



NAAS
Rating
4.23
★★★★★

AGRICULTURE JOURNAL **IJOEAR**

International Journal of Environmental
& Agriculture Research

VOLUME-12,
ISSUE-10,
OCTOBER 2026

Advancing Research
for a Sustainable
Tomorrow



Innovative
Research



Scientific
Excellence



Global
Impact



Sustainable
Future



Peer Reviewed Journal



Refereed Journal



Indexed Journal



Worldwide Visibility



+91-7665235235



www.ijoeear.com



info@ijoeear.com

Preface

We would like to present, with great pleasure, the volume-12, Issue-10, October 2026 of a scholarly journal, *International Journal of Environmental & Agriculture Research*. This journal is part of the AD Publications series in the field of *Environmental & Agriculture Research Development*, and is devoted to the gamut of Environmental & Agriculture issues, from theoretical aspects to application-dependent studies and the validation of emerging technologies.

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

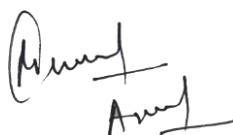
Environmental Research:

Environmental science and regulation, Ecotoxicology, Environmental health issues, Atmosphere and climate, Terrestrial 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:

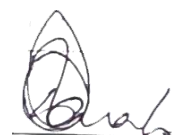
Agriculture, Biological engineering, including genetic engineering, microbiology, Environmental impacts of agriculture, forestry, Food science, Husbandry, Irrigation and water management, Land use, Waste management and all fields related to Agriculture.

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.



Mukesh Arora

(Managing Editor)



Dr. Bhagawan Bharali

(Chief Editor)

Fields of Interests

Agricultural Sciences	
Soil Science	Plant Science
Animal Science	Agricultural Economics
Agricultural Chemistry	Basic biology concepts
Sustainable Natural Resource Utilisation	Management of the Environment
Agricultural Management Practices	Agricultural Technology
Natural Resources	Basic Horticulture
Food System	Irrigation and water management
Crop Production	
Cereals or Basic Grains: Oats, Wheat, Barley, Rye, Triticale, Corn, Sorghum, Millet, Quinoa and Amaranth	Oilseeds: Canola, Rapeseed, Flax, Sunflowers, Corn and Hempseed
Pulse Crops: Peas (all types), field beans, faba beans, lentils, soybeans, peanuts and chickpeas.	Hay and Silage (Forage crop) Production
Vegetable crops or Olericulture: Crops utilized fresh or whole (wholefood crop, no or limited processing, i.e., fresh cut salad); (Lettuce, Cabbage, Carrots, Potatoes, Tomatoes, Herbs, etc.)	Tree Fruit crops: apples, oranges, stone fruit (i.e., peaches, plums, cherries)
Tree Nut crops: Hazlenuts. walnuts, almonds, cashews, pecans	Berry crops: strawberries, blueberries, raspberries
Sugar crops: sugarcane. sugar beets, sorghum	Potatoes varieties and production.
Livestock Production	
Animal husbandry	Ranch
Camel	Yak
Pigs	Sheep
Goats	Poultry
Bees	Dogs
Exotic species	Chicken Growth
Aquaculture	
Fish farm	Shrimp farm
Freshwater prawn farm	Integrated Multi-Trophic Aquaculture

Milk Production (Dairy)	
Dairy goat	Dairy cow
Dairy Sheep	Water Buffalo
Moose milk	Dairy product
Forest Products and Forest management	
Forestry/Silviculture	Agroforestry
Silvopasture	Christmas tree cultivation
Maple syrup	Forestry Growth
Mechanical	
General Farm Machinery	Tillage equipment
Harvesting equipment	Processing equipment
Hay & Silage/Forage equipment	Milking equipment
Hand tools & activities	Stock handling & control equipment
Agricultural buildings	Storage
Agricultural Input Products	
Crop Protection Chemicals	Feed supplements
Chemical based (inorganic) fertilizers	Organic fertilizers
Environmental Science	
Environmental science and regulation	Ecotoxicology
Environmental health issues	Atmosphere and climate
Terrestrial ecosystems	Aquatic ecosystems
Energy and environment	Marine research
Biodiversity	Pharmaceuticals in the environment
Genetically modified organisms	Biotechnology
Risk assessment	Environment society
Theoretical production ecology	horticulture
Breeding	plant fertilization

Board Members

Dr. Bhagawan Bharali (Chief Editor)

Professor & Head, Department of Crop Physiology, Faculty of Agriculture, Assam Agricultural University, Jorhat-785013 (Assam).

Mr. Mukesh Arora (Managing Editor)

M.Tech (Digital Communication), BE (Electronics & Communication), currently serving as Associate Professor in the Department of EE, BIET, Sikar.

Dr. Kusum Gaur (Associate Editor)

Dr. Kusum Gaur working as professor Community Medicine and member of Research Review Board of Sawai Man Singh Medical College, Jaipur (Raj) India.

She has awarded with WHO Fellowship for IEC at Bangkok. She has done management course from NIHF. She has published and present many research paper in India as well as abroad in the field of community medicine and medical education. She has developed Socio-economic Status Scale (Gaur's SES) and Spiritual Health Assessment Scale (SHAS). She is 1st author of a book entitled " Community Medicine: Practical Guide and Logbook.

Research Area: Community Medicine, Biostatistics, Epidemiology, Health and Hospital Management and Spiritual Health

Dr. Darwin H. Pangaribuan

Associate Professor in Department of Agronomy and Horticulture, Faculty of Agriculture, University of Lampung, Indonesia.

Educational background: (Ir.) from Faculty of Agriculture, IPB University, Bogor, Indonesia; (Dipl. Eng) in Land Evaluation from the University of Twente (UT-ITC), Enschede, The Netherlands; (M.Sc) in Crop Production from Wageningen University (WU), The Netherlands. (Ph.D) in Horticulture from University of Queensland (UQ), Brisbane, Australia.

Research Interest: Vegetable Production & Physiology; Biostimulant & Biofertilizers; Organic Farming, Multiple Cropping, Crop Nutrition, Horticulture.

Dr Peni Kistijani Samsuria Mutalib

Working as Research coordinator and HOD in the department of Medical Physics in University of Indonesia.

Dr. Govindaraj Kamalam Dinesh, PhD

Department of Biochemistry, Physiology, Microbiology and Environmental Science College of Agriculture, Iroisemba

Central Agricultural University, Imphal, Manipur – 795004, India

Specialization: Ecosystem services, Conservation agriculture, Climate change, Agroecology, Greenhouse gas emissions from agriculture, Agricultural ornithology, Carbon sequestration

Academic Qualifications: B.Sc. (Agriculture), Annamalai University, M.Sc. (Environmental Science), Tamil Nadu Agricultural University (TNAU), Ph.D. (Environmental Sciences), ICAR-IARI, New Delhi (UGC-JRF, IARI PhD SRF, All India Rank – 5)

Professor Jacinta A.Opara

Working full-time and full-ranked Professor and Director, Centre for Health and Environmental Studies at one of the top 10 leading public Universities in Nigeria, the University of Maiduguri-Nigeria founded in 1975.

Dr. Samir B. Salman AL-Badri

Samir Albadri currently works at the University of Baghdad / Department of Agricultural Machines and Equipment. After graduation from the Department of Plant, Soils, and Agricultural Systems, Southern Illinois University Carbondale. The project was 'Hybrid cooling to extend the saleable shelf life of some fruits and vegetables. I worked in many other subject such as Evaporative pad cooling.

Orchid ID: <https://orcid.org/0000-0001-9784-7424>

Publons Profile: <https://publons.com/researcher/1857228/samir-b-albadri>

Dr. Goswami Tridib Kumar

Presently working as a Professor in IIT Kharagpur from year 2007, He Received PhD degree from IIT Kharagpur in the year of 1987.

Prof. Khalil Cherifi

Professor in Department of Biology at Faculty of Sciences, Agadir, Morocco.

Dr. Josiah Chidiebere Okonkwo

PhD Animal Science/ Biotech (DELSU), PGD Biotechnology (Hebrew University of Jerusalem Senior Lecturer, Department of Animal Science and Technology, Faculty of Agriculture, Nau, AWKA.

Dr. Jadala Shankaraswamy

Specialization: Horticulture, Post-Harvest Technology, Phytochemistry, Nanobiotechnology, 3D Food Printing

Academic Qualifications: B.Sc. (Horticulture), M.Sc. (Post-Harvest Technology of Horticultural Crops), Ph.D. (Horticulture)

Assistant Professor (Senior Scale - IX), College of Horticulture, Mojerla, Sri Konda Laxman Telangana State Horticultural University, Telangana, India

Dr. Jadala Shankaraswamy is an Assistant Professor (Senior Scale – IX) at Sri Konda Laxman Telangana State Horticultural University, Telangana, India. His research focuses on post-harvest technology, phytochemistry, nanobiotechnology, and value addition in horticultural crops. He has contributed to innovative product development, holds patents in horticultural science, and has received several national and international awards for his research excellence.

Dr. Tarun Kumar Maheshwari

Dr. Tarun Kumar Maheshwari, Head of Agricultural Engineering at Dr. BRA College of Agricultural Engineering and Technology, Etawah, specializes in farm machinery and power engineering. He holds a Ph.D. from Sam Higginbottom University and an M.Tech. from IIT Kharagpur.

Prof. Özhan ŞİMŞEK

Agriculture Faculty, Department of Horticulture, Çukurova University, Adana, 01330 Turkey.

Dr. Anka Ozana Čavlović

Working as Professor in the department of Faculty of Forestry, University of Zagreb, Svetošimunska 25, Zagreb.

Dr. Rakesh Singh

Professor in Department of Agricultural Economics, Institute of Agricultural Sciences, Banaras Hindu University, Also Vice President of Indian Society of Agricultural Economics, Mumbai.

Dr. Sunil Wimalawansa

MD, PhD, MBA, DSc, is a former university professor, Professor of Medicine, Chief of Endocrinology, Metabolism & Nutrition, expert in endocrinology; osteoporosis and metabolic bone disease, vitamin D, and nutrition.

Dr. Smruti Sohani

Dr. Smruti Sohani, has Fellowship in Pharmacy & Life Science (FPLS) and Life member of International Journal of Biological science indexed by UGC and e IRC Scientific and Technical Committee. Achieved young women scientist award by MPCOST. Published many Indian & UK patents, copyrights, many research and review papers, books and book chapters. She Invited as plenary talks at conferences and seminars national level, and as a Session chair on many International Conference organize by Kryvyi Rih National University, Ukraine Europe. Designated as state Madhya Pradesh Coordinator in International conference collaborated by RCS. Coordinator of two Professional Student Chapter in collaboration with Agriculture Development society and research Culture Society. her enthusiastic participation in research and academia. She is participating on several advisory panels, scientific societies, and governmental committees. Participant in several worldwide professional research associations; member of esteemed, peer-reviewed publications' editorial boards and review panels. Many Ph.D., PG, and UG students have benefited from her guidance, and these supervisions continue.

Dr. Ajeet singh Nain

Working as Professor in GBPUA&T, Pantnagar-263145, US Nagar, UK, India.

Dr. Salvinder Singh

Presently working as Associate Professor in the Department of Agricultural Biotechnology in Assam Agricultural University, Jorhat, Assam.

Dr. Salvinder received MacKnight Foundation Fellowship for pre-doc training at WSU, USA – January 2000-March 2002 and DBT overseas Associateship for Post-Doc at WSU, USA – April, 2012 to October, 2012.

Dr. V K Joshi

Professor V.K.Joshi is M.Sc., Ph.D. (Microbiology) from Punjab Agricultural University, Ludhiana and Guru Nanak Dev University, Amritsar, respectively with more than 35 years experience in Fruit Fermentation Technology, Indigenous fermented foods, patulin ,biocolour ,Quality Control and Waste Utilization. Presently, heading the dept. of Food Science and Technology in University of Horticulture and Forestry, Nauni-Solan (HP), India.

Dr. Mahendra Singh Pal

Presently working as Professor in the dept. of Agronomy in G. B. Pant University o Agriculture & Technology, Pantnagar-263145 (Uttarakhand).

Dr. Sanjoy Kumar Bordolui

M.Sc. (Ag.), PhD, FSTA, FSIESRP, Assistant Professor, Department of Seed Science and Technology, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia. W.B., India. He received CWSS Young Scientist Award-2016, conferred by Crop and Weed Science Society, received Best Young Faculty Award 2019 conferred by Novel Research Academy, received Innovative Research & Dedicated Teaching Professional Award 2020 conferred by Society of Innovative Educationalist & Scientific Research Professional, Chennai.

Dr. Chiti Agarwal

Dr. Chiti Agarwal works as a postdoctoral associate at the University of Maryland in College Park, Maryland, USA. Her research focuses on fungicide resistance to fungal diseases that affect small fruits such as strawberries. She graduated from North Dakota State University in Fargo, North Dakota, with a B.S. in biotechnology and an M.S. in plant sciences. Dr. Agarwal completed her doctorate in Plant Pathology while working as a research and teaching assistant. During her time as a graduate research assistant, she learned about plant breeding, molecular genetics, quantitative trait locus mapping, genome-wide association analysis, and marker-assisted selection. She wants to engage with researchers from many fields and have a beneficial impact on a larger audience.

DR. Owais Yousuf

Presently working as Assistant professor in the Department of Bioengineering, Integral University-Lucknow, Uttar Pradesh, India.

Dr. Vijay A. Patil

Working as Assistant Research Scientist in Main Rice Research Centre, Navsari Agricultural University, Navsari. Gujarat- 396 450 (India).

Dr. Amit Kumar Maurya

Working as Junior Research Assistant in the Department of Plant Pathology at Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, U.P. India.

Prof. Salil Kumar Tewari

Presently working as Professor in College of Agriculture and Joint Director, Agroforestry Research Centre (AFRC) / Program Coordinator in G.B. Pant University of Agric. & Tech., Pantnagar - 263 145, Uttarakhand (INDIA).

Dr. S. K. Jain

Presently working as Officer Incharge of All India Coordinated Sorghum Improvement Project, S. D. Agricultural University, Deesa, Gujarat.

Dr. Deshmukh Amol Jagannath

Presently working as Assistant Professor in Dept. of Plant Pathology, College of Agriculture polytechnic, NAU, Waghai.

Mr. Anil Kumar

Working as Junior Research Officer/Asstt. Prof. in the dept. of Food Science & Technology in Agriculture & Technology, Pantnagar.

Mr. Jiban Shrestha

Scientist (Plant Breeding & Genetics)

Presently working as Scientist (Plant Breeding and Genetics) at National Maize Research Programme (NMRP), Rampur, Chitwan under Nepal Agricultural Research Council (NARC), Singhdarbar Plaza, Kathmandu, Nepal.

Mr. Aklilu Bajigo Madalcho

Working at Jigjiga University, Ethiopia, as lecturer and researcher at the College of Dry land Agriculture, department of Natural Resources Management.

Mr. Isaac Newton ATIVOR

MPhil. in Entomology, from University of Ghana.

He has extensive knowledge in tree fruit orchard pest management to evaluate insecticides and other control strategies such as use of pheromone traps and biological control to manage insect pests of horticultural crops. He has knowledge in agronomy, plant pathology and other areas in Agriculture which I can use to support any research from production to marketing.

Mr. Bimal Bahadur Kunwar

He received his Master Degree in Botany from Central Department of Botany, T.U., Kirtipur, Nepal. Currently working as consultant to prepare CCA-DRR Plan for Hariyo Ban Program/CARE in Nepal/GONESA.

Table of Contents

Volume-12, Issue-10, October 2026

S.No	Title	Page No.
1	Population Dynamics and Damage Potential of Fruit Flies by Using the Pheromone Traps (Fruit fly traps) in Guava Orchard Authors: Harish Prajapat; Vaishampayan Sanjay  DOI: https://doi.org/10.25125/ijoe-ar-oct-2026-1  Digital Identification Number: IJOEAR-OCT-2026-1	01-06
2	Fabrication and Comparative Evaluation of PVA-Ninhydrin and PVA-Nano ZnO-Ninhydrin Composite Films as Colourimetric Sensors for Soil Fertility Assessment Authors: Unnimaya M; Mubashira Thasni EP; Nafeesathul Misriya TK; Mujeeb Rahman P  DOI: https://doi.org/10.25125/ijoe-ar-oct-2026-2  Digital Identification Number: IJOEAR-OCT-2026-2	07-18
3	The Importance of Electronic Communication in the Use of Artificial Intelligence Programs and Applications in the Field of Smart Agriculture from the Point of View of Agricultural Extension Workers in Nineveh Governorate, Iraq Authors: Luma Monther Adress  DOI: https://doi.org/10.25125/ijoe-ar-oct-2026-3  Digital Identification Number: IJOEAR-OCT-2026-3	19-29
4	Effect of Weaning on Growth Performance and Health Status of Crossbred Calves Authors: Kavita Chauhan; Danveer S. Yadav; Naresh Kurechiya; Sandeep Nanavati; M.S. Jamra; N.S. Rawat  DOI: https://doi.org/10.25125/ijoe-ar-oct-2026-4  Digital Identification Number: IJOEAR-OCT-2026-4	30-36
5	Air-to-Water Condensation Farming and Fogponics for "Zero-Watering" Horticulture in India: A Review of Technologies, Crop Suitability and Readiness for El Niño-Driven Water Scarcity Authors: Jadala Shankaraswamy  DOI: https://doi.org/10.25125/ijoe-ar-oct-2026-6  Digital Identification Number: IJOEAR-OCT-2026-6	37-46
6	Indian Pomegranate Exports: Production, Residue Compliance, Quality and Market Constraints Authors: Durgesh Kailas Narwade; B V Deore; Y S Saindane; S A Hiray; P E More; S B Deore  DOI: https://doi.org/10.25125/ijoe-ar-oct-2026-9  Digital Identification Number: IJOEAR-OCT-2026-9	47-63

7	Optimization of Mineral Fertilization of Cotton (<i>Gossypium hirsutum</i> L.) under Late Sowing Conditions in the Countries of the Regional Program for Integrated Cotton Production in Africa (PR-PICA) Authors: Traoré Amadou; Ouattara Adama; Amonmidé Isidore; Diop Assane; N'Goran Kouadio Emanuel; Koffi Kokou Zovodu; Djinodji Renougal; Kobenan Koffi Christophe; Kamga Dimitri; Takpa O'Nel; Séidou Moudjaidou; Koulibaly Bazoumana  DOI: https://doi.org/10.25125/ijoeear-oct-2026-10  Digital Identification Number: IJOEAR-OCT-2026-10	64-73
8	Utilization of the Stingless Bee (<i>Trigona</i> sp.) as a Natural Pollinator in Rubber (<i>Hevea brasiliensis</i>) Agroforestry Program of PT Pertamina EP Sangatta Field, East Kalimantan, Indonesia Authors: Annisa Nurjanah; Maulita Dwi Hariyanti; Sofian Cahyo Aji; Luisa Febrina Amalo; Luluk Dwi Wulan Handayani  DOI: https://doi.org/10.25125/ijoeear-oct-2026-11  Digital Identification Number: IJOEAR-OCT-2026-11	74-80

Population Dynamics and Damage Potential of Fruit Flies by Using the Pheromone Traps (Fruit fly traps) in Guava Orchard

Harish Prajapat^{1*}; Vaishampayan Sanjay²

^{*1}M.Sc. Scholar, Department of Entomology, J.N.K.V.V. Jabalpur (M.P.) 482004

²Senior Scientist, Department of Entomology, J.N.K.V.V. Jabalpur (M.P.) 482004

*Corresponding Author

Received:- 12 September 2026/ Revised:- 28 September 2026/ Accepted:- 08 October 2026/ Published: 15-10-2026

Copyright @ 2026 International Journal of Environmental and Agriculture Research

This is an Open-Access article distributed under the terms of the Creative Commons Attribution

Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted

Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— A field investigation was undertaken at KVK, Katni, Madhya Pradesh, from September 2025 to January 2026 to characterize the population dynamics and damage potential of fruit flies (*Bactrocera* spp.) in a guava (*Psidium guajava* L.) orchard. Seasonal activity was monitored using fruit fly traps with a methyl eugenol-based biodegradable lure. The relationships between fruit fly population and weather parameters were also examined. Fruit fly abundance exhibited a progressive increase from the 36th SMW, attaining a maximum of 42.50 flies/trap/week in the 43rd SMW, and subsequently declined gradually. A comparable pattern was observed in fruit infestation, which increased from 8.33 per cent to 41.67 per cent during the study period. Significant positive correlations were observed between fruit fly population and maximum temperature, minimum temperature and relative humidity, whereas rainfall and wind speed showed non-significant relationships. The regression model accounted for approximately 81 per cent of the variation in fruit fly population through the selected weather parameters. These findings establish a close relationship between fruit fly population abundance and fruit infestation and support the use of methyl eugenol traps for monitoring seasonal activity and facilitating timely management of fruit flies in guava orchards.

