pose significant threats to public health, agriculture, and infrastructure. In India, heat waves have become more frequent and intense in recent decades, attributed largely to climate change. Various existing studies on the topic was reviewed by searching on numerous databases like Springer, Research gate, Google Scholar, Elsevier, Indian metrology site etc. This review paper synthesizes current knowledge on the occurrence, impacts, and mitigation strategies of heat waves in India. It examines historical trends and future projections of heat wave occurrences, highlighting regional variations and vulnerable populations. The review also explores the physiological and socio-economic impacts, including mortality, morbidity, and economic losses. Additionally, it discusses adaptation and mitigation measures, such as early warning systems, urban planning, and public health interventions, that are being implemented to reduce the adverse effects of heat waves. By consolidating existing research and identifying gaps, this paper aims to provide a comprehensive understanding of heat waves in India and contribute to the development of effective policies and strategies to combat this growing threat.*

***Keywords*— Heat waves, cause, environment, impact, people, trends.**

I. INTRODUCTION

Heat waves are a significant environmental hazard, posing severe threats to human health, agriculture, water resources, and the overall economy. In recent decades, India has experienced a significant increase in the frequency and intensity of heat waves, posing a growing threat to the country's environment and population (Kotharkar and Ghosh, 2021) (Rao *et al*., 2023) (Dubey *et al*., 2021). These episodic occurrences of extremely high surface air temperature spanning multiple days have become more prevalent, particularly across the north, northwest, central, and east coast regions of the country (Rao *et al.*, 2023). The diverse climatic conditions and vast geographical expanse, is particularly vulnerable to extreme weather events. The occurrence of heat waves in the country has shown an alarming upward trend, with record-breaking temperatures becoming more common. These extreme temperature events not only lead to a high number of heat-related illnesses and fatalities but also exacerbate existing socio-economic challenges, especially in densely populated urban areas and agrarian regions. Heatwaves are defined by the India Meteorological Department based on specific criteria (Rao *et al.*, 2023). The criteria for a heatwave in India are when the maximum temperature exceeds 40°C or more for plains regions, and 30°C or more for hilly regions, for at least two consecutive days. These extreme heat events, characterized by soaring temperatures and prolonged periods of intense heat, pose significant challenges to public health, infrastructure, and the economy. The causes of these heat waves are multifaceted, with global climate change playing a significant role (Dubey *et al.*, 2021). Marginal increases in temperature can result in heat wave incidents, leading to serious damage and alterations in animal and plant species (Sharma *et al*., 2022). In 2015 and 2016, severe heat waves affected large parts of India and Pakistan, claiming around 3,500 lives. The combination of high temperatures and humidity during these events has made them particularly lethal (Rao *et al*., 2023). To address this growing challenge, it is crucial to monitor, track, and predict heat waves in real-time, enabling the development of effective heatwave action plans (Dubey *et al.*, 2021).

II. INDEX OF HEAT WAVES

Indian Metrology Department Criteria for Declaring Heat Wave in India:

Heat wave is considered if the maximum temperature of a station reaches at least 40°C or more for Plains and at least 30°C or more for Hilly regions.

2.1 Based on Departure from Normal:

Heat Wave: Departure from normal is 4.5°C to 6.4°C.

Severe Heat Wave: Departure from normal is >6.4°C.

2.2 Based on Actual Maximum Temperature:

Heat Wave: When actual maximum temperature ≥ 45°C.

Severe Heat Wave: When actual maximum temperature ≥47°C.

2.3 Excessive Heat Factors:

The second index considered is the Excessive Heat Factor (EHF) (Nairn and Fawcett 2013; Perkins and Alexander 2013; Rohini *et al*., 2016). This index is based on two excessive heat indices:

- **Excess Heat:** The Excess heat represents unusually high heat arising from a daytime temperature that is not sufficiently discharged overnight due to unusually high overnight temperatures.
- **Heat Stress:** The heat stress which arises from a period where the temperature is warmer, on average than the recent past. Maximum and subsequent minimum temperatures averaged over a three-day period and the previous 30 days are compared to characterize the heat stress.