Keywords— *Bactrocera* spp., Guava, Population dynamics, Methyl eugenol, Fruit infestation, Weather parameters, Fruit fly trap.

I. INTRODUCTION

Guava (*Psidium guajava* L.), a member of the family Myrtaceae, is an important tropical fruit crop cultivated widely for its nutritious value. Commonly referred to as the "Apple of the Tropics," it originated in tropical America and is now extensively grown throughout tropical and subtropical regions (Baloda et al., 2018). India is the world's largest guava producer, contributing nearly 46% of global production. During 2024-25, guava was cultivated on 3.58 lakh ha with an estimated production of 53.50 lakh tonnes. Uttar Pradesh and Madhya Pradesh are the leading producing states (Anonymous, 2025). Guava production is constrained by several insect pests, of which fruit flies (*Bactrocera* spp.) are the most economically damaging. Other important pests include the mealybug (*Ferrisia virgata*), fruit and shoot borer (*Conogethes punctiferalis*), tea mosquito bug (*Helopeltis antonii*), and bark-eating caterpillar (*Indarbela tetraonis*) (Gundappa et al., 2018). Fruit fly infestation can cause severe quantitative and qualitative losses, with damage varying according to pest abundance, cultivar, and environmental conditions (Kumar et al., 2011). Fruit flies belong to the family Tephritidae, which comprises over 4,000 described species. Among them, the genus *Bactrocera* is one of the most economically significant, containing nearly 500 species distributed mainly across Asia and Australia (Majeed et al., 2024). While numerous species are known to infest fruits, merely a limited number are encountered within orchard environments. The recorded data concerning fruit fly population fluctuations in guava cultivation systems presents both prospects and obstacles for adequate strategic planning and implementing appropriate management interventions at optimal timings (Vignesh et al., 2020).

II. MATERIAL AND METHODS

The experiment was conducted at Krishi Vigyan Kendra (KVK), Katni, (23.736181° N, 80.316522° E), affiliated with Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, Madhya Pradesh from September 2025 to January 2026.

2.1 Trap and lure

Me-Gel traps were made of durable plastic with a yellow bowl and a 4 cm entry hole. Each trap contained a plastic dispenser loaded with a wax matrix-based biodegradable lure comprising methyl eugenol, malathion 50 EC, and inert ingredients (water, wax, oils, proteins, food-grade emulsifiers, and preservatives) to attract fruit flies.

2.2 Observations

Fruit fly population was monitored using four traps installed at four observation sites in the guava orchard. Monitoring began during the 36th Standard Meteorological Week (SMW) at the onset of fruiting. Adult catches were recorded weekly and expressed as flies/trap/week. Weekly trap catches were correlated with meteorological variables, including maximum and minimum temperature, relative humidity, rainfall and wind speed, using correlation and regression analyses. Fruit infestation was assessed weekly from the 36th SMW (September 2025) until the end of the fruiting period. Three randomly selected trees at each site were tagged, and five fruits were sampled from each tree (15 fruits per site). Fruits showing oviposition punctures were considered infested. Fruit infestation was calculated as (Umesh, 2018; Abbott, 1925):

$$\text{Fruit infestation (\%)} = \frac{\text{Number of infested fruits}}{\text{Total no. of observed fruits}} \times 100 \quad (1)$$

III. RESULT AND DISCUSSION

3.1 Population dynamics of fruit fly in guava orchard

Fruit fly activity commenced during the 36th Standard Meteorological Week (SMW) and increased steadily, reaching a peak of 42.50 flies/trap/week in the 43rd SMW. Thereafter, the population declined gradually, with the lowest catch (1.00 fly/trap/week) recorded in the 52nd SMW. Peak abundance coincided with the fruiting stage of guava, while the winter season was associated with a sharp decline in adult population (Table 1 and Fig. 1).

TABLE 1
POPULATION DYNAMICS OF FRUIT FLY AND WEATHER PARAMETERS IN GUAVA ORCHARD DURING SEPTEMBER TO JANUARY IN 2025-26

SMW	Average No. of fruit flies/trap/week	Max. Temp. (°C)	Min. Temp. (°C)	R.H. (%)	Rainfall (mm)	Wind speed (km/h)
36	11.5	29.36	23.17	89.15	6.26	2.98
37	19	29.49	23.31	88.55	6.13	2.04
38	26.25	30.13	22.77	84.57	1.85	2.01
39	27.5	29.55	22.7	87.88	5.27	3.11
40	30.5	30.55	22.7	87.88	5.27	3.11
41	35.5	27.48	18.01	80.71	0.06	1.92
42	38.75	28.26	18.2	79.49	0.62	1.97
43	42.5	28.43	19.25	83.63	1.04	2.28
44	38.5	28.23	19.79	82.51	2.69	2.69
45	31.25	24.96	12.87	65.7	0	1.87
46	25.75	23.47	10.49	66.51	0.05	1.8
47	16.5	24.34	10.95	75.24	0	1.83
48	15.75	23.77	10.53	74.01	0	2.28
49	11.5	24.02	9.61	63.24	0	2.23
50	8.25	24.32	8.9	64.46	0	2.03
51	5.5	23.44	8.51	71.04	0	2.29
52	1	23.91	7.36	65.7	0	2.36
1	1.75	23.62	8.29	70.35	0	2.64
2	2.25	25.01	8.37	63.1	0	2.64
3	3.25	26.67	9.82	54.38	0.01	2.48
4	4.5	26.67	11.5	63.59	0.32	2.78
5	5.25	27.14	11.6	61.8	0.01	2.68

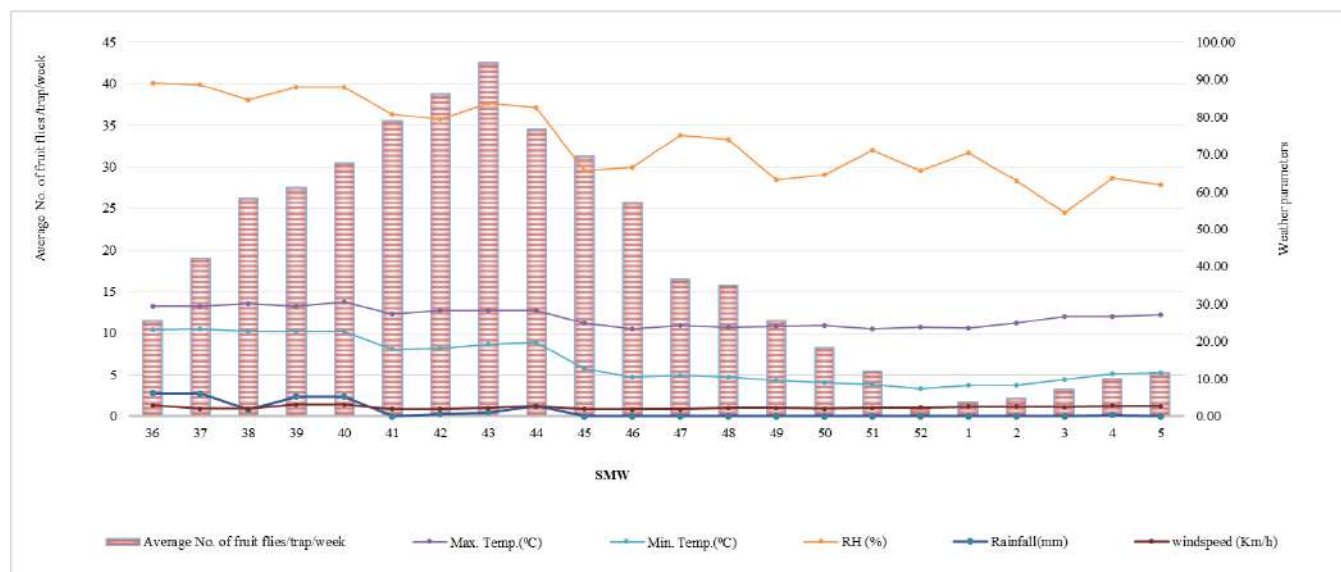


FIGURE 1: Population dynamics of fruit fly and its relation with weather parameters in guava orchard during September to January in 2025-26

TABLE 2

CORRELATION OF FRUIT FLY POPULATION TRAPPED IN FRUIT FLY TRAPS WITH WEATHER PARAMETERS

Weather parameters	Fruit fly	Weather parameters	Fruit fly
Maximum Temperature	0.519*	Relative humidity	0.630**
Minimum Temperature	0.670**	Rainfall	0.275NS
Wind speed	-0.225NS		

**** Significant at 1% level of significance, *Significant at 5% level of significance, NS - Non-significant**

The present findings agree with Sarada et al. (2001) and Verghese and Sudhadevi (1998), who reported maximum fruit fly activity during fruit ripening followed by a decline after harvest. Similar observations were made by Su (1984) and Shukla and Prasad (1985), who found a positive association between temperature and fruit fly catches. The seasonal trend observed in this study is also consistent with reports of Vignesh et al. (2020), Math et al. (2018) and Gupta and Bhatia (2000), who identified *Bactrocera dorsalis* as the predominant species in guava and recorded peak populations during the fruiting period. Chandra et al. (2022) further demonstrated that temperature and relative humidity were the major weather factors influencing fruit fly abundance. In agreement with Raina et al. (2023) and Khomane et al. (2023), weather variables significantly affected fruit fly incidence. The regression model developed in the present study explained approximately 81% of the variation in fruit fly population, indicating that weather parameters had a strong influence on seasonal population dynamics under the prevailing conditions.

3.2 Damage potential of fruit fly in guava orchard

Fruit infestation began during the 36th SMW (8.33%), increased progressively with adult trap catches and reached a maximum of 41.67 per cent in the 43rd SMW. Thereafter, infestation declined steadily and no damaged fruits were observed from the 1st to 5th SMW, indicating a close relationship between adult fruit fly abundance and fruit damage (Table 3 and Fig. 2).

These findings are consistent with Agarwal and Kumar (1999), Haseeb (2007) and Kruthika et al. (2025), who reported that fruit infestation increased with fruit maturity and peaked during periods of maximum fruit fly activity. Similar observations were made by Math et al. (2018), Khomane et al. (2023), Singh et al. (2024) and Giddi and Emmanuel (2023), who found that infestation was highest during the fruiting period and declined after harvest. Umesh et al. (2025) also reported fruit losses ranging from 18-68 per cent in guava due to *Bactrocera* spp. and emphasized the importance of methyl eugenol traps for monitoring and management. The close association between trap catches and fruit damage observed in the present study

highlights the usefulness of pheromone traps as an effective tool for forecasting infestation and supporting timely management decisions.

TABLE 3
DAMAGE POTENTIAL CAUSED BY FRUIT FLY IN GUAVA ORCHARD

SMW	Total No. of infested fruits	Total No. of observed fruits	Damage potential (%)
36	5	60	8.333
37	7	60	11.667
38	9	60	15
39	11	60	18.333
40	12	60	20
41	14	60	23.333
42	17	60	28.333
43	25	60	41.667
44	23	60	38.333
45	20	60	33.333
46	18	60	30
47	16	60	26.667
48	11	60	18.333
49	4	60	6.667
50	4	60	6.667
51	2	60	3.333
52	1	60	1.667
1	0	60	0
2	0	60	0
3	0	60	0
4	0	60	0
5	0	60	0



FIGURE 2: Damage potential caused by fruit fly in guava orchard

IV. CONCLUSION

The fruit fly population exhibited a clear seasonal pattern, first appearing in the 36th SMW, reaching its peak in the 43rd SMW, and declining thereafter. The highest trap catch (42.50 flies/trap/week) and maximum fruit infestation (41.67%) were both recorded during the 43rd SMW, identifying this as the most critical period for fruit fly damage in guava. Fruit infestation closely followed adult fly abundance, indicating that pheromone trap catches are a reliable predictor of infestation. Multiple regression analysis showed that weather variables explained approximately 81% of the variation in fruit fly population, confirming the important role of climatic factors in seasonal population dynamics.

ACKNOWLEDGEMENT

The authors express heartfelt gratitude to members of the Advisory Committee and the Professor and Head, Department of Entomology, College of Agriculture, JNKVV, Jabalpur, for their valuable suggestions and continuous support provided during the research work. We also wish to express our deep sense of gratitude to the scientists and staff members of Krishi Vigyan Kendra, Katni for extending their cooperation and providing experimental facilities.

CONFLICT OF INTEREST

The author(s) declare that there is no conflict of interest regarding the publication of this work as this research work was conducted for the partial fulfillment of the degree of M.Sc. Ag. Entomology.

REFERENCES

- [1] Abbott, W. S. (1925). A method of computing the effectiveness of insecticide. *Journal of Economic Entomology*, *18*, 265-267.
- [2] Agarwal, M. L., & Kumar, P. (1999). Population dynamics and damage potential of fruit flies in guava. *Indian Journal of Entomology*, *61*(2), 123-128.
- [3] Anonymous. (2025). *Agricultural marketing report—Guava (Ambe Bahar): Pre-sowing and pre-harvest forecast report (2025)*. Department of Agricultural Economics and Farm Management, Punjab Agricultural University.
- [4] Baloda, S., Sharma, J. R., Kumar, M., Singh, S., & Malik, A. (2018). Studies on performance of rejuvenated plants and fresh plants of guava. *International Journal of Pure and Applied Bioscience*, *6*(1), 939-941.
- [5] Chandra, A., Bhagawati, K., Kalita, H., & Angami, T. (2022). Weather-based fruit fly population dynamics prediction model for the mid-hills of Eastern Himalayan region of India. *Current World Environment*, *17*(3), 690-697.
- [6] Giddi, T. D., & Emmanuel, N. (2023). Seasonal incidence of fruit fly in guava cv. Taiwan White. *Ecology, Environment and Conservation*, *29*(3), 218-221.
- [7] Gundappa, B., Rajkumar, M. B., Singh, S., & Rajan, S. (2018). Pests of guava. In O. Omkar (Ed.), *Pests and their management* (pp. 491-510). Springer Nature Singapore.
- [8] Gupta, J. P., & Bhatia, R. (2000). Seasonal incidence of *Bactrocera dorsalis* and *Bactrocera zonata* in North India. *Journal of Fruit Science*, *17*(1), 12-18.
- [9] Haseeb, M. (2007). Seasonal incidence of fruit flies and fruit infestation in guava. *Annals of Plant Protection Sciences*, *15*(1), 89-93.
- [10] Khomane, K. B., Datkhile, R. V., Aghav, S. T., Kadu, R. V., & Todkar, A. A. (2023). Seasonal incidence and management of guava fruit fly. *The Pharma Innovation Journal*, *12*(1), 1187-1191.
- [11] Kruthika, K. S., Gundannavar, K. P., Kambrekar, D. N., & Biradar, M. S. (2025). Studies on population dynamics of major pests of guava and their natural enemies in Dharwad, Karnataka, India. *Plant Archives*, *25*(Supplement 1), 3068-3072.
- [12] Kumar, P., Abubakar, Linda, A., Ketelaar, J. W., & Shanmugam, V. (2011). Fruit fly damage and crop losses. In *Field exercise guide on fruit flies integrated pest management* (p. 17). Asian Fruit Fly IPM Project.
- [13] Majeed, D. M., Majeed, A., Jamali, M., & Mir, R. A. (2024). Species diversity of fruit flies (*Bactrocera* spp.) in guava orchards of Sahanpur District of Uttar Pradesh. *Journal of Entomology and Zoology Studies*, *12*(1), 11-16.
- [14] Math, M. A., Kotikal, Y. K., & Ganiger, V. M. (2018). Species diversity and population dynamics of fruit flies in guava ecosystem. *International Journal of Current Microbiology and Applied Sciences*, *7*(12), 2269-2283.
- [15] Raina, S., Sharma, D., & Singh, M. (2023). Impact of weather parameters on population dynamics of fruit flies (*Bactrocera* spp.) on phalsa (*Grewia asiatica* Linn.). *International Journal of Environment and Climate Change*, *13*(11), 735-741.
- [16] Sarada, G., Maheswari, T. U., & Purushotham, K. (2001). *Seasonal incidence of fruit flies in guava orchard*.
- [17] Shukla, R. P., & Prasad, P. G. (1985). Population fluctuation of the oriental fruit fly, *Dacus dorsalis* Hendel, in relation to host and abiotic factors. *Tropical Pest Management*, *31*, 273-275.
- [18] Singh, A., Singh, K., & Singh, B. (2024). Seasonal incidence of the guava fruit fly, *Bactrocera* spp. in Talwandi Sabo, Punjab. *Environment and Ecology*, *42*(4C), 2068-2074.
- [19] Su, C. Y. (1984). The study on the relationship between seasonal succession of male adult of melon fly, *Dacus cucurbitae*, and meteorological factors. *Journal of Agriculture and Forestry*, *32*, 105-109.

- [20] Umesh, Kumar, R., & Meenu. (2025). Seasonal incidence and ecofriendly management of *Bactrocera* spp. fruit flies in guava (*Psidium guajava* L.): A review. *International Journal of Horticulture and Food Science*, *7*(5), 97-101.
- [21] Verghese, A., & Sudhadevi, K. (1998). Relation between trap catches of *Bactrocera dorsalis* and abiotic factors. In *Advances in IPM for horticultural crops*.
- [22] Vignesh, S., Chandrasekaran, M., Ambethgar, V., & Jeeva, S. (2020). Species diversity and population dynamics of fruit flies in guava orchards. *Journal of Entomology and Zoology Studies*, *8*(3), 615-619.

Fabrication and Comparative Evaluation of PVA-Ninhydrin and PVA-Nano ZnO-Ninhydrin Composite Films as Colourimetric Sensors for Soil Fertility Assessment

Unnimaya M¹; Mubashira Thasni EP²; Nafeesathul Misriya TK³; Mujeeb Rahman P^{4*}

^{1,2,3}P.G Department of Chemistry, Grace Valley College of Arts& Science, Maravattam, Malappuram, Kerala

^{*4}Department of Chemistry, Government Arts and Science College Calicut, University of Calicut, Kerala, India

*Corresponding Author

Received:- 12 September 2026/ Revised:- 23 September 2026/ Accepted:- 04 October 2026/ Published: 15-10-2026

Copyright @ 2026 International Journal of Environmental and Agriculture Research

This is an Open-Access article distributed under the terms of the Creative Commons Attribution

Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted

Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— The fabrication of a rapid, simple and cost-effective method for soil fertility assessment is crucial for sustainable agricultural practices. Since nitrogen is an essential nutrient for soil fertility, its detection in soil helps to quickly identify the quality and fertility of the soil. In this study, two different composite films comprising polyvinyl alcohol (PVA)–ninhydrin and PVA–nano zinc oxide (ZnO)–ninhydrin were prepared and evaluated for their soil fertility sensing ability. Both films were prepared by the solution-casting method and dried under sunlight. The fabricated films were well characterized and investigated for thermal stability, mechanical properties, and antibacterial activities. The simple and rapid method of soil fertility testing was carried out with different soil samples. Thermogravimetric analysis revealed that ZnO incorporation enhanced the thermal stability of the composite films by delaying thermal degradation and increasing the residual mass. Mechanical studies proved enhanced flexibility and durability of the ZnO-containing film compared to the PVA–ninhydrin film. Similarly, the nano ZnO-containing film exhibited enhanced antibacterial activity, attributed to the intrinsic antimicrobial properties of ZnO nanoparticles.