III. CAUSE OF HEAT WAVES

Over the past decade, India has experienced a concerning increase in the frequency and intensity of heat waves, leading to significant challenges for both the population and the nation's infrastructure. This phenomenon is largely driven by the impacts of climate change, as rising global temperatures and shifting weather patterns have contributed to these extreme heat events. (Shandas *et al*., 2019). The primary driver of heat waves in India is the gradual rise in carbon dioxide concentrations and associated global temperature increase. (Mazdiyasni *et al*., 2017) Climate models predict that with a doubling of $CO2$ levels, the average temperature in India is expected to rise by 2.33°C to 4.78°C, leading to more pronounced seasonal variations with greater warming in the winter months compared to the summer. (Kumar *and* Gautam, 2014) As a result, the longevity of heat waves has extended, with warmer night temperatures and hotter days becoming increasingly common. (Kumar *and* Gautam, 2014). These changes in temperature patterns have had a significant impact on India's vulnerable populations. Using a novel probabilistic model, researchers have found that the increase in summer mean temperatures in India over recent years corresponds to a 146% increase in the probability of heat-related mortality events involving more than 100 people. (Mazdiyasni *et al*., 2017). Global warming exacerbates the frequency and intensity of heat waves, compounded by urban heat islands and reduced soil moisture. Oceanic phenomena like ENSO further influence weather patterns, contributing to heat wave occurrences. Geographical features, such as topography and proximity to the equator, also play a crucial role in determining the severity and duration of heat waves. Understanding these causes is essential for developing effective mitigation strategies, enhancing weather forecasting, and implementing heat action plans. Addressing anthropogenic factors, particularly greenhouse gas emissions, is critical to mitigating the future impacts of heat waves.

Heat waves in India can be attributed to a combination of meteorological, geographical, and environmental factors. Some of the primary causes include:

3.1 Meteorological Factor:

- **High pressure systems:** During certain times of the year, particularly in summer, high-pressure systems can dominate over large areas, leading to sinking air and stable atmospheric conditions. This traps heat at the surface, resulting in high temperatures.
- **Absence of cloud cover**: Clear skies allow more solar radiation to reach the Earth's surface, contributing to heating.
- **Dry air:** Low humidity levels can exacerbate heat, as dry air can heat up more quickly and retain less heat during the night, leading to extreme temperature variations.

3.2 Geographical Factors:

- **Latitude:** India's location near the equator means it receives intense sunlight throughout the year, contributing to higher temperatures.
- **Topography:** The presence of deserts in western India, such as the Thar Desert, and the relatively flat terrain in many regions can contribute to heat build-up.
- **Coastal regions:** Coastal areas may experience heat waves due to the moderating influence of the sea being less pronounced compared to inland areas.

3.3 Urbanization and Heat Island Effect:

- **Global warming:** Rising global temperatures due to greenhouse gas emissions contribute to an overall increase in the frequency and intensity of heat waves worldwide, including in India.
- **Changes in weather patterns:** Climate change can alter atmospheric circulation patterns, potentially leading to more frequent and severe heat waves in certain regions.

3.4 Monsoon Dynamics:

- **Delayed or weak monsoon:** If the onset of the monsoon is delayed or if it is weaker than usual, it can prolong periods of high temperatures, leading to heat waves.
- **Break in monsoon:** Interruptions in the monsoon season can result in extended periods of hot and dry weather, exacerbating heat wave conditions.