The soil fertility sensing ability of the films was tested using four different soil samples: chicken manure-amended soil, cow dung-amended soil, black soil, and normal soil. The rate and intensity of colour development followed the order: chicken manure-amended soil > cow dung-amended soil > black soil > normal soil, reflecting their fertility order. The PVA–ninhydrin film exhibited a faster colour response, whereas ZnO incorporation slightly delayed colour formation, suggesting that ZnO influences reactant diffusion and the reaction kinetics within the polymer matrix.

Altogether, both films exhibited excellent potential as simple, portable, and low-cost colourimetric sensors for the rapid qualitative detection of soil fertility. Although the PVA–ninhydrin film provided a faster sensing response, the PVA–nano ZnO–ninhydrin composite film offered superior thermal stability, mechanical robustness, and antibacterial performance, making it a promising candidate for practical agricultural sensing applications.

Keywords— Polyvinyl alcohol; Ninhydrin; Zinc oxide nanoparticles; Colourimetric sensor; Ruhemann's purple; Soil fertility; Nitrogen-containing compounds; Nanocomposite film.

I. INTRODUCTION

Agricultural productivity and sustainable crop production are necessarily related to soil fertility. It determines the availability of essential nutrients required for plant growth and development (Khan et al., 2024). Among the primary macronutrients present in soil, nitrogen is predominantly important as it is a major constituent of amino acids, proteins, nucleic acids, enzymes, and chlorophyll, thereby playing a vital role in plant metabolism, growth, and crop yield. Consequently, rapid and reliable assessment of soil fertility in connection with nitrogen status is essential for efficient nutrient management and sustainable agricultural practices (Ali et al., 2025).

A significant source of soil nitrogen is organic matter such as cow dung, chicken manure, etc. Nitrogen produced through the decomposition of such organic matter makes soil fertile. The nitrogen present in the soil as amino acids can be qualitatively detected and provide information on soil fertility status. Conventional methods for soil fertility assessment, including Kjeldahl analysis, elemental analysis, and spectroscopic techniques, provide accurate results but often require sophisticated instrumentation, extensive sample preparation, skilled personnel, and laboratory-based analysis. These limitations highlight the need for simple, rapid, portable, and cost-effective sensing methods suitable for on-site applications.

The organic molecule ninhydrin (1,2,3-indanetrione hydrate) is one of the most widely used analytical reagents for detecting amino acids and other primary amine-containing compounds. It reacts with free amino groups through oxidative deamination and decarboxylation to produce the characteristic deep purple known as Ruhemann's purple. These characteristics make ninhydrin an attractive reagent for the development of colourimetric sensors for nitrogen-containing compounds. The intensity and rate of colour formation depend on the concentration of reactive amino groups. Due to this, ninhydrin reactions have been extensively employed in analytical chemistry, biochemistry, forensic science, chromatography, and protein analysis (Gelaye, 2024; Stauß et al., 2024).

Conventional ninhydrin assays have portability issues and on-site practical difficulties owing to their liquid nature and complicated laboratory procedures. Hence, developing solid-state colourimetric sensors which are easy to handle, reusable, portable, and suitable for rapid on-site detection has great significance in soil fertility analysis (Jeong et al., 2023; Wang et al., 2020). This can be achieved by immobilizing ninhydrin molecules in a polymer matrix. Among various polymeric materials, polyvinyl alcohol (PVA) has attracted considerable attention owing to its excellent film-forming ability, transparency, flexibility, biocompatibility, non-toxicity, and favorable mechanical properties (Abazari et al., 2025). Furthermore, the abundant hydroxyl groups present in PVA facilitate the immobilization of functional sensing reagents while maintaining their chemical reactivity, making PVA an excellent matrix for colourimetric sensor fabrication (Elgharbawy et al., 2024).

The incorporation of ZnO nanoparticles in a PVA matrix has emerged as an effective approach for enhancing the functional properties of sensing materials (Liang et al., 2024; Jailani et al., 2026; Etemadi et al., 2022). Zinc oxide (ZnO) nanoparticles have characteristic thermal and mechanical properties. They exhibit a large specific surface area, ultraviolet shielding ability, and intrinsic antimicrobial activity. Nanoparticle–polymer interactions may influence molecular diffusion, reagent accessibility, and reaction kinetics within the polymer network, thereby affecting the sensing behavior of immobilized colourimetric reagents (Khaydarov, 2025; Nosheen et al., 2021).

In the present study, two different films—PVA–ninhydrin composite films and PVA–nano ZnO–ninhydrin composite films—were fabricated and comparatively evaluated as colourimetric sensing materials for rapid qualitative soil fertility assessment. Nano ZnO nanoparticles were synthesized by the sol–gel method and incorporated in the PVA matrix to obtain the nanocomposite film. The fabricated films were characterized, and their thermal stability, mechanical properties, and antibacterial activity were investigated. The practical applicability as soil fertility testing films was examined using soil samples with different nitrogen levels by monitoring the formation of Ruhemann's purple colour. The findings confirmed the potential of PVA-based ninhydrin films as simple, portable, environmentally friendly, and low-cost colourimetric sensing materials for rapid qualitative soil fertility assessment.

II. EXPERIMENTAL

2.1 Materials

Polyvinyl alcohol (PVA, 95% hydrolysed) was purchased from Qualikems Lifesciences, India. Ninhydrin and ethanol were purchased from Merck, India. Zinc acetate and sodium hydroxide were obtained from Nice Chemicals, India. Distilled water prepared in the laboratory was used throughout the study. All chemicals were analytical grade and used as received without further purification.

2.2 Fabrication of PVA-Ninhydrin Film

A homogeneous PVA solution was prepared by dissolving 6 g of polyvinyl alcohol in 88 mL of distilled water under continuous stirring using a hot plate magnetic stirrer at 80 °C and then cooled to room temperature. In parallel, 1 g of ninhydrin was dissolved in 5 mL of ethanol, and the ninhydrin solution was added dropwise to the previously prepared PVA solution with continuous stirring. The resulting mixture was further stirred for 10 min to ensure the uniform distribution of ninhydrin throughout the polymer matrix. The homogeneous film-forming solution was cast onto clean, levelled polypropylene plates and dried at room temperature. The resulting PVA–ninhydrin composite film was carefully peeled from the plate and stored in a clean, airtight bag for further analysis.

2.3 Synthesis of ZnO Nanoparticles

Nano ZnO particles were synthesized by the sol–gel method by dissolving 0.5521 g of zinc acetate dihydrate in 50 mL of distilled water with continuous stirring to get a clear solution. In parallel, 0.1 M sodium hydroxide solution was prepared by dissolving 0.2 g of sodium hydroxide in 50 mL of distilled water. The previously prepared zinc acetate solution was added dropwise to the sodium hydroxide solution under continuous stirring at room temperature until a homogeneous mixture was obtained. The resulting mixture was kept in a hot-air oven at 90 °C for 1 hr; the precipitate was collected by gravimetric filtration using Whatman No. 40 filter paper and washed repeatedly with distilled water. The recovered ZnO nanoparticles were dried, collected, and stored in an airtight container for subsequent preparation.

2.4 Fabrication of PVA-Nano ZnO-Ninhydrin Composite Film

PVA–nano ZnO–ninhydrin composite film was prepared by dispersing 0.025 g ZnO nanoparticles in 88 mL of distilled water with continuous stirring to obtain a homogeneous dispersion. To this mixture, 6.5 g polyvinyl alcohol was gradually added with continuous stirring at 80 °C for 1 hr, then cooled to room temperature. The ninhydrin solution, prepared by dissolving 0.5 g of ninhydrin in 5 mL of ethanol, was added dropwise to the PVA–nano ZnO mixture with continuous stirring. The resulting mixture was stirred for an additional 10 minutes to obtain a homogeneous film-forming solution. The prepared solution was cast on a clean and dry polypropylene plate and dried at room temperature. The resulting PVA–nano ZnO–ninhydrin composite film was carefully peeled and stored in an airtight bag.

2.5 Characterization

The structural, crystalline, thermal, and surface morphological properties of the fabricated films were characterized using X-ray diffraction (XRD) (Model: Rigaku Miniflex 600 diffractometer), Fourier transform infrared (FTIR) spectroscopy (Model: PerkinElmer Inc. USA), scanning electron microscopy (SEM) (Model: Hitachi SU-6600 FESEM), UV–Visible spectrophotometer (Model: Shimadzu), thermogravimetric analysis (TGA) (Model: TGA/DTA 851e), and a Universal Testing Machine (UTM Model 3345), respectively.

2.6 Antibacterial Activity

The antibacterial activity of the fabricated PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films was evaluated against the Gram-negative bacterium *Escherichia coli* (ATCC 25922) and the Gram-positive bacterium *Staphylococcus aureus* (ATCC 25923) using the agar diffusion method. Pure cultures of *E. coli* (ATCC 25922) and *S. aureus* (ATCC 25923) were inoculated separately in sterile nutrient broth and incubated at 37 °C for 18–24 hrs to obtain actively growing cultures. Mueller-Hinton Agar (MHA) was prepared and sterilized by autoclaving at 121 °C for 15 minutes, poured into pre-sterilized Petri plates, and allowed to solidify. Each standardized bacterial suspension was uniformly spread over the MHA surface using a sterile cotton swab to obtain a lawn culture. PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films were cut into equal circular discs and placed on the inoculated agar plates. An uninoculated MHA plate containing the film specimens was maintained as a control. The plates were incubated at 37 °C for 18–24 h under aerobic conditions. Antibacterial activity was assessed by measuring the diameter of the inhibition zone (mm) surrounding each film specimen.

2.7 Soil Fertility Evaluation of Films

The fabricated PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films were tested for their ability to qualitatively detect the fertility of different soil samples. Four different types of soil samples representing different fertility conditions were selected: normal soil amended with chicken droppings (S1), normal soil amended with cow dung (S2), black soil collected from an area where kitchen waste was regularly discarded (S3), and normal soil (S4). Equal quantities of each soil sample were placed in separate labeled containers. Films of identical dimensions were placed in direct contact with the respective soil samples and kept under identical ambient conditions. Colour development was monitored after 2.5, 4, and 24 hrs, respectively, and photographed at each time interval. The intensity of the characteristic Ruhemann's purple colour was used as a qualitative indicator, and the colour responses of the films were compared to evaluate their suitability for soil fertility assessment.

III. RESULTS AND DISCUSSION

3.1 Physical Appearance and Characteristics of the Fabricated Films

Both films were successfully prepared by the solution-casting method, producing continuous, flexible, and self-supporting films without visible cracks or bubbles. The photographs of the fabricated PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films are shown in Figure 1, and their physical characteristics are summarized in Table 1.



FIGURE 1: Images of fabricated (A) PVA–ninhydrin and (B) PVA–nano ZnO–ninhydrin composite films

TABLE 1

PHYSICAL CHARACTERISTICS OF FABRICATED FILMS

Property	PVA–Ninhydrin film	PVA–Nano ZnO–Ninhydrin composite film
Transparency	High; transparent	Slightly translucent
Colour	Colorless	Pale yellow
Surface	Smooth & homogeneous	Smooth with slight surface irregularity
Edge quality	Well-defined	Slightly irregular
Flexibility	Flexible	Flexible
Visual defects	None observed	None observed

The PVA–ninhydrin film exhibited a transparent, smooth, and homogeneous appearance with well-defined edges, indicating uniform incorporation of ninhydrin within the PVA matrix. Whereas the PVA–nano ZnO–ninhydrin composite film appeared slightly translucent with a pale yellow colour and comparatively rougher edges. The reduced transparency is attributed to light scattering by the incorporated ZnO nanoparticles. Despite these differences, the composite film maintained good flexibility and structural integrity, indicating successful incorporation of ZnO nanoparticles without disrupting the continuity of the polymer matrix.

3.2 Fourier Transform Infrared (FTIR) Spectroscopy

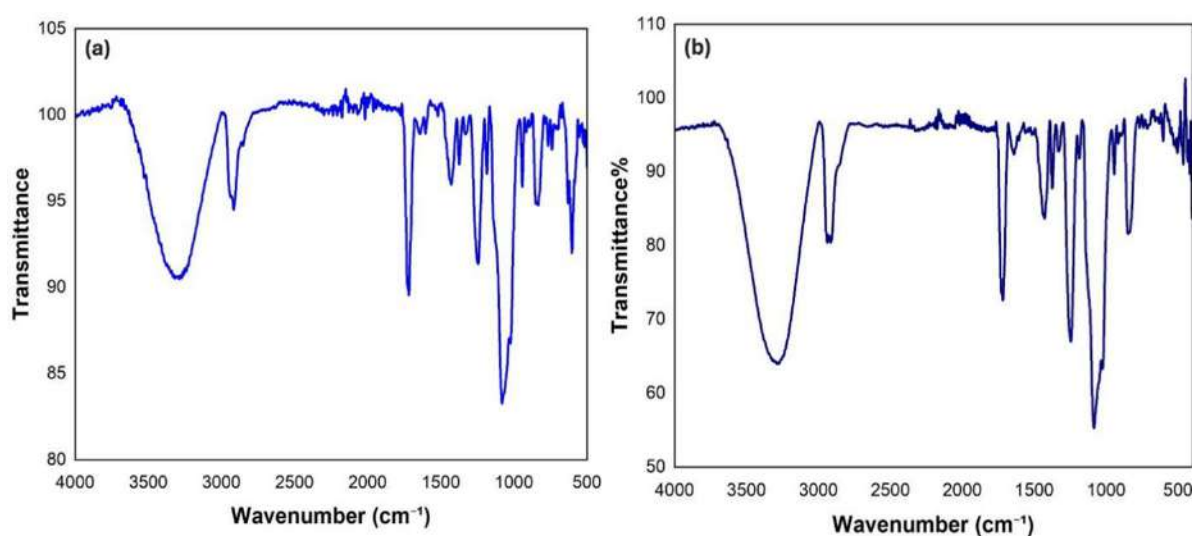


FIGURE 2: FTIR Spectrum of PVA-Ninhydrin (a) and PVA-Nano ZnO-Ninhydrin (b) Composite films

The FTIR spectra of the films are exhibited in Figure 2. The FTIR spectrum of the PVA–ninhydrin film (Figure 2a) exhibited a broad absorption band at 3288 cm^{-1} , corresponding to the O–H stretching vibration of hydroxyl groups in PVA, indicating extensive intermolecular hydrogen bonding within the polymer matrix. The absorption band at 2916 cm^{-1} is assigned to the C–H stretching vibration of the PVA backbone and ninhydrin molecules. A distinct peak at 1719 cm^{-1} corresponds to the C=O stretching vibration of the carbonyl groups of ninhydrin, confirming its successful incorporation into the PVA matrix. The bands at 1428 cm^{-1} , 1246 cm^{-1} , and 1082 cm^{-1} are attributed to CH_2 bending and C–O stretching vibrations characteristic of PVA and ninhydrin. The PVA–nano ZnO–ninhydrin composite film shown in Figure 2b showed similar characteristic absorption bands corresponding to PVA and ninhydrin; the incorporation of ZnO nanoparticles did not alter the fundamental chemical structure of the polymer matrix. The characteristic absorption band observed in the $500\text{--}600\text{ cm}^{-1}$ region is assigned to the Zn–O stretching vibration, confirming the presence of ZnO nanoparticles within the composite film. Minor variations in the intensity and position of the absorption bands are attributed to intermolecular interactions among PVA, ninhydrin, and ZnO nanoparticles (Saini et al., 2025; Shafiee et al., 2021).

3.3 X-ray Diffraction (XRD) Analysis

The X-ray diffraction (XRD) patterns of the fabricated PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films are presented in Figure 3.

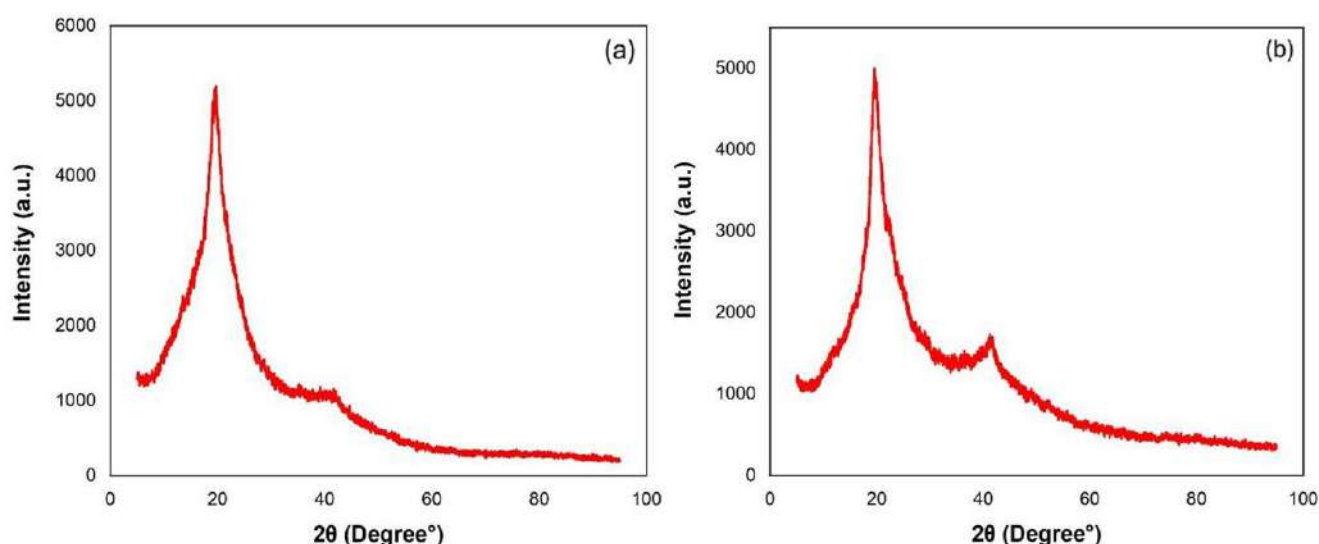


FIGURE 3: X-ray diffraction pattern of PVA-Ninhydrin (a) and PVA-Nano ZnO-Ninhydrin (b) Composite film

The XRD pattern of the PVA–ninhydrin film (Figure 3a) exhibited a broad diffraction peak at $2\theta = 19.72^\circ$, characteristic of the semicrystalline nature of polyvinyl alcohol, which is typical of PVA due to the partial ordering of polymer chains through intermolecular hydrogen bonding. The XRD pattern of the PVA–ninhydrin film did not show any other diffraction peaks, suggesting that ninhydrin is well incorporated within the PVA matrix without forming separate crystalline domains. The XRD pattern of the PVA–nano ZnO–ninhydrin composite film (Figure 3b) also exhibited the characteristic broad diffraction peak of PVA at $2\theta = 19.5^\circ$, indicating that the semicrystalline nature of the polymer matrix is retained after ZnO incorporation. In addition to this distinct diffraction peak, a few other characteristic peaks were observed at $2\theta = 34.4^\circ$, 36.2° , 47.5° , 56.6° , and 62.8° , corresponding to the different crystallographic planes of hexagonal wurtzite ZnO particles (Lopez-Miranda et al., 2023). The appearance of these characteristic peaks confirmed the successful incorporation of crystalline ZnO nanoparticles into the polymer matrix while preserving their crystalline structure.

3.4 UV-Visible Spectra

The UV–Visible transmittance spectra of the fabricated PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films are depicted in Figure 4.