IV. TRENDS AND PATTERNS OBSERVED OF HEAT WAVES IN INDIA

4.1 Heat Waves (1961-2020):

Heat waves are anomalous episodes with extremely high surface air temperatures, lasting for several days with serious consequences. The Fig. 1 shows the spatial distribution of the duration (days) of heat waves. The plot shows that heat waves last on an average 4-8 days. In some areas of central and north-western India and parts of Odisha and coastal Andhra Pradesh, the duration is more than 8 days. Over Gujarat and Chhattisgarh, heat waves last 2-4 days. Fig. 2 shows the long-term trends in the duration of heat waves for the individual stations during the period 1961-2020. It clearly shows that most IMD stations show an increasing trend in the duration of heat waves during the March-June season.

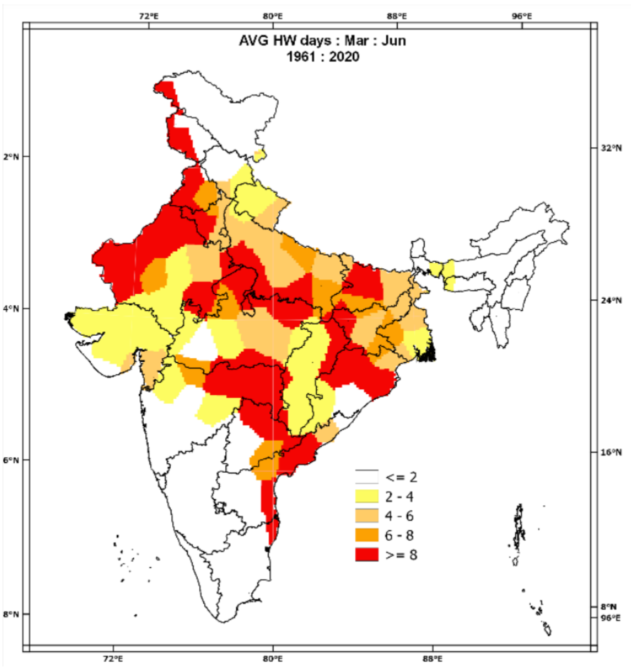

FIGURE 1: Heat wave average total duration (days) during March-June for the period 1961-2020

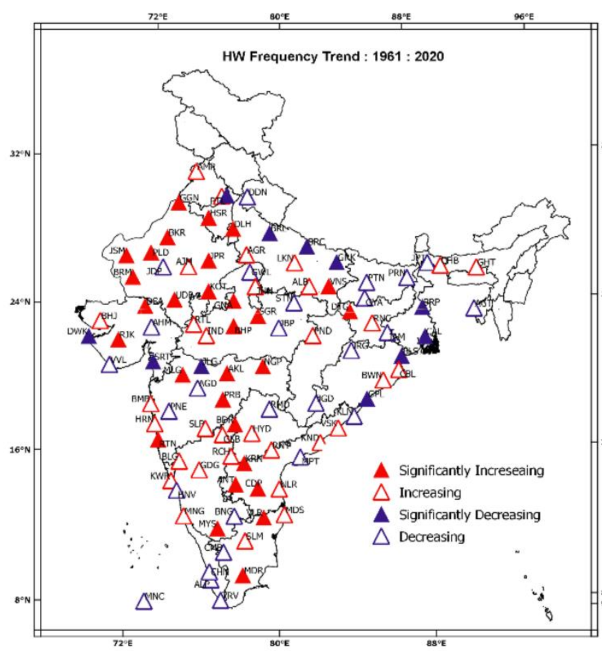

FIGURE 2: Station wise, HW duration trends during March-June for the period 1961-2020