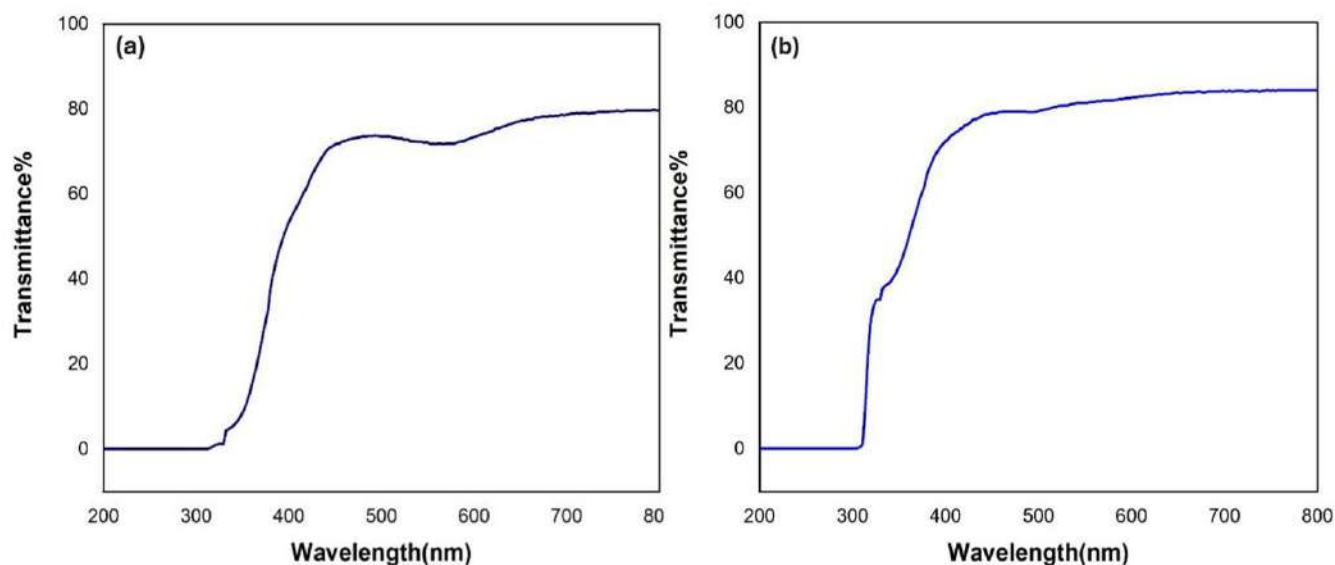


FIGURE 4: UV-Visible transmittance Spectra of PVA-Ninhydrin (a) and PVA-Nano ZnO-Ninhydrin (b) Composite films

As shown in Figure 4, the PVA–ninhydrin film (Figure 4a) exhibited negligible transmittance in the ultraviolet region below 320 nm, indicating strong absorption of UV radiation. The transmittance increases progressively with increasing wavelength, reaching approximately 80% in the visible region, indicating its good optical transparency. The spectrum of the PVA–nano ZnO–ninhydrin film (Figure 4b) displayed a pronounced absorption edge in the 320–350 nm region, which is attributed to the intrinsic UV absorption of ZnO nanoparticles. Beyond the UV region, the transmittance increases rapidly and reaches approximately 85% at 800 nm, indicating that the incorporation of ZnO nanoparticles does not adversely affect the visible-light transparency of the polymer film. The retention of high visible-light transmittance in both films is advantageous for colourimetric sensing, as it enables clear visual observation of colour changes during the detection of nitrogen-containing compounds (Amin et al., 2020).

3.5 Thermogravimetric Analysis

The thermogravimetric (TGA) curves of the fabricated PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films are presented in Figure 5. Both films exhibited a characteristic multistep thermal degradation profile characteristic of PVA-based polymeric materials (Furhan & Ramesan, 2022).

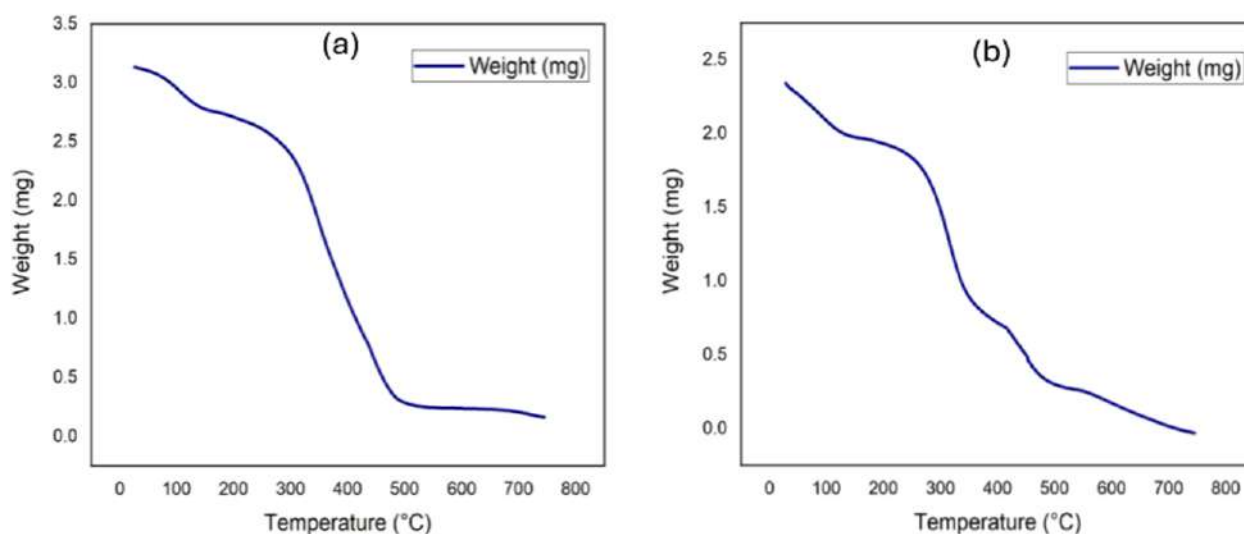


FIGURE 5: Thermogravimetric (TGA) curves of PVA-Ninhydrin composite film (a) and PVA-Nano ZnO-Ninhydrin (b) composite film

As shown in Figure 5a, both films showed an initial weight loss below approximately 150 °C, attributed to the removal of physically adsorbed moisture and residual solvent. In the case of the PVA–ninhydrin composite film, the major degradation occurred between 200 and 470 °C, corresponding to the decomposition of the PVA matrix and incorporated ninhydrin. Above 500 °C, only a slight additional weight loss was observed, indicating the formation of a stable carbonaceous residue. In the PVA–nano ZnO–ninhydrin composite film, the principal decomposition was recorded in the range of 220 to 480 °C. Compared with the PVA–ninhydrin film, the degradation of the PVA–nano ZnO–ninhydrin composite film occurred more gradually, and a higher residual mass was retained at elevated temperatures due to the presence of thermally stable ZnO nanoparticles within the polymer matrix (Duygulu et al., 2024).

The comparison of thermograms indicated that the incorporation of ZnO nanoparticles enhanced the thermal stability of the PVA–ninhydrin film. The improved thermal resistance can be attributed to interactions between ZnO nanoparticles and the PVA matrix, which restricted polymer chain mobility and retarded thermal decomposition. In addition, the inorganic ZnO particles act as thermally stable reinforcing fillers, contributing to the higher residual mass observed after degradation.

3.6 SEM Analysis

The surface morphologies of the fabricated PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films were investigated by scanning electron microscopy (SEM) and are shown in Figure 6.

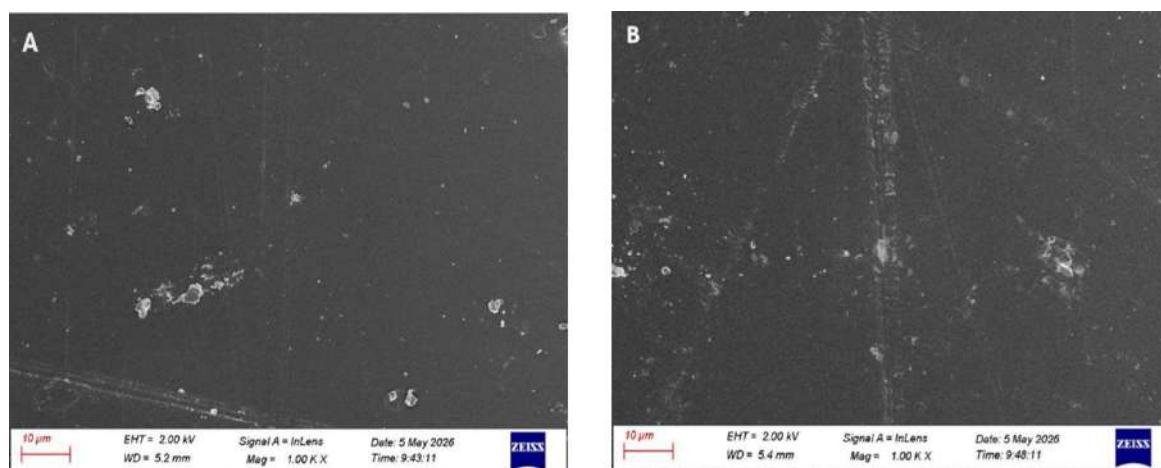


FIGURE 6: SEM micrographs of PVA-Ninhydrin (A) and PVA-NanoZnO-Ninhydrin (B) Composite film

The SEM micrograph of the PVA–ninhydrin film (Figure 6a) exhibited a relatively smooth, compact, and homogeneous surface without noticeable cracks, voids, or structural defects, indicating the formation of a continuous polymer matrix. The absence of distinct particulate features suggests that ninhydrin is uniformly incorporated within the PVA matrix without the formation of visible aggregates. However, the PVA–nano ZnO–ninhydrin composite film (Figure 6b) displayed a comparatively rougher surface with several bright particle-rich regions distributed over the polymer matrix. These bright regions are attributed to ZnO-rich regions due to the higher electron density of ZnO relative to the surrounding polymer. A few localized agglomerates are also observed, which are commonly encountered in nanoparticle-reinforced polymer composites as a result of the high surface energy of nanoparticles. Despite these localized agglomerations, the composite film retains a continuous morphology without apparent cracks or voids. The incorporation of ZnO nanoparticles modifies the surface morphology of the PVA–ninhydrin film by increasing the surface roughness and introducing ZnO-rich domains while preserving the integrity of the polymer matrix. These observations confirm the successful fabrication of the PVA–nano ZnO–ninhydrin composite film and the effective incorporation of ZnO nanoparticles into the polymer matrix (Lopez-Miranda et al., 2023; Amin et al., 2020; Furhan & Ramesan, 2022; Duygulu et al., 2024).

3.7 Mechanical Properties

The tensile properties of the fabricated films were evaluated using a Universal Testing Machine (UTM), and the results are summarized in Table 2. The PVA–nano ZnO–ninhydrin composite film exhibited a higher tensile strength (43.84 MPa) than the PVA–ninhydrin film (24.24 MPa), indicating the reinforcing effect of ZnO nanoparticles on the polymer matrix (Sultan et al., 2024; Shen et al., 2020; Erol et al., 2023; Sirelkhatim et al., 2015). Similarly, the Young's modulus increased from 1.18 MPa to 12.51 MPa, suggesting enhanced stiffness and rigidity following ZnO incorporation. On the other hand, the elongation

at break of the nano ZnO incorporated films decreased from 37.78% to 3.62%, while the maximum displacement decreased from 7.56 mm to 0.72 mm, indicating reduced flexibility of the composite film. The decrease in ductility is attributed to the restriction of polymer chain mobility by the dispersed ZnO nanoparticles.

TABLE 2
MECHANICAL PROPERTIES OF FABRICATED FILMS

Mechanical property	PVA–Ninhydrin film	PVA–Nano ZnO–Ninhydrin composite film
Tensile strength (MPa)	24.24	43.84
Young's modulus (MPa)	1.18	12.51
Elongation at break (%)	37.78	3.62
Maximum displacement (mm)	7.56	0.72

3.8 Antibacterial Properties

The antibacterial activity of the fabricated PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films was evaluated against Gram-negative *Escherichia coli* (ATCC 25922) and Gram-positive *Staphylococcus aureus* (ATCC 25923) using the agar diffusion method. The inhibition zones are presented in Figure 7, and the corresponding zone diameters are summarized in Table 3.

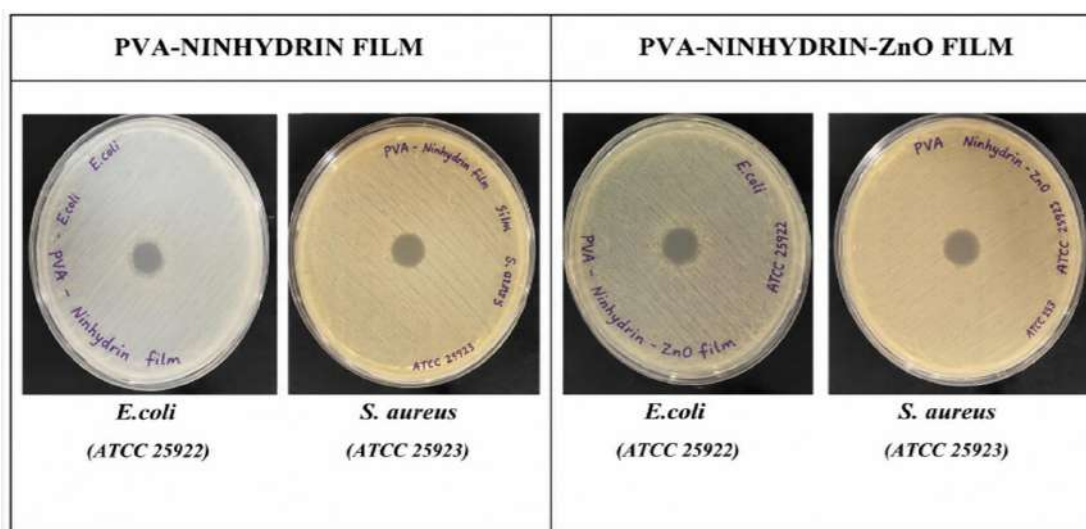


FIGURE 7: Antibacterial activity of the fabricated PVA–Ninhydrin and PVA–Nano ZnO–Ninhydrin composite films against *Escherichia coli* (ATCC 25922) and *Staphylococcus aureus* (ATCC 25923) determined by the agar diffusion method.

TABLE 3
ANTIBACTERIAL ACTIVITY OF THE FABRICATED FILMS

Bacterial strain	PVA–Ninhydrin film (Zone of inhibition, mm)	PVA–Nano ZnO–Ninhydrin composite film (Zone of inhibition, mm)
<i>Escherichia coli</i> (ATCC 25922)	11	12
<i>Staphylococcus aureus</i> (ATCC 25923)	9	12

The PVA–ninhydrin film exhibited inhibition zones of 11 mm against *E. coli* and 9 mm against *S. aureus*, indicating moderate antibacterial activity. While the PVA–nano ZnO–ninhydrin composite film produced inhibition zones of 12 mm against both bacterial strains, demonstrating enhanced antibacterial performance following the incorporation of ZnO nanoparticles. The improved antibacterial activity of the composite film is attributed to the intrinsic antimicrobial properties of ZnO nanoparticles, which are known to inhibit bacterial growth through the generation of reactive oxygen species (ROS), release of Zn²⁺ ions, and

disruption of bacterial cell membranes (Zhao et al., 2018; Abebe et al., 2020; Sudalaimani et al., 2020). The comparable inhibition observed against both Gram-negative and Gram-positive bacteria indicates the antibacterial activity of the fabricated films.

3.9 Application in Soil Fertility Assessment

The practical applicability of the fabricated PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films for soil fertility assessment was evaluated by monitoring their colourimetric response toward nitrogen-containing compounds in soils with different fertility levels. The sensing mechanism is based on the reaction of ninhydrin with free amino compounds, producing Ruhemann's purple, the intensity and rate of which serve as qualitative indicators of soil organic nitrogen availability. Four soil samples with different fertility levels—normal agricultural soil, black soil, cow dung-amended soil, and chicken manure-amended soil—were examined using both films. The result of colour development has been summarized in Table 4.

TABLE 4
QUALITATIVE EVALUATION OF SOIL FERTILITY USING THE FABRICATED FILMS

Soil sample	Relative nitrogen content	Colour development rate	Soil fertility
Chicken manure-amended soil	Very high	Fastest (~2.5 h)	Very high
Cow dung-amended soil	High	Fast	High
Black soil	Moderate	Moderate	Moderate
Normal soil	Low	Slowest	Low

The rapid response observed for chicken manure-amended soil is attributed to its higher concentration of readily available organic nitrogen compounds, whereas the delayed response of normal soil reflects its comparatively lower nitrogen availability. Both films successfully differentiated soils based on their relative fertility. The PVA–ninhydrin film exhibited a faster colorimetric response, producing the characteristic Ruhemann's purple more rapidly than the PVA–nano ZnO–ninhydrin composite film. In contrast, the ZnO-containing film displayed a slightly delayed response and developed a brownish-purple colouration, which is attributed to the influence of ZnO nanoparticles on the optical properties of the polymer matrix rather than any alteration of the ninhydrin–amino acid reaction.

The slower response of the PVA–nano ZnO–ninhydrin composite film is likely due to the restricted diffusion of amino compounds through the reinforced polymer network, resulting from interactions between ZnO nanoparticles and PVA chains. Nevertheless, the composite film retained effective sensing capability while offering improved thermal stability, mechanical strength, and antibacterial activity compared with the PVA–ninhydrin film (Vavaiya et al., 2026).

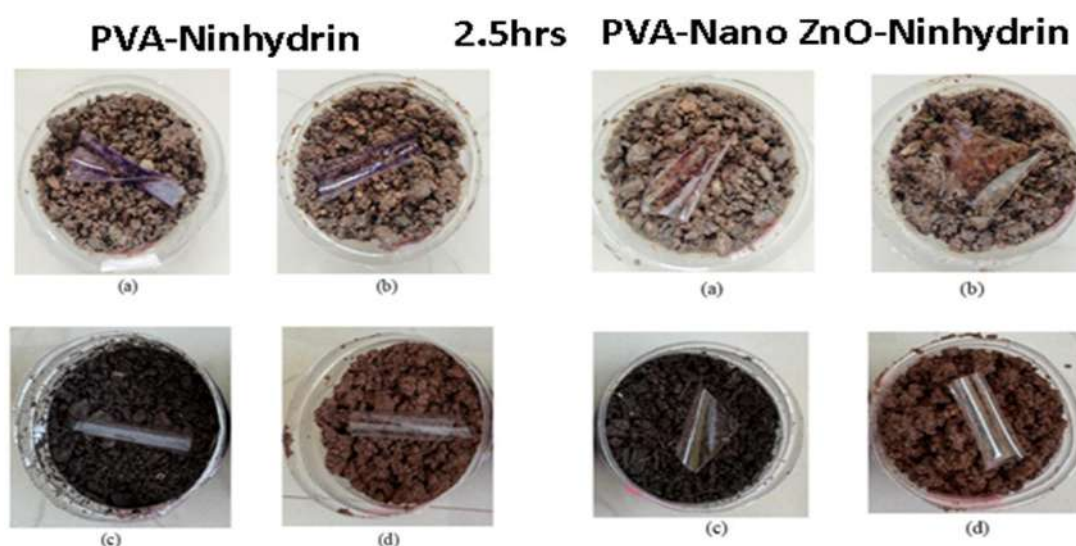


FIGURE 8: Colourimetric response of PVA-Ninhydrin & PVA-Nano ZnO-Ninhydrin Composite film after 2.5 hrs of exposure to different soil samples: chicken manure-amended soil (a), cow dung-amended soil (b), black soil (c) and normal soil (d)

Overall, both fabricated films demonstrated their suitability as qualitative colourimetric sensors for soil fertility assessment. While the PVA–ninhydrin film provided a faster analytical response, the PVA–nano ZnO–ninhydrin composite film offered enhanced physicochemical properties, making it a durable alternative for practical sensing applications.