Source: Indian Metrological Department

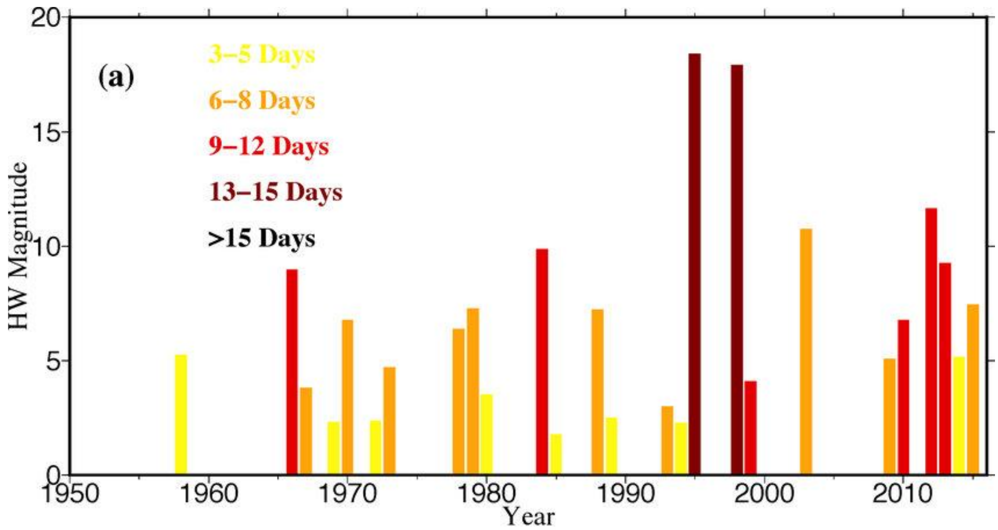

FIGURE 3: No. of heat waves days from the period 1950-2010

Source: Centre for Science and Environment

The Fig 3. Show the heat waves days from the period 1950-2010 in India. The maximum heat waves days was recorded between 1990-2000 that is around 13-15 days continually in severe and extreme heat waves. The study by Murari *et al*. (2015) using CMIP (Coupled Model Intercomparison Project) data suggests that heat waves are projected to be more intense, have longer durations and occur at a higher frequency and earlier in the year. Southern India, currently not influenced by heat waves is expected to be severely affected by the end of the 21st century. Projections indicate that a sizable part of India will experience heat stress conditions in the future (Dholakia, *et al*., 2020). In a study conducted over the Indian subcontinent, Jaswal *et al*. (2017) examined rising trends in temperature and moisture-induced heat index and their impact on human health in the context of climate change. They examined the heat index (HI) during the summer and monsoon seasons using dry bulb temperature and relative humidity data from 283 surface meteorological stations across India. At a 95% level of statistical significance, the average national increase in HI during the summer and monsoon seasons is +0.560 C/decade and +0.320 C/decade, respectively. The rising HI indicates a high degree of discomfort in both seasons, which is mostly brought on by the summer's increased humidity and the monsoon season's highest temperature. The spatial distribution of HI suggests higher risk of heat-related illness in India; this is especially true in the summer months in the southeast coastal regions of Andhra Pradesh, Orissa, and Tamil Nadu, and over northwest India during the monsoon season in Rajasthan and the Indo-Gangetic plains.

The inter-annual variability of heat wave occurrences along India's east coast was studied by Sandeep and Prasad (2018). The occurrences of heat waves show notable intra-annual fluctuation. An increase of 0.060 C has been observed in the average intensity of heat waves along India's east coast. Significant intra-annual variability is seen between the episodes in the geopotential height anomaly, vertical velocity, and soil moisture, which turn into critical parameters for maintenance and variability. The impact of Atlantic Ocean SST anomalies on Indian heat waves was investigated by Vittal *et al*., (2020). They demonstrated that throughout the 1961–2010 era, Indian heat waves were substantially correlated with Atlantic Ocean SST rather than the Indian Ocean SST, using both data and climate model experiments. Rather of being the result of natural forcing, greenhouse emissions worsened the conditions in the Atlantic that caused those heat waves.

4.2 Heat Waves (2021- 2024):

Heat waves in 2021 are recognized as a weather disaster all over the world, because of the causation of human deaths. 2022 had recorded 280 heat wave days between March and May, the highest instance in the last 12 years, as per the Centre for Science and Environment. According to a study published in 2021, the number of heat wave events per year has increased by 138 per cent in the last 20 years. According to the Ministry of Earth Sciences and the India Meteorological Department (2021) studied the 17,362 people lost their lives due to heat waves between 1970 and 2019.The study reported an overall increase in the mortality rate per million by 62.2 per cent in the last 20 years because of heat waves. Venkata Bhaskar *et al*. (2021) predicts that India would experience heat waves. Humans and all other living things depend on the energy that the sun emits as radiation, or heat, which is commonly used to measure temperature. Tropical areas that record the greatest temperatures do so for this reason. According to Zhao *et al*. (2023), during the most recent 20-year period of 2000-2019, excessive temperatures claimed the lives of around 0.5 million individuals globally. An estimate of the number of deaths caused by heat waves between 1998 and 2017 is roughly 166,000. Kishore *et al*. (2022) used the Heat Wave Magnitude Index daily (HWMId) to study how human activity affects the evolving patterns of heat waves in India. According to their research, throughout the 20th century, human activity has doubled the likelihood that severe heat waves will occur in central and central-southern India. It is predicted that the likelihood of heatwaves will grow tenfold in the 21st century. Heat waves with a magnitude greater than nine are predicted to affect more than 70 per cent of India's land area. The India Meteorological Department's All India Weather Summary and Forecast report shows that on April 18, 2023, the maximum temperature in 22 states and Union territories was above normal. Three states recorded heatwaves, according to data by IMD and the number went up further 11 states and UTs recorded heat waves from March 3 to April 18, 2023. Due to this 34 per cent rise in deaths between 2003-2012 and 2013-2022, according to IMD data. On April 20,2023 a University of Cambridge study reported that 90 per cent of the country was at risk of suffering losses in livelihood capacity, food grains yields, vector-borne disease spread and urban sustainability due to heat. Rao *et al*. (2023) investigates summertime (March–June) heatwave characteristics in India under present and future climate conditions. Rising trends in heatwave characteristics (frequency, intensity, duration, season length) were observed, mainly in India's northwest, central, and south peninsular regions.

TABLE 1
NO OF DEATH DUE TO HEAT WAVE IN PAST YEARS IN INDIA

Sr. No	Year	Recorded deaths caused by Heat waves	Sr. No	Year	Recorded deaths caused by H eat waves
1.	1992	612	**18.**	2009	1071
2.	1993	631	**19.**	2010	1274
3.	1994	773	**20.**	2011	793
4.	1995	1677	**21.**	2012	1247
5.	1996	434	**22.**	2013	1216
6.	1997	393	**23.**	2014	1677
7.	1998	3058	**24.**	2015	2040
8.	1999	628	**25.**	2016	700
9.	2000	534	**26.**	2017	375
10.	2001	505	**27.**	2018	33
11.	2002	720	**28.**	2019	498
12.	2003	807	**29.**	2020	2
13.	2004	756	**30.**	2021	374
14.	2005	1075	**31.**	2022	2227
15.	2006	612	**32.**	2023	2300
16.	2007	932	**33.**	2024	-
17.	2008	616			

Source: NDMA Heat wave Death details

4.3 Impacts of Heat Waves:

In India, heat waves have been observed to be increasing in frequency, intensity, and duration in recent years, a trend that is consistent with global climate change. Here are some key trends and patterns observed regarding heat waves in India:

- **Increasing frequency**: There has been a noticeable increase in the frequency of heat waves in India over the past few decades. Heat waves, defined as periods of abnormally high temperatures lasting for several days, are becoming more common across various regions of the country. It become increasingly frequent and intense, posing significant challenges to both the population and the environment. These heat waves can have severe impacts on human health and wellbeing, as well as on various sectors of the environment. Heat waves can cause a range of health issues, including dehydration, heat exhaustion, and heatstroke (Mukherjee and Mishra, 2018).