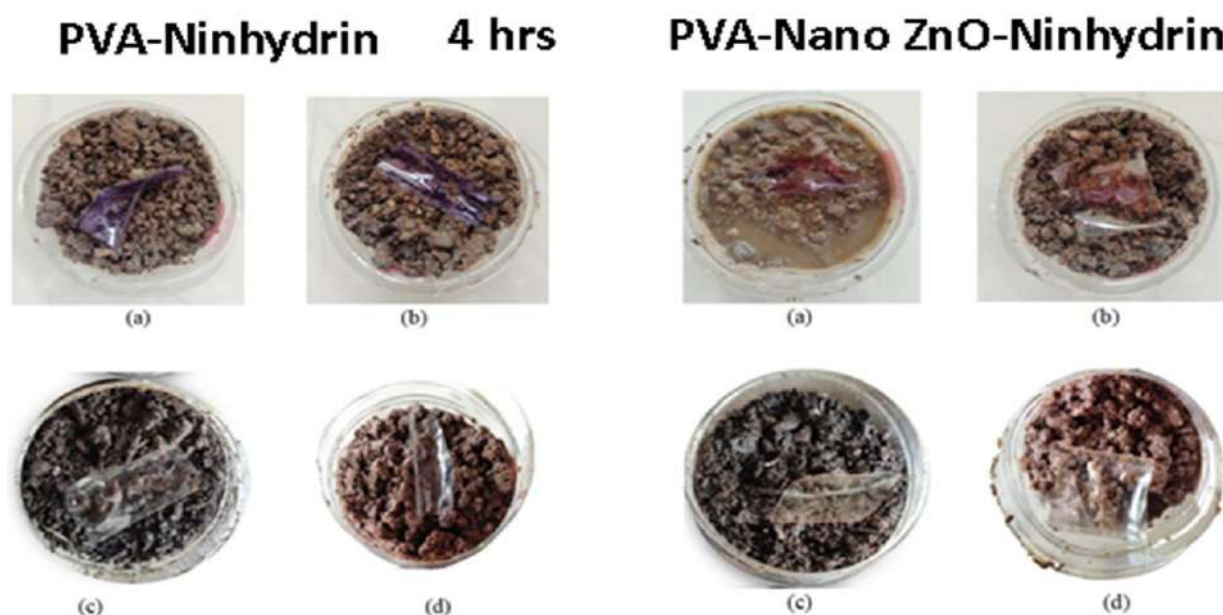


FIGURE 9: Colourimetric response of PVA-Ninhydrin & PVA-Nano ZnO-Ninhydrin Composite film after 4 hrs of exposure to different soil samples: chicken manure-amended soil (a), cow dung-amended soil (b), black soil (c) and normal soil (d)

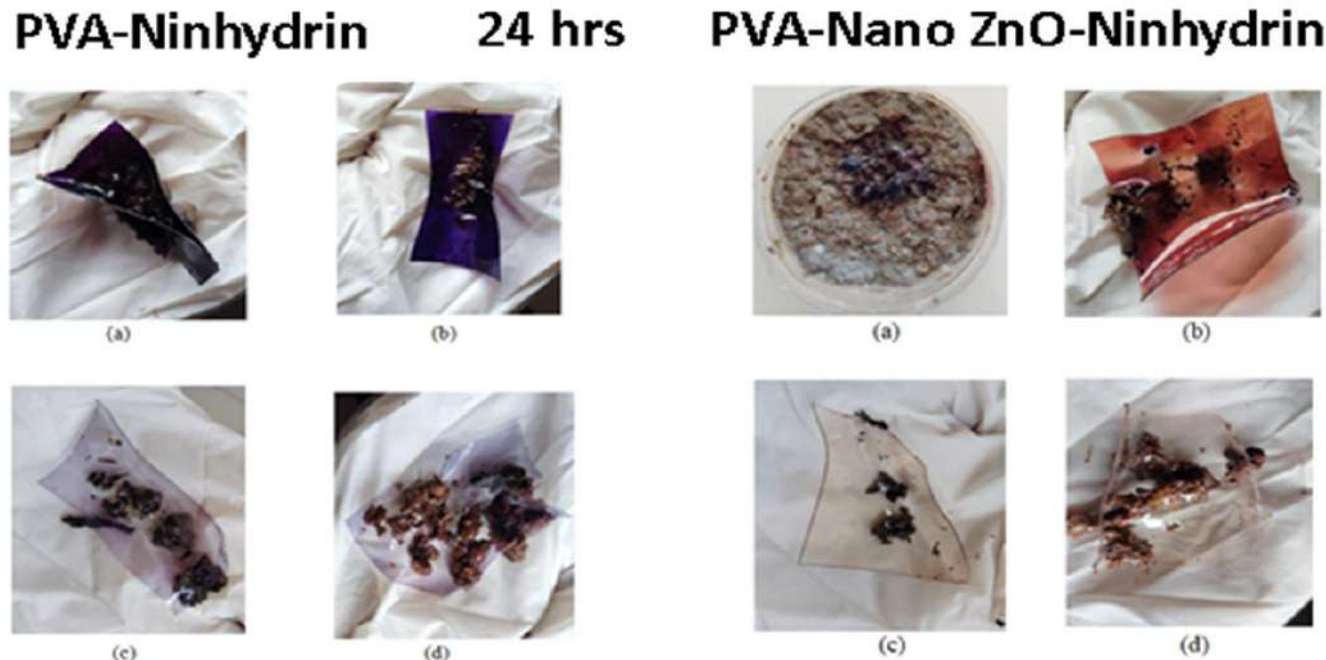


FIGURE 10: Colourimetric response of PVA-Ninhydrin and PVA-Nano ZnO-Ninhydrin Composite film after 24 hrs of exposure to different soil samples: chicken manure-amended soil (a), cow dung-amended soil (b), black soil (c) and normal soil (d)

IV. CONCLUSION

In this study, PVA–ninhydrin and PVA–nano ZnO–ninhydrin composite films were successfully fabricated by the solution-casting method and evaluated as colourimetric sensing materials for qualitative soil fertility assessment. Structural,

morphological, thermal, mechanical, optical, and antibacterial characterizations confirmed the successful incorporation of ZnO nanoparticles into the PVA–ninhydrin matrix. Compared with the PVA–ninhydrin film, the PVA–nano ZnO–ninhydrin composite film exhibited enhanced thermal stability, improved tensile strength and stiffness, and superior antibacterial activity, demonstrating the reinforcing effect of ZnO nanoparticles. Both films effectively detected nitrogen-containing compounds in soils through the ninhydrin colorimetric reaction, with the rate of colour development following the order: chicken manure-amended soil > cow dung-amended soil > black soil > normal soil, consistent with their relative fertility levels. Although the incorporation of ZnO nanoparticles slightly delayed the colorimetric response, the composite film retained excellent sensing capability while offering improved physicochemical properties and durability. Overall, the developed PVA–nano ZnO–ninhydrin composite film represents a simple, low-cost, environmentally friendly, and promising material for qualitative soil fertility assessment, with potential applications in sustainable agriculture and environmental monitoring. Future studies should focus on quantitative evaluation of soil nitrogen, long-term storage stability, and field validation under diverse agricultural conditions.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

Unnimaya M: Writing – original draft, Formal analysis, Data curation, Conceptualization. Mubashira Thasni EP: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Nafeesathul Misriya TK: Writing – original draft, Methodology, Formal analysis. Mujeeb Rahman P: Writing – review & editing, Supervision, Project administration, Funding acquisition.

FUNDING

No specific funding was received for this research.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

- [1] Abazari, M., Badeleh, S. M., Barkhordari, S., Mohammed, S. S., Ahmed, M. M., Ameen, M. S. M., & Abdollahi, H. (2025). Preparation and characterization of polyvinyl alcohol thin films: Rheological, physicochemical and functional properties. *Heliyon*, *11*(12), e43604. <https://doi.org/10.1016/j.heliyon.2025.e43604>
- [2] Abebe, B., Zereffa, E. A., Tadesse, A., & Murthy, H. C. A. (2020). A review on enhancing the antibacterial activity of ZnO: Mechanisms and microscopic investigation. *Nanoscale Research Letters*, *15*, 190. <https://doi.org/10.1186/s11671-020-03418-6>
- [3] Ali, A., Jabeen, N., Farruhbek, R., Chachar, Z., Laghari, A. A., Chachar, S., Ahmed, N., Ahmed, S., & Yang, Z. (2025). Enhancing nitrogen use efficiency in agriculture by integrating agronomic practices and genetic advances. *Frontiers in Plant Science*, *16*, 1543714. <https://doi.org/10.3389/fpls.2025.1543714>
- [4] Amin, K. M., Partila, A. M., Abd El-Rehim, H. A., & Deghiedy, N. M. (2020). Antimicrobial ZnO nanoparticle–doped polyvinyl alcohol/Pluronic blends as active food packaging films. *Particle & Particle Systems Characterization*, *37*(4), 2000006. <https://doi.org/10.1002/ppsc.202000006>
- [5] Duygulu, N. E., Altinbay, A., & Ciftci, F. (2024). Antibacterial, mechanical, and thermal properties of Ag, ZnO, TiO₂ reinforced PVA nanocomposite fibers. *ChemistrySelect*, *9*(30), e202402311. <https://doi.org/10.1002/slct.202402311>
- [6] Elgharbawy, A. S., El Demerdash, A.-G. M., Sadik, W. A., Kasaby, M. A., Lotfy, A. H., & Osman, A. I. (2024). Synthetic degradable polyvinyl alcohol polymer and its blends with starch and cellulose—A comprehensive overview. *Polymers*, *16*(10), 1356. <https://doi.org/10.3390/polym16101356>
- [7] Erol, I., Hazman, Ö., & Aksu, M. (2023). Preparation of novel composites of polyvinyl alcohol containing hesperidin loaded ZnO nanoparticles and determination of their biological and thermal properties. *Journal of Inorganic and Organometallic Polymers and Materials*, *33*(3), 731-746. <https://doi.org/10.1007/s10904-023-02532-z>
- [8] Etemadi, H., Khezaqa, H., & Hermeni, M. (2022). Incorporation of amino-functionalized ZnO nanoparticles into polycarbonate/polyvinyl alcohol thin-film membrane for enhanced water treatment. *Polymer Engineering & Science*, *62*(9), 2891-2899. <https://doi.org/10.1002/pen.26070>
- [9] Gelaye, Y. (2024). A systematic review on effects of nitrogen fertilizer levels on cabbage (*Brassica oleracea* var. *capitata* L.) production in Ethiopia. *The Scientific World Journal*, *2024*, 6086730. <https://doi.org/10.1155/2024/6086730>
- [10] Hasnidawani, J. N., Azlina, H. N., Norita, H., Bonnia, N. N., Ratim, S., & Ali, E. S. (2016). Synthesis of ZnO nanostructures using sol-gel method. *Procedia Chemistry*, *19*, 211-216. <https://doi.org/10.1016/j.proche.2016.03.095>
- [11] Jailani, A., Hidzer, M. H., Firdaus, A. H. M., Sapuan, S. M., Zainudin, E. S., Atiqah, A., Wan Jaafar, W. M., & Suryanegara, L. (2026). Enhancing polyvinyl alcohol (PVA) nanocomposites: Key properties, applications and challenges in advanced engineering. *Defence Technology*, *55*, 11-29. <https://doi.org/10.1016/j.dt.2025.05.020>

- [12] Jeong, S., Jeon, Y., Mun, J., Jeong, S. M., Liang, H., Chung, K., Yi, P.-I., An, B.-S., & Seo, S. (2023). Ninhydrin loaded microcapsules for detection of natural free amino acid. *Chemosensors*, *11*(1), 49. <https://doi.org/10.3390/chemosensors11010049>
- [13] Khan, M. A., Basir, A., Shah, S. T., Rehman, M. U., Hassan, M. U., Zheng, H., Basit, A., Székely, Á., Jamal, A., Radicetti, E., Dewir, Y. H., & Mancinelli, R. (2024). Sustainable soil management in alkaline soils: The role of biochar and organic nitrogen in enhancing soil fertility. *Land*, *13*(11), 1869. <https://doi.org/10.3390/land13111869>
- [14] Khaydarov, M. M. (2025). The role of amino acids in soil. *J Open*, *1*(3), 8-11. <https://doi.org/10.70728/jopen.be.0325.002>
- [15] Liang, X., Zhong, H.-J., Ding, H., Yu, B., Ma, X., Liu, X., Chong, C.-M., & He, J. (2024). Polyvinyl alcohol (PVA)-based hydrogels: Recent progress in fabrication, properties, and multifunctional applications. *Polymers*, *16*(19), 2755. <https://doi.org/10.3390/polym16192755>
- [16] Lopez-Miranda, J. L., Molina, G. A., González-Reyna, M. A., España-Sánchez, B. L., Esparza, R., Silva, R., & Estévez, M. (2023). Antibacterial and anti-inflammatory properties of ZnO nanoparticles synthesized by a green method using *Sargassum* extracts. *International Journal of Molecular Sciences*, *24*(2), 1474. <https://doi.org/10.3390/ijms24021474>
- [17] Nosheen, S., Ajmal, I., & Song, Y. (2021). Microbes as biofertilizers, a potential approach for sustainable crop production. *Sustainability*, *13*(4), 1868. <https://doi.org/10.3390/su13041868>
- [18] Saini, T., Meena, J., Verma, V., Saini, S., & Malik, R. (2025). Polyvinyl alcohol: Recent advances and applications in sustainable materials. *Polymer-Plastics Technology and Materials*, *64*(6), 794-825. <https://doi.org/10.1080/25740881.2024.2438046>
- [19] Shafiee, P., Reisi Nafchi, M., Eskandarinezhad, S., Mahmoudi, S., & Ahmadi, E. (2021). Sol-gel zinc oxide nanoparticles: Advances in synthesis and applications. *Synthesis and Sintering*, *1*(4), 242-254. <https://doi.org/10.53063/synsint.2021.1477>
- [20] Shen, L., Huang, Z., Liu, Y., Li, R., Xu, Y., Jakaj, G., & Lin, H. (2020). Polymeric membranes incorporated with ZnO nanoparticles for membrane fouling mitigation: A brief review. *Frontiers in Chemistry*, *8*, 224. <https://doi.org/10.3389/fchem.2020.00224>
- [21] Sirelkhatim, A., Mahmud, S., Seeni, A., Mohamad Kaus, N. H., Ann, L. C., Mohd Bakhori, S. K., Hasan, H., & Mohamad, D. (2015). Review on zinc oxide nanoparticles: Antibacterial activity and toxicity mechanism. *Nano-Micro Letters*, *7*(3), 219-242. <https://doi.org/10.1007/s40820-015-0040-x>
- [22] Stauf, A. C., Fuchs, C., Jansen, P., Repert, S., Alcock, K., Ludewig, S., & Rozhon, W. (2024). The ninhydrin reaction revisited: Optimisation and application for quantification of free amino acids. *Molecules*, *29*(14), 3262. <https://doi.org/10.3390/molecules29143262>
- [23] Sultan, M., Youssef, A., & Baseer, R. A. (2024). Fabrication of multifunctional ZnO@tannic acid nanoparticles embedded in chitosan and polyvinyl alcohol blend packaging film. *Scientific Reports*, *14*, 18533. <https://doi.org/10.1038/s41598-024-68571-9>
- [24] Sudalaimani, S., Esokkiya, A., Hansda, S., Suresh, C., Tamilarasan, P., & Giribabu, K. (2020). Colorimetric sensing of putrescine and cadaverine using ninhydrin as a food spoilage detection reagent. *Food Analytical Methods*, *13*(3), 629-636. <https://doi.org/10.1007/s12161-019-01671-9>
- [25] Vavaiya, P. P., Malviya, N. J., Alshehri, A. A., Alqarni, M., & Varu, H. L. (2026). The reaction of ninhydrin revisited: Applications in quantification of analytes, active pharmaceutical ingredients and amino acids. *Journal of Molecular Structure*, *1350*(2), 144034. <https://doi.org/10.1016/j.molstruc.2025.144034>
- [26] Wang, Y.-T., Wang, Y., Guo, J., & Zhou, Q.-X. (2020). Preparation of polyvinyl alcohol/ninhydrin blend nanomembranes by needleless electrospinning and their application in latent finger mark detection. *Journal of Macromolecular Science, Part B: Physics*, *59*(1), 49-64. <https://doi.org/10.1080/00222348.2019.1687137>
- [27] Zhao, S.-W., Guo, C.-R., Hu, Y.-Z., Guo, Y.-R., & Pan, Q.-J. (2018). The preparation and antibacterial activity of cellulose/ZnO composite: A review. *Open Chemistry*, *16*(1), 9-20. <https://doi.org/10.1515/chem-2018-0006>

The Importance of Electronic Communication in the Use of Artificial Intelligence Programs and Applications in the Field of Smart Agriculture from the Point of View of Agricultural Extension Workers in Nineveh Governorate, Iraq

Luma Monther Adress

University of Mosul – College of Agriculture and Forestry – Department of Agricultural Extension and Technology Trasfer

Received:- 14 September 2026/ Revised:- 25 September 2026/ Accepted:- 07 October 2026/ Published: 15-10-2026

Copyright @ 2026 International Journal of Environmental and Agriculture Research

This is an Open-Access article distributed under the terms of the Creative Commons Attribution

Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted

Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— The study aimed to identify the level of importance of electronic communication among agricultural extension workers in using artificial intelligence (AI) programs and applications in the field of smart agriculture. It also aimed to identify the most frequently used electronic communication means by extension workers in employing AI programs and applications and rank them according to their relative importance; measure the contribution of electronic communication to improving extension workers' efficiency in using AI programs and applications in smart agriculture; identify individual differences in the importance of electronic communication and the use of AI applications according to selected independent variables, namely gender, educational qualification, years of service, training courses, level of Internet use, and willingness to use social networking sites concerning smart-agriculture technologies; and identify the obstacles facing extension workers in using AI applications in smart agriculture. To obtain the study data, a questionnaire consisting of five parts was used. The first part concerned the respondents' personal and occupational information. The second part included a scale measuring the importance of electronic communication among extension workers in using AI programs and applications in smart agriculture. The third part measured the electronic communication means most frequently used by extension workers in employing AI programs and applications. The fourth part measured the contribution of electronic communication to improving extension workers' efficiency in using AI programs and applications in smart agriculture. The fifth part contained 15 items measuring the major obstacles facing extension workers in using AI applications in smart agriculture. After establishing the face validity of the questionnaire, reliability was assessed using Cronbach's alpha, which reached 0.95. The study population consisted of extension workers in the Nineveh Directorate of Agriculture and its 32 agricultural divisions, totaling 256 extension workers. A simple random sample of 128 extension workers, representing approximately 50% of the population, was selected. The data were coded, tabulated, and analyzed using SPSS. The results showed that the level of importance of electronic communication among extension workers in using AI programs and applications in smart agriculture was moderate and tended toward high, with a percentage of 48%. The item "Using electronic platforms belonging to agricultural institutions to obtain information related to AI programs and applications" ranked first, with a mean of 4.34. The contribution of electronic communication to improving extension workers' efficiency in using AI programs and applications in smart agriculture was high, with a percentage of 46%. No significant differences were found in the importance of electronic communication according to gender or training courses, whereas significant differences were reported according to educational qualification, years of occupational service, level of Internet use, and willingness to use social networking sites concerning smart-agriculture technologies. The item "Poor compatibility of some AI applications with the nature and needs of agricultural extension work in Nineveh Governorate" was identified as the most important obstacle. The major recommendation was for the Ministry of Agriculture to establish or develop official agricultural electronic platforms affiliated with agricultural and extension institutions and containing updated information on AI applications and their use in different agricultural fields. The main proposed future study was to investigate the obstacles to using AI applications in agricultural extension work in Nineveh Governorate from the perspective of extension workers.