- **Intensification of heat waves**: Not only are heat waves occurring more frequently, but they are also becoming more intense. Heat waves are the most obvious indicator of climate change, appearing more frequently, intensely, and for longer periods of time than other extreme weather events. In 2022, there were heat wave episodes that were unusual and beyond prior standards. These events had significant consequences for various places across the planet. These extreme temperature during heat wave events are reaching higher levels, posing greater risks to human health, agriculture, ecosystems and infrastructure (Singh and Mall, 2023). Marked increase in heat wave intensity, frequency, and duration in the past half century (Singh *et al.* 2021) found a spatiotemporal shift in the heat wave events over India in the last seven decades which has given rise to the three heat wave hotspots of the country, i.e., Northwestern, Central, and South-Central India.

- **Geographical distribution**: Heat waves are observed across different regions of India, but they tend to be particularly severe in central and northern parts of the country, including states like Rajasthan, Gujarat, Madhya Pradesh, Uttar Pradesh, and parts of Maharashtra and Telangana. However, southern states like Andhra Pradesh, Tamil Nadu, and Karnataka also experience heat wave conditions, especially during the summer months. Satyanarayana *et al.* (2020) analyzed the maximum temperatures and heat wave vulnerability during the hottest month of May. Based on both the magnitude and frequency days of maximum temperatures, three separate regions of maximum temperatures across West Rajasthan in the Northwest, North Madhya Pradesh and Southwest Uttar Pradesh in North-central, and East Maharashtra in South-central parts of India. The maximum temperatures and heat wave vulnerability and identifies the causation to be triggered by wind flow from the maximum temperature zones under favorable atmospheric circulations.

- **Urban heat island effect**: Urban areas in India are particularly susceptible to heat waves due to the urban heat island effect, where cities experience higher temperatures compared to surrounding rural areas due to human activities, infrastructure, and reduced vegetation. Large cities like Delhi, Mumbai, Chennai, and Kolkata often experience more intense and prolonged heat waves compared to rural areas. The land increases the vulnerability of the urban population to extreme weather events and climate change with the decline in the quality of living among urban regions. The increase in urban development in a haphazard manner will impact the microclimate due to significant environmental changes. The increased built-up area, changes in land use, and high population density will increase the vulnerability and health losses due to temperature extremes in all the Indian cities as they have higher population density and economic activities than their surrounding regions (Goyal, *et al.*, 2023).

- **Seasonality**: Heat waves in India are most commonly observed during the summer months, typically between March and June, when temperatures are highest. However, heat wave events can also occur during other times of the year, particularly in regions with semi-arid or arid climates. The study of Satyanarayana et al. (2020) analysed the maximum temperatures and heat wave vulnerability during the hottest month of May. Heat waves events with a significantly increasing trend in three prominent heat wave prone regions that is northwestern, central, and south-central India, the highest being in West Madhya Pradesh (0.80 events/year), while a significantly decreasing trend was observed over an eastern region that is Gangetic West Bengal (−0.13events/year) (Singh *et al.*, 2021).

  Srivastava *et al.* (2022) analysed heat weather hazard over India, attempting to quantify the impact of different meteorological parameters on heat waves in different regions of India for different summer months (March to June). The impact of different meteorological parameters is determined for different months and regions of the country. The cumulative values are calculated for different regions considering different meteorological parameters to make an initial analysis of the heat wave and zonation for the entire country.

- **Impacts on health**: Heat waves have significant impacts on human health, with an increase in heat-related illnesses and mortality during extreme heat events. Vulnerable populations such as the elderly, young children, and those with pre-existing health conditions are particularly at risk. The high temperatures during heat waves can also lead to increased air pollution and poorer air quality, as the combination of heat and sunlight can trigger the formation of ground-level ozone and other pollutants (Srivastava *et al*., 2022). The rising temperatures and prolonged heat waves also put additional strain on already stressed water resources, as evaporation rates increase and water bodies dry up. These impacts are further exacerbated by factors such as urbanization and industrialization, which contribute to the overall temperature rise and vulnerability to heat waves. Overall, the impact of heat waves on people and the environment in India is significant and calls for immediate attention and action (Singh and Rao, 2020).