Keywords— Electronic Communication; Artificial Intelligence Applications; Smart Agriculture; Agricultural Extension Workers.

I. INTRODUCTION

In recent years, the agricultural sector has undergone a rapid transformation toward employing digital technologies and modern communication technologies to produce and exchange agricultural information and support production- and resource-management decisions in order to increase production and achieve food security. Information and communication technologies are no longer limited to the traditional transfer of agricultural information and knowledge; rather, they have become part of an integrated system that includes smartphones, applications, digital platforms, the Internet, and artificial intelligence, which contribute to improving access to agricultural knowledge and developing services provided to farmers in a safe and effective manner. Recent literature indicates that digital agricultural services provided to farmers have become one of the major pathways for developing extension and advisory services, particularly in delivering agricultural information and knowledge to farmers more rapidly and effectively (Shaikh, Rasool, & Lone, 2022). Social communication, driven by digital technology, has become a major means of communication in general and agricultural information production in particular, changing the course of communication and making it easier to obtain information, knowledge, and experience in an organized and rapid manner through AI applications, placing them among the leading achievements of the information revolution (Al-Janabi et al., 2023). Electronic communication represents one of the fundamental components of transformation in agricultural extension work, as it enables extension workers to communicate with farmers through multiple channels, such as smartphone applications, social networking platforms, electronic messages, extension websites and platforms, educational videos, and interactive digital media. It also provides agricultural information at the appropriate time, creates greater opportunities for interaction and experience exchange, and facilitates responses to agricultural problems, while emphasizing the importance of developing the digital skills of workers and beneficiaries (FAO, 2023). Artificial intelligence has become one of the technologies incorporated into modern agricultural systems through the use of machine-learning algorithms, data and image analysis, environmental-condition monitoring, decision support, and other functions. Recent studies indicate that AI applications in agriculture are moving toward more data-driven systems that combine AI with sensors, the Internet of Things, and communication technologies to provide information that supports more precise management of agricultural operations (Klie et al., 2018). The effectiveness of AI in agriculture is not limited to the availability of programs, applications, and technical devices; it is also associated with the availability of electronic communication channels capable of transmitting data, information, and results among smart systems, extension workers, and farmers. Communication represents the link between technology and its users and helps agricultural extension workers access information generated by AI applications, interpret it, and transform it into understandable and applicable extension messages and recommendations (Hamada, 2014). Therefore, modern extension systems are moving toward integrating AI with digital extension platforms and decision-support systems while maintaining the human role of the extension worker in verifying information, interpreting it, and presenting it to farmers (Lin & Shyu, 2020). Smart agriculture relies on a set of interconnected digital technologies aimed at improving resource-use efficiency, increasing productivity, and enhancing the capacity to respond to agricultural and environmental problems. AI is an important component of this system, alongside the Internet of Things, sensors, data analytics, communication networks, and cloud computing. Scientific reviews indicate that AI applications in agriculture include crop monitoring, water management, nutrient management, pest and disease detection, yield prediction, agricultural robots, and protected agriculture (Tan et al., 2024). Agricultural extension workers represent an important link in transferring agricultural knowledge and technology from scientific and technical sources to farmers, and their role becomes increasingly important with the emergence of AI technologies, which may be complex for some users (Jad, 2021). In the digital environment, extension workers need the ability to deal with electronic information sources, understand AI applications, communicate through digital platforms, interpret technical outputs for farmers, and verify the suitability of information to local agricultural conditions. Recent literature indicates that developing the human capacities of extension workers is an essential pathway for digital transformation in agricultural extension and advisory systems (Kpodo, 2026). The study of electronic communication in agriculture is particularly important in Nineveh Governorate because of the importance of agricultural activity, the diversity of production systems, crops, and rural areas, as well as the need to develop communication methods and transfer agricultural information in ways compatible with digital transformations. A recent study examined the use of digital technology to obtain agricultural extension information in Tel Kaif District, Nineveh Governorate, indicating growing research interest in the role of digital technology in obtaining agricultural information in the local environment of the governorate (Wank et al., 2022). Despite the increasing development of AI applications and smart agriculture, the actual benefit from these technologies in agricultural extension work requires an effective electronic communication system linking digital knowledge sources with extension workers and farmers. The spread of smart applications does not necessarily mean that they are used efficiently (Azimi et al., 2019), as factors such as weak digital skills, limited or problematic connectivity, difficulty accessing data, insufficient training courses, and low confidence in technology may

constrain their use. The Food and Agriculture Organization has pointed to a digital divide related to digital skills and access to digital services, while recent studies have indicated that cost, infrastructure, and human skills represent challenges to expanding smart agricultural environments (Al-Jailawi & Al-Mashhadani, 2026). The research problem arises from the fact that the rapid development of AI programs and applications in agriculture has created new opportunities for developing smart agriculture in Iraq in general and Nineveh Governorate in particular, and for improving resource management and agricultural decision-making (Rodríguez et al., 2021). However, benefiting from these applications in extension work depends not only on the availability of technology, but also on an effective electronic communication system that enables extension workers to access and exchange information and data, interact with digital applications and platforms, and transfer their outputs to farmers clearly and appropriately. In Iraq, recent studies indicate a need to develop the use of information and communication technologies in extension work, strengthen workers' capacities and infrastructure, and improve access to digital extension knowledge (Alvarez & Nuthall, 2006). In Nineveh Governorate, the use of digital technology to obtain agricultural extension information highlights the need to study electronic communication as an essential component in employing modern agricultural technologies. Consequently, there is a need to determine the importance of electronic communication in using AI programs and applications in smart agriculture from the perspective of extension workers in Nineveh Governorate. This can help diagnose the communication situation and identify the development, training, and technical-support areas required to strengthen the use of AI in agricultural extension work. The importance of addressing this problem is further increased by the need to develop the use of information and communication technologies in agricultural extension work. Recent studies of technology use among extension workers in Iraq have emphasized the need to improve infrastructure, skills, and capacities and to enhance beneficiaries' access to extension information and knowledge. This raises the question of the extent to which extension workers recognize the importance of electronic communication when dealing with modern applications and programs, particularly AI applications related to smart agriculture (Ferris, 2017). The need for this type of study is particularly evident in Nineveh Governorate in light of recent indications of the use of digital technology to obtain agricultural information in some areas of the governorate. This calls for moving from studying the use of digital technology in general to a more specialized examination of the importance of electronic communication in using AI programs and applications in smart agriculture from the perspective of the extension workers themselves. Accordingly, the research problem is represented by the need to identify the level of importance of electronic communication in supporting the use of AI programs and applications in smart agriculture from the perspective of extension workers in Nineveh Governorate; identify the most important communication means used for this purpose; and examine their relationship to extension workers' ability to access smart applications, exchange agricultural data and information, communicate with farmers, and provide extension recommendations based on modern technologies.

II. RESEARCH OBJECTIVES

- 1) To identify the level of importance of electronic communication among extension workers in using AI programs and applications in the field of smart agriculture in general.
- 2) To identify the electronic communication means most frequently used by extension workers in employing AI programs and applications and rank them according to their relative importance.
- 3) To measure the contribution of electronic communication to improving extension workers' efficiency in using AI programs and applications in the field of smart agriculture.
- 4) To identify individual differences in the importance of electronic communication and the use of AI applications according to selected independent variables among extension workers, namely gender, educational qualification, years of service, training courses, level of Internet use, and willingness to use social networking sites concerning smart-agriculture technologies.
- 5) To identify the obstacles facing extension workers in using AI applications in the field of smart agriculture.

III. MATERIAL AND METHODS

The study was conducted in Nineveh Governorate, Iraq. The study population included all agricultural employees working at the Nineveh Directorate of Agriculture and its affiliated 32 agricultural divisions. The total population consisted of 256 extension workers distributed between the Directorate headquarters and its agricultural divisions. A simple random sample of 128 extension workers, representing 50% of the population, was selected. Data were collected using a questionnaire consisting of five parts. The first part concerned the personal and occupational information of agricultural extension workers. The second part consisted of 26 items measuring the level of importance of electronic communication among extension workers in using

AI programs and applications in smart agriculture, with five response alternatives: strongly agree, agree, neutral, disagree, and strongly disagree, coded 5, 4, 3, 2, and 1, respectively. The third part included 15 communication means to identify the electronic communication means most frequently used by extension workers in employing AI programs and applications, using the same five-point response scale. The fourth part included 15 items measuring the contribution of electronic communication to improving extension workers' efficiency in using AI programs and applications in smart agriculture, also using the five-point scale. The fifth part included 15 items measuring the major obstacles facing extension workers in using AI applications in smart agriculture, with response alternatives: very high, high, moderate, low, and very low, coded 5, 4, 3, 2, and 1, respectively. The items were developed after reviewing previous studies and literature relevant to the topic. Face validity and content validity were established by presenting the questionnaire to a group of experts and specialists in educational and psychological sciences at the College of Education for Humanities, University of Mosul; faculty members in the Department of Agricultural Extension and Technology Transfer, College of Agriculture and Forestry, University of Mosul; a specialist in educational and psychological sciences at the College of Education, University of Zakho; and a specialist in agricultural engineering sciences at the University of Baghdad. Their comments and suggestions concerning the question types, wording, clarity, and suitability to the respondents' level were considered. Some items were revised, some were reworded, and others were deleted. A criterion of 70% agreement among experts was adopted. For reliability testing, a sample of 30 employees was selected and excluded from the main population. Cronbach's alpha was used to assess scale reliability, and the coefficient was 0.95, indicating excellent reliability. The statistical analyses were conducted using SPSS.

IV. RESULTS AND DISCUSSION

4.1 First: To identify the level of importance that extension workers place on digital communication when using artificial intelligence programs and applications in the field of smart agriculture in general.

To achieve this objective, the minimum observed value for the importance of electronic communication among extension workers was 62, while the maximum observed value was 130. Using the range and class width, respondents were divided into three categories. The arithmetic mean was 103.53 and the standard deviation was 15.27, as shown in Table 1.

TABLE 1
LEVEL OF IMPORTANCE THAT EXTENSION WORKERS PLACE ON ELECTRONIC COMMUNICATION

Range	Frequency	Percentage
62–84 (Low)	17	11.33
85–107 (Medium)	73	48.67
108–130 (High)	60	40
Total	150	100
Arithmetic mean	103.53	
Standard deviation	15.27	

The results showed that the level of importance of electronic communication among extension workers in using AI programs and applications in smart agriculture was moderate and tended toward high, with a percentage of 48%. This may be attributed to the fact that extension workers recognize the importance of electronic communication in using AI programs and applications in agricultural extension work, but the level of importance has not yet reached a high level and the utilization of these programs and applications is not fully integrated among all workers. Electronic communication has also become an important means of obtaining up-to-date agricultural information, following technological developments, communicating with specialists and farmers, and exchanging experiences related to AI applications.

4.2 Second: To identify the electronic communication tools most commonly used by extension workers in the implementation of artificial intelligence programs and applications, and rank them in order of relative importance.

To achieve this objective, the arithmetic mean and percentage weight were calculated for each electronic communication means and ranked according to priority, as shown in Table 2.

TABLE 2
RANKING OF THE MOST COMMONLY USED ELECTRONIC COMMUNICATION METHODS AMONG EXTENSION WORKERS

T	Paragraphs	Mean	Rank
1	I prefer using electronic communication means rather than traditional communication means when dealing with AI programs and applications in smart agriculture.	4.12	3
2	Electronic communication means facilitate the exchange of experiences among extension workers regarding the use of AI applications in smart agriculture.	3.77	15
3	I use electronic communication means and applications to coordinate with researchers and experts regarding AI applications in smart agriculture.	3.95	9
4	Cloud applications are important for sharing information related to AI-based extension work.	3.8	14
5	I use specialized electronic platforms to exchange experiences between extension workers and scientific research centers concerning AI applications in extension work.	4.02	7
6	I benefit from generative AI platforms via the Internet to obtain information or prepare agricultural extension content related to smart agriculture.	4.16	2
7	I use electronic search engines to access information related to AI programs and applications for smart agriculture.	4.06	6
8	It is important to follow digital educational channels, such as webinars and online training courses, to learn about the latest AI applications.	3.91	10
9	I use agricultural extension smartphone applications to access AI services and learn how to use them.	3.97	8
10	I use specialized smart-agriculture websites to obtain information about AI applications.	4.08	4
11	I use electronic platforms belonging to agricultural institutions to obtain information related to AI programs and applications.	4.34	1
12	I benefit from virtual meetings through video-communication applications, such as Zoom, Google Meet, or Microsoft Teams, to discuss AI applications in extension work.	4.07	5
13	I use social networking platforms to publish and follow information related to AI applications in agriculture.	3.9	11
14	I use email to exchange information and files related to AI programs and applications.	3.86	12
15	I use instant-messaging applications, such as WhatsApp or Telegram, to communicate about AI programs and applications in smart agriculture.	3.83	13

The results in Table 2 showed that the item "I use electronic platforms belonging to agricultural institutions to obtain information related to AI programs and applications" ranked first, with a mean of 4.34. This may be attributed to the fact that agricultural extension workers regard these affiliated electronic platforms as important and reliable sources for obtaining up-to-date agricultural information related to AI programs and applications. AI applications are characterized by rapid development and continuous updating, which makes extension workers need electronic information sources that enable them to follow developments and applications that can be employed in agricultural extension work. Electronic platforms also provide workers with rapid access to information without being restricted by location or official working hours, which is consistent with the nature of extension work, where information must be obtained at the appropriate time and transferred to farmers in a way that contributes to sustainable food security.

In contrast, the item "Electronic communication means facilitate the exchange of experiences among extension workers regarding the use of AI applications in smart agriculture" ranked last, with a mean of 3.77. This may be because agricultural extension workers do not rely heavily on electronic communication means to exchange experiences and agricultural knowledge among themselves. This may be related to limited practical experience in this field, as the use of AI applications in agricultural and extension work still requires more training and practical experience. Experience exchange also requires the existence of diverse practical experiences that can be shared and discussed, whereas workers' experiences with AI applications may still be similar or limited, reducing the perceived need to use electronic communication means for exchanging them.

4.3 Third: To assess the contribution of electronic communication to improving the proficiency of extension workers in using artificial intelligence programs and applications in the field of smart agriculture.

To achieve this objective, the minimum observed value for the contribution of electronic communication was 36, while the maximum observed value was 75. Using the range and class width, respondents were divided into three categories. The arithmetic mean was 59.98 and the standard deviation was 9.33, as shown in Table 3.

TABLE 3
CONTRIBUTION OF ELECTRONIC COMMUNICATION TO IMPROVING EMPLOYEE EFFICIENCY

Range	Frequency	Percentage
36–48 (Low)	18	12
49–61 (Medium)	62	41.33
62–75 (High)	70	46.67
Total	150	100
Arithmetic mean	59.98	
Standard deviation	9.33	

The results showed that the contribution of electronic communication to improving extension workers' efficiency in using AI programs and applications in smart agriculture was high, with a percentage of 46%. This may be attributed to the fact that extension workers recognize electronic communication as an important means of developing their knowledge, experience, and attitudes toward using AI programs and applications in agricultural extension work by providing rapid access to up-to-date agricultural information, learning about agricultural applications, following agricultural experiences and practices through these programs, communicating with specialists, and exchanging knowledge and experience.

4.4 Fourth: To identify individual differences in the importance of electronic communication and the use of artificial intelligence applications according to certain independent variables among extension workers, namely (gender, educational qualification, years of service, training courses, level of Internet use, and willingness to use social media platforms related to smart farming technologies).

To achieve this objective and identify individual differences, the T-test was used for independent variables with two categories, whereas one-way analysis of variance (ANOVA) was used for variables with more than two categories, as follows.

4.4.1 Gender

To identify individual differences in the importance of electronic communication and the use of AI applications according to gender, the T-test was used, as shown in Table 4.

TABLE 4
INDIVIDUAL DIFFERENCES IN THE IMPORTANCE OF ELECTRONIC COMMUNICATION, THE USE OF ARTIFICIAL INTELLIGENCE APPLICATIONS, AND GENDER

Gender	N	Mean	SD	T-test	Sig.
Male	122	103.07	14.92	0.156	0.214
Female	28	105.5	16.84	0.156	0.214
Total	150			0.156	0.214

The results showed no significant differences between the importance of electronic communication and the use of AI applications according to gender, as the calculated t-test value was 0.156 and the reported significance value was 0.214. This indicates that males and females had relatively similar assessments of the importance of electronic communication and the use of AI applications in agricultural extension work. Gender therefore did not appear to be a direct factor shaping their attitudes

toward these technologies. The use of electronic communication means and AI applications has become associated more with the nature and requirements of professional extension work than with workers' personal characteristics. Males and females also work in a relatively similar extension environment and are similarly exposed to digital sources and modern communication means, such as smartphones and electronic platforms, making these technologies accessible to both genders without a substantial difference.

4.4.2 Educational Qualification

To identify individual differences according to educational qualification, one-way ANOVA was used, as shown in Table 5.

TABLE 5

INDIVIDUAL DIFFERENCES BETWEEN THE IMPORTANCE OF ELECTRONIC COMMUNICATION AND ACADEMIC QUALIFICATIONS

Source of variation	Sum of squares	df	Mean square	F	Sig.
Between groups	1112.062	2	370.68	1.609	0.19
Within groups	33409.052	148	230.4		
Total	34521.114	150			

The results indicated no significant differences between the importance of electronic communication and educational qualification, with a calculated F value of 1.609 and a reported significance value of 0.190, which is not significant at the 0.05 level. This may be attributed to the fact that differences in educational level did not produce substantial differences in the extent to which workers use modern information and technologies. Workers with different educational qualifications may have similar exposure to scientific and electronic sources and similar interest in electronic communication related to AI and digital technologies. Educational attainment may not necessarily be associated with greater opportunities to consult scientific and electronic sources and follow recent developments in information technology and AI.

4.4.3 Years of Service

To identify individual differences according to years of occupational service, one-way ANOVA was used, as shown in Table 6.

TABLE 6

INDIVIDUAL DIFFERENCES BETWEEN THE IMPORTANCE OF ELECTRONIC COMMUNICATION AND YEARS OF SERVICE

Source of variation	Sum of squares	df	Mean square	F	Sig.
Between groups	130.205	2	65.102	0.276	0.039
Within groups	34390.909	148	235.554		
Total	34521.114	150			

The results indicated significant differences between the importance of electronic communication and years of occupational service, with a calculated F value of 0.276 and a reported significance value of 0.039, which is significant at the 0.05 level. This may be attributed to differences in extension workers' assessment of the importance of electronic communication according to their length of service. Differences in years of service may lead to differences in professional experience and in the extent to which electronic communication means and AI applications are used in extension work, which may affect workers' perception of the importance of electronic communication for obtaining agricultural information, communicating with farmers and colleagues, and following agricultural developments.

4.4.4 Training Courses

To identify individual differences according to participation in training courses, the T-test was used, as shown in Table 7.

TABLE 7

INDIVIDUAL DIFFERENCES BETWEEN THE IMPORTANCE OF ELECTRONIC COMMUNICATION AND TRAINING COURSES

Training	N	Mean	SD	T-test	Sig.
Trained	38	106.71	16.35	0.226	0.276
Untrained	112	102.79	14.98		
Total	150				

The results showed no significant differences between the importance of electronic communication and the use of AI applications according to training-course participation, as the calculated t-test value was 0.226 and the reported significance value was 0.276. This may be attributed to the fact that participation in training courses did not produce a substantial difference in workers' assessment of the importance of electronic communication. Both participants and non-participants may be directly or indirectly exposed to modern digital means, particularly AI applications, enabling them to develop relatively similar perceptions of the importance of electronic communication and AI applications in agricultural extension work.

4.4.5 Level of Internet Use

To identify individual differences according to level of Internet use, one-way ANOVA was used, as shown in Table 8.

TABLE 8

INDIVIDUAL DIFFERENCES BETWEEN THE IMPORTANCE OF ELECTRONIC COMMUNICATION AND THE LEVEL OF INTERNET USE

Source of variation	Sum of squares	df	Mean square	F	Sig.
Between groups	84.563	2	57.231	0.201	0.019
Within groups	24456.651	148	435.799		
Total	24541.214				

The results indicated significant differences between the importance of electronic communication and the use of AI applications according to Internet-use level, with a reported calculated value of 0.201 and a reported significance value of 0.019. This may be attributed to differences in the extent to which extension workers use the Internet during their extension work and corresponding differences in their awareness of the importance of electronic communication means and AI applications. Greater Internet use provides workers with more opportunities to encounter recent agricultural ideas and information, learn about digital applications and platforms, communicate with farmers, and follow developments related to AI and smart agriculture.

4.4.6 Willingness to Use Social Networking Sites for Smart-Agriculture Technologies

To identify individual differences according to willingness to use social networking sites concerning smart-agriculture technologies, the T-test was used, as shown in Table 9.

TABLE 9

INDIVIDUAL DIFFERENCES BETWEEN THE IMPORTANCE OF USING ELECTRONIC COMMUNICATION AND THE DESIRE TO USE SOCIAL MEDIA PLATFORMS REGARDING SMART FARMING TECHNOLOGIES

Willingness	N	Mean	SD	T-test	Sig.
Willing	111	134.63	15.79	0.614	0.321
Unwilling	39	99.86	15.91		
Total	150				

The results indicated no significant differences between the importance of electronic communication and the use of AI applications according to the use of social networking sites concerning smart-agriculture technologies. The reported calculated t-test value was 0.614 and the reported significance value was 0.321, which is not significant at the 0.01 level. This may be attributed to the fact that workers' perceptions of the importance of electronic communication for using AI applications did not differ substantially according to their level of use of these communication media. Workers who use such communication sites more frequently may be more exposed to digital agricultural information, knowledge, and experience related to AI applications, but this did not translate into a statistically significant difference in their perceptions.

4.5 Fifth: Identifying the barriers that extension workers face in using artificial intelligence applications in the field of smart agriculture.

To achieve this objective, the arithmetic mean was calculated for each item and the items were ranked according to their importance, as shown in Table 10.

TABLE 10
BARRIERS THAT EXTENSION WORKERS FACE IN USING ARTIFICIAL INTELLIGENCE APPLICATIONS

T	Paragraphs	Mean	Rank
1	Limited availability of modern devices required for using AI applications in agricultural extension work.	4.12	9
2	Weak technical support when facing problems related to the use of AI applications in agricultural extension work.	3.77	11
3	Lack of clear planning by agricultural institutions for employing AI in extension programs and activities.	3.95	4
4	High costs of AI applications and tools and their updating and maintenance.	3.8	3
5	Limited experience and digital skills among some extension workers in using AI.	4.02	7
6	The technical complexity of some AI applications makes them difficult to use.	4.16	6
7	Limited training courses addressing extension workers' skills in using AI applications.	4.06	14
8	Inadequate digital infrastructure in agricultural institutions required for applying AI technologies in agricultural extension work.	3.91	10
9	Slow Internet service limits the use of AI applications in extension work.	3.97	2
10	Insufficient financial support allocated to employing AI technologies in agricultural extension work.	4.08	13
11	Fear of assuming responsibility when using AI applications in extension work and dealing with them.	4.34	5
12	Insufficient confidence in the accuracy of some information and recommendations provided by agricultural AI applications in smart agriculture.	4.07	12
13	Poor compatibility of some AI applications with the nature and needs of agricultural extension work in Nineveh Governorate.	3.9	1
14	Difficulty convincing some farmers to use AI-based agricultural technologies and applications.	3.86	8
15	Limited availability of agricultural smart-application content that meets the needs of extension workers and farmers.	3.83	15

The results showed that the item "Poor compatibility of some AI applications with the nature and needs of agricultural extension work in Nineveh Governorate" ranked first, with a mean of 4.50. This may be attributed to the fact that some available AI applications are still designed for agricultural environments whose conditions differ from those of Nineveh Governorate, which may limit their suitability to the actual needs of extension workers. Agricultural production practices also differ from one region to another, making some applications require adaptation to local agricultural characteristics. In addition, some applications may not provide specialized content or extension recommendations appropriate to the agricultural problems encountered by extension workers in the governorate.

In contrast, the item "Limited availability of agricultural smart-application content that meets the needs of extension workers and farmers" ranked last, with a mean of 2.97. This may be because agricultural extension workers perceive that the available

smart agricultural applications provide a reasonable amount of information, knowledge, and agricultural services that support their work. They can also access diverse digital sources related to smart agriculture and use them according to their extension knowledge needs.

V. CONCLUSION

- 1) The importance of electronic communication in using AI programs and applications in smart agriculture, from the perspective of extension workers, was at an acceptable level because workers still perceive the presence of factors affecting the application of these means in extension work.
- 2) Using electronic platforms belonging to agricultural institutions to obtain information related to AI programs and applications was the most frequently used electronic communication means by extension workers.
- 3) The contribution of electronic communication to improving extension workers' efficiency in using AI programs and applications in smart agriculture was high, reflecting the importance of these applications in smart agriculture and food security.
- 4) Respondents' gender and the training courses received by agricultural extension workers were not significant factors in the importance of electronic communication for using AI applications in smart agriculture.
- 5) Educational qualification, years of occupational service, level of Internet use in extension work, and willingness to use social networking sites concerning smart-agriculture technologies were all reported as factors associated with differences in the use of AI applications in agricultural extension work.
- 6) Poor compatibility of some AI applications with the nature and needs of agricultural extension work in Nineveh Governorate was the most important obstacle facing agricultural extension workers in using electronic communication.

ACKNOWLEDGEMENT

The researcher extends sincere thanks and appreciation to the Department of Agricultural Extension at the College of Agriculture and Forestry, University of Mosul, for its outstanding scientific and academic efforts in supporting scientific research and advancing knowledge in the field of agricultural extension. The researcher also expresses pride in being affiliated with this academic institution, wishing the department and its faculty continued progress and success in serving the scientific and research mission.

CONFLICT OF INTEREST

The researcher declares that there is no conflict of interest that could influence the results or interpretation of this research.

REFERENCES

- [1] Hamada, S. A.-H. (2014). The impact of modern communication media on social and family relations. In *The Fourth Annual International Scientific Conference of the Faculty of Sharia: Social Media and Its Impact on Society—A Sharia, Social, and Legal Perspective*. An-Najah National University.
- [2] Jad, M. J., & Shaeer, S. J. (2021). Extension workers' use of information and communication technology in agricultural extension work in Menoufia Governorate. *Alexandria Journal of Agricultural Sciences*, *42*(4).
- [3] Shaikh, T. A., Rasool, T., & Lone, F. R. (2022). *Towards leveraging the role of machine learning and artificial intelligence in precision agriculture and smart farming*.
- [4] FAO. (2023). *Guide on digital agricultural extension and advisory services*. Food and Agriculture Organization.
- [5] Kpodo, J., & Nejadhashemi, A. P. (2025). Navigating challenges/opportunities in developing smart agricultural extension platforms: Multi-media data mining techniques. *Artificial Intelligence in Agriculture*.
- [6] Al-Janabi, A. A., Al-Janabi, S. T. F., & Al-Khateeb, B. (2023). Secure data computation using deep learning and homomorphic encryption: A survey. *International Journal of Online and Biomedical Engineering*, *19*, 53-82.
- [7] Klie, J.-C., Bugert, M., & Boullosa, B. (2018). The INCEpTION platform: Machine-assisted and knowledge-oriented interactive annotation. In *Proceedings of the 27th International Conference on Computational Linguistics: System Demonstrations* (pp. 5-9). Santa Fe, New Mexico, USA.
- [8] Lin, L., & Shyu, M.-L. (2020). Weighted association rule mining for video semantic detection. *International Journal of Multimedia Data Engineering and Management*, *1*, 37-54.
- [9] Tan, Z., Li, D., Wang, S., Beigi, A., Jiang, B., Bhattacharjee, A., Karami, M., Li, J., Cheng, L., & Liu, H. (2024). *Large language models for data annotation: A survey*.

- [10] Kpodo, J., & Nejadhashemi, A. P. (2026). Navigating challenges/opportunities in developing smart agricultural extension platforms: Data source, compilation, and conversion. *Global Food Security*, *32*, Article 100577. <https://doi.org/10.1016/j.gfs.2021.100577>
- [11] Wang, H., Wu, H., Wang, Q., Qiao, S., Xu, T., & Zhu, H. (2022). A dynamic attention and multi-strategy-matching neural network based on BERT for Chinese rice-related answer selection. *Agriculture*, *12*, 176.
- [12] Al-Jailawi, H. M. H., & Al-Mashhadani, M. A. S. (2026). *The reality of using information and communication technology in agricultural extension work/Iraq*. FAO AGRIS – International System for Agricultural Science and Technology.
- [13] Rodríguez, J. P., Montoya-Munoz, A. I., Rodríguez-Pabon, C., Hoyos, J., & Corrales, J. C. (2021). IoT-Agro: A smart farming system for Colombian coffee farms. *Computers and Electronics in Agriculture*, *190*.
- [14] Alvarez, J., & Nuthall, P. (2006). Adoption of computer-based information systems: The case of dairy farmers in Canterbury, New Zealand, and Florida, Uruguay. *Computers and Electronics in Agriculture*, *50*, 48-60.
- [15] Ferris, J. L. (2017). Data privacy and protection in the agriculture industry: Is federal regulation necessary? *Minnesota Journal of Law, Science & Technology*, *18*, 309-342.
- [16] Azimi, I., Pahikkala, T., Rahmani, A. M., Niela-Vilén, H., Adeline, A., & Liljeberg, P. (2019). Missing data resilient decision-making for healthcare IoT through personalization: A case study on maternal health. *Future Generation Computer Systems*, *96*, 297-308.

Effect of Weaning on Growth Performance and Health Status of Crossbred Calves

Kavita Chauhan¹; Danveer S. Yadav^{2*}; Naresh Kurechiya³; Sandeep Nanavati⁴;
M.S. Jamra⁵; N.S. Rawat⁶

¹PG Scholar, Department of Livestock Production and Management, C.V.Sc. and A.H., N.D.V.S.U., Mhow (M.P.)

²Associate Professor, Department of Livestock Production and Management, C.V.Sc. and A.H., N.D.V.S.U., Mhow (M.P.)

³Associate Professor, Department of Animal Nutrition, C.V.Sc. and A.H., N.D.V.S.U., Mhow (M.P.)

⁴Professor and Head, Department of Livestock Production and Management, C.V.Sc. and A.H.,
N.D.V.S.U., Mhow (M.P.)

^{5,6}Assistant Professor, Department of Livestock Production and Management, C.V.Sc. and A.H., N.D.V.S.U., Mhow (M.P.)

*Corresponding Author

Received:- 15 September 2026/ Revised:- 23 September 2026/ Accepted:- 03 October 2026/ Published: 15-10-2026

Copyright @ 2026 International Journal of Environmental and Agriculture Research

This is an Open-Access article distributed under the terms of the Creative Commons Attribution

Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted

Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— The present study entitled "Effect of weaning on growth performance and health status of crossbred calves" was performed at Livestock Farm Complex, College of Veterinary Science and A.H., Mhow. Twelve calves were selected at the age of 6 days after calving and divided randomly into two groups, control (suckled) and treatment (weaned), with six calves in each group. The duration of the study was 90 days. Growth performance values such as average body weight, daily gain, body length and height at wither were found to be significantly higher in suckled calves as compared to weaned calves, while the average incidence of diseases in weaned calves (50.00%) was found to be higher than in suckled calves (33.33%). The results indicate better performance of suckled calves than weaned calves.

Keywords— Growth Performance, Health Status, Suckled Calves and Weaned Calves.

I. INTRODUCTION

Crossbred cows contribute 28.0% of total milk production in the country and average milk yield (kg/day) of crossbred and indigenous cows are 7.22 and 3.34, respectively (Livestock Census, 2019). Calf rearing during the milk feeding period is a laborious management practice on livestock farms. Therefore, calf management should be scientific, proper and appropriate. Rearing after birth may have a significant impact on subsequent performance and behaviour of animals (Soberon et al., 2012). It is done either by natural suckling or artificial rearing. Artificial rearing involves the separation of neonatal calves from the dam and rearing them without suckling from their mother, a practice called weaning. Under the artificial rearing system, morbidity and mortality could be reduced significantly. The most common reasons for adopting this practice are the accurate recording of milk yield, the economical and scientific feeding of the calves, the facilitation of the mechanization and automation of farm operations such as machine milking, the saving of labour cost and ensuring clean milk production (Singh et al., 2017). Considering the significance of calf weaning, an experiment was designed to study the effect of weaning on the growth performance and health status of crossbred calves.

II. MATERIALS AND METHODS

Location of the work: The present study was conducted at Livestock Farm Complex, Department of Livestock Production Management, College of Veterinary Science and Animal Husbandry, Mhow, N.D.V.S.U. (M.P.).

Plan and duration of experiment: The study was conducted for 90 days. Twelve calves were selected at the age of 6 days after calving. Twelve calves were divided randomly into two groups, control (suckled) and treatment (weaned), with six calves in each group.

TABLE 1
DETAILS OF EXPERIMENTAL GROUPS

S. No.	Groups	No. of calves	Period (days)
1	Control/suckled group	6	90
2	Treatment/weaned group	6	90

The control calves were allowed to suckle from the dam twice a day before milking from birth to 90 days of age, while the treatment calves were separated from the dam on the 6th day of age and termed the weaned group. The amount of milk was given to treatment calves with the help of a milk pail (wide mouth bucket) as per their age and body weight. The calves were kept in a well-ventilated pucca floor house and in groups. Free access to fresh and clean water was provided to the calves. Deworming was done for all the experimental calves.

2.1 Management of experimental crossbred calves:

The experimental crossbred calves were housed under an asbestos-roofed shed. All the experimental crossbred calves were offered green fodder ad libitum from the 16th day onwards. Free access to fresh and clean water was provided to the calves. The veterinary aid measures were provided for all the experimental crossbred calves as per the farm schedule.

TABLE 2
FEEDING SCHEDULE OF WEANED CALVES

Age of calves (days)	Colostrum	Whole milk	Calf starter (g)	Green fodder
0-5	1/10th of b. wt.	Nil	Nil	Nil
13-20	Nil	1/10th of b. wt.	50-100	Ad libitum from 16th day onwards
21-30	Nil	1/10th of b. wt.	250	
31-40	Nil	1/15th of b. wt.	500	
41-60	Nil	1/20th of b. wt.	750	
61-90	Nil	1/40th of b. wt.	800	

(Upadhyay et al., 2014)

Medication: Prophylactic measures against disease and endo-ectoparasitic infestations were carried out as prescribed by the health calendar of the farm to ensure that the calves were in healthy condition throughout the study.

Housing: The experimental crossbred calves were reared under a shed made of asbestos roofing with a cement concrete floor sloped towards the drain to avoid dampness. The crossbred calves of the treatment groups were kept in a different shed. The crossbred calves were kept in groups within the houses.

2.2 Parameters studied:

2.2.1 Growth performance

a) Birth weight (kg)

The birth weight of experimental crossbred calves of both groups was recorded and thereafter at fortnightly intervals using a digital weighing machine before offering feed and water.

b) Average daily gain (g)

Average daily gain of each individual calf was recorded at fortnightly intervals from birth to 90 days of age.

$$\text{Average daily gain} = \frac{\text{Current body weight (kg)} - \text{Previous body weight (kg)}}{\text{Number of days in interval}} \quad (1)$$

c) Body measurements of crossbred calves (cm) were recorded at fortnightly intervals using a measuring tape.

- 1) Body length: Measurement from the point of shoulder to the point of pin bone.
- 2) Height at wither: Measurement from ground level to the highest point above the shoulder.
- 3) Heart girth: Measurement of the circumference of the body just behind the shoulder blade.

2.2.2 Health status

a) Incidence of disease:

All calves were visually examined every day in the morning and evening for their health status, and records were maintained for any injuries or illnesses (such as diarrhoea/dysentery, alopecia, calf mortality, bruises, injury, and other health problems including lameness, eye infection, fever, navel ill, weakness, nasal discharge, joint ill, and maggot wound), which were immediately recorded and treated accordingly.

b) Eggs per gram of faeces:

Data was recorded at fortnightly intervals in both groups by the McMaster egg counting technique.

2.2.3 Statistical analysis:

The data obtained in the study were subjected to statistical analysis as per the procedure described by Snedecor and Cochran (1994). The significance of differences between the mean values of various parameters studied was tested by employing an independent t-test.

III. RESULTS AND DISCUSSION

3.1 Growth performance of crossbred calves

3.1.1 Body weight (kg)

The body weight (kg) of crossbred calves under the suckled and weaned groups is presented in Table 3, which revealed a highly significant difference ($p < 0.01$) fortnightly in both groups. The crossbred suckled calves showed a significantly higher body weight (36.47 ± 4.44 kg) than that of the weaned calves (29.46 ± 2.92 kg), which signifies high dry matter intake from whole milk in the suckling group. These observations are congruent with the earlier studies reported by Kantharaja (2011) and Yilma et al. (2006).

TABLE 3
AVERAGE BODY WEIGHT (kg) OF CROSSBRED CALVES UNDER SUCKLED AND WEANED GROUP

Fortnightly	Suckled	Weaned
0 ^{NS}	21.85 ± 0.67	20.02 ± 0.48
1 ^{**}	26.10 ± 0.57	22.85 ± 0.70
2 ^{**}	29.85 ± 1.07	25.30 ± 0.58
3 ^{**}	35.15 ± 1.23	28.24 ± 0.68
4 ^{**}	40.47 ± 1.11	31.45 ± 0.70
5 ^{**}	47.34 ± 1.20	36.57 ± 0.61
6 ^{**}	54.56 ± 1.06	41.80 ± 0.75
Overall Average ^{**}	36.47 ± 4.44	29.46 ± 2.92

NS = non-significant

**= Significant difference ($p < 0.01$)

3.1.2 Average daily gain (g)

The average daily gain (g) of crossbred calves was calculated fortnightly under the suckled and weaned groups and is presented in Table 4. A highly significant difference ($p < 0.01$) was observed in the 3rd fortnight and a significant difference ($p < 0.05$) was observed in the 4th and 5th fortnights in both experimental groups. A significant difference ($p < 0.05$) was observed between

the two groups. The overall mean of the suckled group (363.49 ± 37.60 g) was higher than that of the weaned group (248.04 ± 37.39 g). It might have happened due to the fact that the suckled group of calves had a slower rate of colostrum as well as milk ingestion per unit time, which may have resulted in more secretion of saliva, better mixing of the milk digestive enzymes and hence better utilization of colostrum and milk. The present findings were in agreement with Solanki et al. (2021) and Singh et al. (2019).