- **Impacts on agriculture**: Agriculture is also adversely affected, with heat stress leading to reduced crop yields, livestock losses, and water scarcity. Heat waves, characterized by prolonged periods of abnormally high temperatures, have emerged as a significant threat to global agricultural productivity. Increasing heat intensity and variations in rainfall patterns have had a direct impact on crop yields, with estimates suggesting reductions ranging from 10 to 25 percent. In many regions, rising temperatures have led to increased crop moisture stress, sun-scorch, and wilting, ultimately reducing crop growth and productivity (Ngure *et al*., 2021). This sector is intrinsically linked to environmental conditions, and the intensification of heat waves has presented a significant challenge. In southern Australia, for example, rising heat and protracted drying have threatened the viability of agriculture in certain regions, potentially leading to the collapse of some communities that depend on primary production (Hanna *et al*., 2011). Moreover, environmental degradation resulting from carbon emissions and greenhouse gases has exacerbated the impact of heat waves, as these pollutants release a variety of toxins that can harm the ecosystem and deplete soil nutrients (Adeleye *et al*., 2021). It can have devastating effects on water resources also. Crop production can be severely affected by high temperatures, leading to reduced yields and even crop failure (Srivastava *et al*., 2022).

- **Climate change attribution**: While natural climate variability plays a role in the occurrence of heat waves, climate change resulting from human activities is exacerbating the frequency and intensity of extreme heat events in India and globally. Rising greenhouse gas emissions and global warming are contributing to the observed trends in heat waves. The waves posing significant challenges to both the population and the environment. These heat waves can have severe impacts on human health and wellbeing, as well as on various sectors of the environment. Heat waves can cause a range of health issues, including dehydration, heat exhaustion, and heatstroke (Mukherjee and Mishra, 2018). The drought land increasing fastly due to heat waves. Meteorological drought condition, which is characterized by low rainfall can be amplified with simultaneous occurrence of heat waves. The research studies found significant changes in concurrent meteorological droughts and heat waves. There is substantial increase in the frequency of concurrent meteorological droughts and heat waves across whole India. Statistically significant trends were found in the spatial extent of droughts are observed in Central northeast India and west central India. However, the spatial extend affected by concurrent droughts and heatwaves is increasing across whole India (Sharma and Mujumdar, 2017).

  Overall, understanding the impact of heat waves in India is crucial for developing effective adaptation and mitigation strategies to reduce the impacts of extreme heat on society, economy, and the environment.

4.4 Future Predictions and Patterns:

Future projections indicate that heat waves in India will become more frequent, intense, and prolonged due to climate change. Temperature records are expected to be broken more frequently, with heat waves occurring across a wider geographic area. Additionally, changes in precipitation patterns and land use will influence the spatial distribution of heat waves, impacting vulnerable communities differently. A new update from the World Meteorological Organization suggests that global temperatures between the years 2023 and 2027 may rise to over 1.5°C above pre-industrial levels for at least one year. Experts caution about the more intense heat waves that are predicted to occur in India in the years indicated in the WMO update, particularly in 2024. According to a new UN research, as global temperatures surpass the 1.5-degree Celsius threshold, the following five years may be the warmest on record. The new update released by World Meteorological Organization (WMO) discusses the upcoming El Nino, combined with heat-trapping greenhouse gases, which will result in global temperatures between the years 2023 and 2027 rise to over 1.5°C above pre-industrial levels for at least one year.

V. ADAPTATION STRATEGIES

1) **Assessing Vulnerability and Identifying Hotspots:** Understanding heat waves involves assessing vulnerability at both individual and community levels. By identifying demographic groups, geographical areas, and sectors most susceptible to heat-related hazards, policymakers can prioritize resources and interventions where they are most needed. This entails analysing factors such as socio-economic status, access to healthcare, housing conditions, and exposure to outdoor work environments to pinpoint vulnerable populations and regions.

2) **Improving Early Warning Systems and Response Mechanisms:** An essential objective in understanding heat waves is to enhance early warning systems and response mechanisms. This includes leveraging advances in meteorological forecasting and data analytics to provide timely and accurate heat alerts to communities and decision-makers. Additionally, developing coordinated response plans involving government agencies, healthcare providers, emergency services, and community organizations can ensure swift and effective action during heat wave events, thereby minimizing adverse impacts on public health and safety. Narkhede *et al* (2022) developed an empirical model-based framework for operational monitoring and forecasting of heat waves based on temperature data. In this study, they proposed an operationally applicable empirical model that uses a set of indices to monitor and forecast heat waves on the short-term time scale. The model consists of two main components, firstly index-based monitoring over a spatial domain and 15 temporal predictions over different locations. Secondly heat wave indices are calculated the

heat stress index, heat stress index and the heat stress factor. They have also considered the effects of meteorological parameters such as wind and humidity on the intensity and duration of heat waves. For the prediction component, they have used a simple machine learning based method for predicting the overheating factor index. The study shows that the heat wave indices can be predicted with this simple model up to a lead time of 2-3 days for most regions of India.

3) **Enhancing Climate Resilience and Adaptation:** Understanding heat waves is integral to building climate resilience and adaptation measures that can withstand the impacts of a warming climate. This involves integrating heat-related risks into long-term planning processes, infrastructure development, and land-use policies. Implementing nature-based solutions such as green spaces, cool roofs, and heat-reflective pavements can mitigate the urban heat island effect and reduce temperatures in urban areas. Furthermore, promoting sustainable practices in agriculture, water management, and energy consumption can help buffer against heat-related disruptions and ensure food and water security in the face of changing climatic conditions.

4) **Fostering Research and Knowledge Exchange:** A key objective in understanding heat waves is to foster research and knowledge exchange among scientists, policymakers, practitioners, and communities. This includes supporting interdisciplinary research initiatives to advance our understanding of the complex drivers and impacts of heat waves in India. Furthermore, facilitating knowledge exchange platforms such as conferences, workshops, and collaborative networks can facilitate the sharing of best practices, lessons learned, and innovative solutions for addressing heat-related challenges. By promoting dialogue and collaboration, stakeholders can collectively work towards building a more resilient and sustainable future in the face of escalating heat waves.

VI. CONCLUSION

Heat waves in India represent a significant and escalating challenge, exacerbated by climate change and rapid urbanization. The increasing frequency, intensity, and duration of these events have profound implications for public health, agriculture, and overall socio-economic stability. The key findings of current paper indicate a clear trend towards more severe heat waves, with vulnerable populations, such as the elderly, children, and outdoor workers, being disproportionately affected. The economic toll on agriculture and labor productivity calls for adaptive strategies to safeguard livelihoods. Effective mitigation and adaptation strategies are crucial in managing the risks associated with heat waves. These include the development and implementation of early warning systems, community awareness programs, and infrastructure improvements, such as green spaces and heat-resistant buildings. Strengthening urban planning and design to incorporate heat-resilient practices can further mitigate the adverse effects. However, significant gaps remain in our understanding and response capabilities. There is a pressing need for comprehensive data collection, interdisciplinary research, and policy integration to enhance resilience against heat waves. Collaborative efforts between government agencies, academic institutions, and communities are essential to develop and implement sustainable solutions. In conclusion, addressing the challenges posed by heat waves in India requires a concerted effort to enhance adaptive capacities, improve public health infrastructure, and integrate climate resilience into developmental policies. By prioritizing these strategies, India can better protect its population and economy from the detrimental impacts of this escalating climate phenomenon.

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