TABLE 4
AVERAGE DAILY GAIN (g) OF CROSSBRED CALVES UNDER SUCKLED AND WEANED GROUP

Fortnightly	Suckled	Weaned
1 ^{NS}	283.34 ± 40.51	188.89 ± 23.83
2 ^{NS}	250.00 ± 90.22	163.34 ± 24.93
3 ^{**}	353.34 ± 56.93	195.56 ± 18.67
4 [*]	354.45 ± 64.62	214.45 ± 23.18
5 [*]	457.78 ± 29.85	341.12 ± 34.32
6 ^{NS}	482.00 ± 09.53	384.89 ± 20.12
Overall average*	363.49 ± 37.60	248.04 ± 37.39

NS = non-significant

** = Significant difference ($p < 0.05$)*

*** = Significant difference ($p < 0.01$)*

3.2 Body measurements of crossbred calves

3.2.1 Body length (cm)

The body length (cm) of crossbred calves under this study was calculated fortnightly under the suckled and weaned groups as presented in Table 5. A highly significant difference ($p < 0.01$) was observed in the 2nd, 3rd, and 4th fortnights, and a significant difference ($p < 0.05$) was observed in the 1st, 5th, and 6th fortnights in both experimental groups. The crossbred suckling calves showed a significantly higher estimate of body length (70.86 ± 3.07 cm), which was more than the weaned group (67.00 ± 2.68 cm), reflecting better growth due to higher milk consumption. The present finding was in harmony with those reported by Kantharaja (2011), who found a significant ($p < 0.01$) effect of calf rearing system on most of the weekly body lengths.

TABLE 5
AVERAGE BODY LENGTH (cm) OF CROSSBRED CALVES UNDER SUCKLED AND WEANED GROUP

Fortnightly	Suckled	Weaned
0 ^{NS}	58.00 ± 0.45	57.00 ± 0.37
1 [*]	63.00 ± 0.52	60.33 ± 0.67
2 ^{**}	67.50 ± 0.67	64.00 ± 0.45
3 ^{**}	70.17 ± 0.60	66.00 ± 0.26
4 ^{**}	74.83 ± 0.48	69.33 ± 0.61
5 [*]	79.67 ± 0.80	74.67 ± 1.65
6 [*]	82.83 ± 0.60	77.67 ± 1.71
Overall average*	70.86 ± 3.07	67.00 ± 2.68

NS = non-significant

** = Significant difference ($p < 0.05$)*

*** = Significant difference ($p < 0.01$)*

3.2.2 Heart girth (cm)

The heart girth (cm) of crossbred calves under the suckled and weaned groups is presented in Table 6. Non-significant changes were observed for heart girth of crossbred calves in the entire experiment under both the suckled and weaned groups.

TABLE 6
AVERAGE HEART GIRTH (cm) OF CROSSBRED CALVES UNDER SUCKLED AND WEANED GROUP

Fortnightly	Suckled	Weaned
0 ^{NS}	67.50 ± 2.32	70.16 ± 2.32
1 ^{NS}	73.00 ± 1.86	74.00 ± 2.57
2 ^{**}	78.16 ± 1.82	76.67 ± 2.55
3 ^{**}	82.00 ± 1.84	80.17 ± 3.07
4 ^{**}	86.17 ± 2.01	83.83 ± 3.22
5 ^{NS}	90.00 ± 2.02	87.17 ± 3.66
6 ^{NS}	93.16 ± 1.83	91.17 ± 3.36
Overall average NS	81.43 ± 3.07	80.45 ± 2.64

NS = non-significant

3.2.3 Height at wither (cm)

The height at wither (cm) of crossbred calves was calculated fortnightly under the suckled and weaned groups as presented in Table 7, which showed a highly significant difference ($p < 0.01$) in the 2nd, 3rd, and 4th fortnights in both groups. Limiting milk consumption at the end of the pre-weaning period appears to increase body size, which seems to be positively affected by the suckling process.

TABLE 7
AVERAGE HEIGHT AT WITHER (cm) OF CROSSBRED CALVES UNDER SUCKLED AND WEANED GROUP

Fortnightly	Suckled	Weaned
0 ^{NS}	68.34 ± 0.61	67.67 ± 0.33
1 ^{NS}	73.00 ± 0.86	72.00 ± 1.61
2 ^{**}	77.17 ± 0.48	74.17 ± 0.65
3 ^{**}	80.67 ± 0.33	77.34 ± 0.67
4 ^{**}	84.67 ± 0.33	79.67 ± 0.92
5 ^{NS}	88.00 ± 0.45	84.50 ± 1.69
6 ^{NS}	90.67 ± 0.49	88.00 ± 1.55
Overall average*	80.36 ± 2.73	77.62 ± 2.49

NS = non-significant

*** = Significant difference ($p < 0.01$)*

** = Significant difference ($p < 0.05$)*

3.3 Health status of crossbred calves

The average incidence of diseases of crossbred calves under the suckled group was recorded as diarrhoea/bruises/injury/lameness/fever/navel ill, with 1 (16.67%) found from birth up to 90 days. The overall incidence of diseases recorded in crossbred calves under the suckled and weaned groups was found to be 33.33% and 50.00%, respectively. The incidence of diseases recorded in crossbred calves is presented in Table 8. These results are consistent with the reports of Sikka et al. (2002), Singh et al. (2019), and Ahmad et al. (2004).

TABLE 8
OVERALL INCIDENCE OF DISEASES (%) OF CROSSBRED CALVES UNDER SUCKLED AND WEANED GROUP

Condition	Suckled calf no. (%)	Weaned calf no. (%)
Diarrhoea	1 (16.67)	2 (33.33)
Alopecia	0 (0.00)	0 (0.00)
Calf Mortality	0 (0.00)	0 (0.00)
Bruises	1 (16.67)	1 (16.67)
Injury	1 (16.67)	1 (16.67)
Lameness	1 (16.67)	1 (16.67)
Eye Infection	0 (0.00)	1 (16.67)
Fever	1 (16.67)	1 (16.67)
Navel ill	1 (16.67)	2 (33.33)
Nasal Discharge	0 (0.00)	0 (0.00)
Joint ill	0 (0.00)	0 (0.00)
Maggot Wound	0 (0.00)	0 (0.00)
Total	2 (33.33)	3 (50.00)

IV. CONCLUSIONS

The results indicate that all the growth traits, namely average body weight, average daily gain, and body measurements, showed an increasing trend over the experimental duration in suckling calves as compared to non-suckling or weaned calves. The higher live weight of suckling calves strongly favours the maternal instinct of the experimental animals. The experiment also revealed that the overall incidence of diseases was quite high in weaned calves, which indicates that unweaned calves remain healthier on account of natural suckling rather than weaned calves.

ACKNOWLEDGEMENT

We are highly thankful to the Dean, College of Veterinary Science & A.H., Mhow, for the facilities provided, and to our major advisor for the cooperation extended to conduct this study, and to Dr. S. Nanavati for his moral support and guidance during our research period.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- [1] Ahmad, F. M., Jabbar, A., Ahmad, I., Rafique, M., & Ahmad, I. (2004). Comparative efficiency of calf starter and conventional rations in buffalo suckling calves. *Pakistan Veterinary Journal*, *24*, 161-172.
- [2] Kantharaja, K. J. (2011). Comparative study of weaned Murrah buffalo calves at cattle and buffalo farm of Indian Veterinary Research Institute [Doctoral dissertation, Indian Veterinary Research Institute].
- [3] Livestock Census. (2019). Ministry of Fisheries, Animal Husbandry and Dairying. Department of Animal Husbandry and Dairying, Animal Husbandry Statistical Division.
- [4] Sikka, P., Sethi, R. K., & Tomer, A. K. S. (2002). Biochemical studies of suckling vs non-suckling buffalo calves in relation to performance of dams. *Indian Journal of Animal Sciences*, *72*(6), 492-495.
- [5] Singh, P. K., Kamboj, M. L., Chandra, S., & Singh, R. K. (2017). Effect of calf suckling dummy calf used and weaning on milk ejection stimuli and milk yield of Murrah buffaloes (*Bubalus bubalis*). *Journal of Pharmacognosy and Phytochemistry*, *6*(6S), 1012-1015.
- [6] Singh, P. K., Kamboj, M. L., Chandra, S., Kumar, A., & Kumar, N. (2019). Influence of weaning on growth, health and behaviour of buffalo (*Bubalus bubalis*) calves. *Indian Journal of Animal Research*, *53*(5), 680-684.

- [7] Soberon, F., Raffrenato, E., Everett, R. W., & Van Amburgh, M. E. (2012). Early life milk replacer intake and effects on long term productivity of dairy calves. *Journal of Dairy Science*, *95*(2), 783-793.
- [8] Solanki, C. P. S., Lakhani, G. P., Roy, B., Mishra, A., Joshi, S. K., & Aharwal, B. (2021). Growth and intake of Murrah buffalo calves under suckling and non-suckling system of management. *Journal of Veterinary Science*, *5*(1), 34-38.
- [9] Snedecor, G. W., & Cochran, W. G. (1994). *Statistical methods* (7th ed., pp. 312-317). Oxford and IBH Publishing Corporation.
- [10] Upadhyay, V. K., Tomar, A. K. S., Patel, B. H. M., Sahu, S., Bharti, P. K., & Golher, D. M. (2014). Performance of Tharparkar calves following a suckling or non-suckling rearing system. *Veterinary World*, *7*(12), 930-940.
- [11] Yilma, Z., Gojjam, Y., & Shumye, M. (2006). Milk production level and calf-rearing system affecting Boran, Ethiopian zebu cattle breed, cow-calf performance. *Livestock Research for Rural Development*, *18*(5), 56-59.



Air-to-Water Condensation Farming and Fogponics for "Zero-Watering" Horticulture in India: A Review of Technologies, Crop Suitability and Readiness for El Niño-Driven Water Scarcity

Jadala Shankaraswamy

Department of Fruit Science, College of Horticulture, Mojerla, Wanaparthi-509 382, Telangana, India
Sri Konda Laxman Telangana Horticultural University (SKLTGHU)
Orcid : 0000-0002-5623-6384

Received:- 15 September 2026/ Revised:- 21 September 2026/ Accepted:- 04 October 2026/ Published: 15-10-2026

Copyright © 2026 International Journal of Environmental and Agriculture Research

This is an Open-Access article distributed under the terms of the Creative Commons Attribution

Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted

Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— India produced an estimated 369.05 million tonnes of horticultural produce from 29.48 million ha in 2024–25. Its per-capita water availability, however, has fallen to about 1,486 m³ (2021) and is projected to reach 1,367 m³ by 2031, below the 1,700 m³ water-stress threshold. Greenhouse warming is expected to strengthen the inverse El Niño–monsoon relationship. Future El Niño years may therefore cause crop-yield losses about 30% larger than those observed historically, and nearly 200 Indian districts have been identified as highly vulnerable in 2026. This review examines two complementary pathways that decouple high-value horticulture from rainfall and groundwater: (i) air-to-water condensation farming, in which atmospheric water generators (AWGs), sorbent-based harvesters, dew condensers or fog collectors, preferably solar-powered, supply condensate to the root zone of sheltered crops; and (ii) fogponics, an aeroponic variant that delivers nutrient solution as a 5–30 µm fog to suspended roots. Published evidence shows that solar-driven atmospheric water can irrigate leafy vegetables with growth comparable to tap water, that fog collectors can yield 2.9–3.3 L m⁻² day⁻¹ (annual mean) at favourable coastal sites, and that aeroponic seed-potato systems are commercially established in India. Specific energy demand nevertheless ranges from about 0.02 kWh L⁻¹ in humid air to 3.64 kWh L⁻¹ in very dry air, and levelized water costs of US\$ 0.09–0.40 L⁻¹ have been reported. These figures confine the approach, at present, to high-value, small-footprint protected cultivation, nurseries and propagation. A crop-suitability matrix for Indian fruits, vegetables and flowers, an agro-climatic zoning framework, a sizing procedure and a research roadmap are proposed. "Zero watering" is best understood as zero dependence on irrigation from surface or groundwater, not zero water input. The technology can serve as climate-insurance infrastructure for nurseries and protected horticulture during El Niño years.

Keywords— Atmospheric water generator, Fogponics, Aeroponics, Protected cultivation, El Niño, Water scarcity, Solar energy, Indian horticulture.

I. INTRODUCTION

Horticulture is the fastest-growing segment of Indian agriculture. The Third Advance Estimates for 2024–25 place total horticultural production at 369.05 million tonnes from 29.48 million ha, about 4% higher than the previous year [1]. This output is grown on a shrinking water base. The Ministry of Jal Shakti reports that average annual per-capita water availability fell to 1,486 m³ in 2021 and will decline to 1,367 m³ by 2031; availability below 1,700 m³ is classed as water-stressed [2]. Groundwater, the backbone of horticultural irrigation in peninsular and north-western India, is already heavily used. Most fruit, vegetable and flower crops in rainfed or semi-irrigated tracts are highly sensitive to the timing and quantity of monsoon rainfall.

The El Niño–Southern Oscillation (ENSO) adds a recurrent shock to this structural scarcity. In June 2026 the USDA Foreign Agricultural Service reported that India was moving from ENSO-neutral conditions towards El Niño. The India Meteorological Department expected El Niño to influence the July–September monsoon, and the Government of India had identified nearly 200 districts as highly vulnerable to El Niño-related agricultural impacts [3]. Zhao et al. [4] showed that greenhouse warming

strengthens rather than weakens the inverse ENSO–Indian summer monsoon rainfall relationship. Their constrained projections indicate that monsoon sensitivity to ENSO could be nearly 40% greater than historical levels, and that crop-yield losses in El Niño years could be about 30% larger than in the past. Horticulture therefore needs water sources that do not depend on the monsoon.

The atmosphere is one such source. Even in dry seasons, the air above Indian farms holds water vapour. Two families of technology can deliver this vapour to plants. Air-to-water condensation farming uses atmospheric water generators (AWGs), sorbent-based harvesters, radiative dew condensers or fog nets to produce liquid water, ideally powered by solar photovoltaics (PV), and supplies it to the root zone of crops grown under shelter. Fogponics, a variant of aeroponics, delivers water and nutrients to suspended roots as a fine fog of 5–30 μm droplets [5], minimising the volume of water a crop needs. Combined in a closed protected structure that also recaptures crop transpiration, the two approaches underpin the idea of "zero-watering" horticulture, meaning cultivation with no irrigation drawn from wells, canals or tanks.

Most research on these technologies addresses drinking water, space farming or materials science. It has rarely been synthesized for Indian horticultural crops or framed as an El Niño adaptation. This review aims to (i) explain the physical principles and technology options; (ii) summarize the experimental evidence on crop production with atmospheric water and fog-based root nutrition; (iii) assess the suitability of major Indian fruits, vegetables and flowers; (iv) propose an agro-climatic deployment framework and sizing procedure for India; and (v) critically discuss energy, cost and hygiene limits and outline a research and policy roadmap. A conceptual mind map of the review is shown in Fig. 1.



FIGURE 1: Mind map of zero-watering horticulture based on air-to-water condensation farming and fogponics, covering principles, technologies, delivery, crop groups, Indian agro-climatic zones and constraints.

II. METHODOLOGY OF THE REVIEW

This is a narrative, evidence-based review. Literature was identified through web and scholarly searches (Google Scholar, ScienceDirect, MDPI, Nature Portfolio, ACS Publications and ISHS Acta Horticulturae) and Government of India and international agency portals (Ministry of Agriculture & Farmers Welfare, Ministry of Jal Shakti/PIB, NITI Aayog, ICAR and USDA FAS). Search strings combined the terms atmospheric water generator, atmospheric water harvesting, sorbent, hydrogel, metal–organic framework, dew, fog collection, fogponics, aeroponics, ultrasonic fogger, minituber, protected cultivation, El Niño and India. Priority was given to peer-reviewed studies from 2018–2026 that report quantitative crop, water-yield, energy or cost outcomes, and to official statistics for the Indian context. Where a quantitative value is quoted, the original source is cited. Crop-suitability ratings and zoning recommendations are the author's synthesis of the reviewed evidence and established horticultural practice, and are presented as hypotheses for field validation rather than tested results.

III. PHYSICAL PRINCIPLES OF HARVESTING WATER FROM AIR

3.1 Psychrometric basis

Water vapour condenses on a surface cooled below the dew-point temperature (T_d) of the surrounding air. The closer T_d is to air temperature (i.e., the higher the relative humidity, RH), the less cooling is needed per litre. The harvestable quantity, however, is governed by absolute humidity, so hot and humid air (coastal India, the monsoon season) holds far more extractable water than cool or dry air. Diurnally, RH is highest at night and before dawn, when air temperature is lowest. This is why passive dew condensers and sorbent systems run their capture phase at night.

3.2 Energy floor

Condensing water releases its latent heat of vaporisation (about 2.45 MJ kg^{-1} at ambient temperature). Removing this heat therefore requires at least about 0.68 kWh per litre ($2.45 \text{ MJ} \div 3.6 \text{ MJ kWh}^{-1}$), before compressor, fan and heat-exchanger losses. Practical systems can use less electricity than this only where the thermodynamic work is shifted to free energy sources such as solar heat for sorbent regeneration or radiative sky cooling. A recent comprehensive review reported specific energy consumption from about 0.02 kWh L^{-1} under high-humidity conditions to 3.64 kWh L^{-1} in very low-humidity environments [6]. Machine-level reviews quote about 3 kWh L^{-1} for a vapour-compression unit producing 14 L day^{-1} [7]. Climate is thus the single largest determinant of feasibility.

3.3 Closed-loop water recapture

In an enclosed growing space, most water supplied to plants is transpired back to the air. A dehumidifying condenser inside a sealed polyhouse or container farm can recover this vapour and return it to the nutrient tank. This makes the structure partly self-sustaining, so that the AWG has to supply only the net water fixed in biomass and lost through leakage. This recapture concept is central to realistic zero-watering designs (Fig. 2).

IV. AIR-TO-WATER TECHNOLOGIES FOR CROP PRODUCTION

TABLE 1
COMPARISON OF AIR-TO-WATER TECHNOLOGIES RELEVANT TO HORTICULTURE

Technology	Working principle	Best climate	Energy input	Reported performance (source)	Horticultural fit
Refrigerative (vapour-compression) AWG	Coil cooled below T_d by a compressor; condensate collected	Warm, humid (RH > ~60%)	Electricity (grid or solar PV)	~3 kWh L ⁻¹ for a 14 L day ⁻¹ unit [7]; 0.02–3.64 kWh L ⁻¹ across humidity range [6]	Polyhouse supplementary water; nursery misting; fogponic tanks in coastal/NE India
Sorbent-based AWH (MOF, hydrogel, hygroscopic salt gels)	Night-time vapour sorption; daytime solar-heated desorption and condensation	Semi-arid to arid	Mostly solar heat; low electricity	Off-grid solar system irrigated Chinese cabbage with growth comparable to tap water [8]; arid-climate solar-desiccant AWH: levelized water cost US\$ 0.09–0.40 L ⁻¹ depending on power source [9]	Drip/wick supply for containers and small polyhouses in Deccan and Thar
Soil-applied hygroscopic gels/aerogels	Gel captures vapour and releases it in the root zone	Dry, sandy soils	Passive	PAM–chitosan–CaCl ₂ aerogel extended ryegrass survival by 5–12 days at 20–30% RH without irrigation [10]; super-moisture-absorbent gels used for atmospheric water irrigation [11]	Establishment of seedlings and orchard transplants; drought bridging
Passive radiative dew condenser	Surface cooled by night-sky radiation below T_d	Clear, calm, humid nights	None	Low and highly variable output; site-specific	Supplementary water for nurseries and potted plants
Fog nets / mesh collectors	Wind-driven fog droplets intercepted by mesh	Coastal or hill sites with frequent fog	None	2.9–3.3 L m ⁻² day ⁻¹ annual mean at Atacama sites feeding a hydroponic greenhouse [12]; up to ~10 L m ⁻² day ⁻¹ reported at Alto Hospicio [13]	Western Ghats, Nilgiris and NE hill stations

The strongest crop-level evidence comes from Yang et al. [8], who built a stand-alone, maintenance-free solar-driven atmospheric water extraction (SAWE) system for off-grid irrigation. Chinese cabbage irrigated only with harvested atmospheric water showed growth, soil volumetric water content and electrical conductivity comparable to plants irrigated with tap water. This demonstrates that condensate is agronomically adequate when supplied to the root zone. Alborno et al. [12] linked fog collectors to a hydroponic greenhouse in the Atacama Desert and recorded annual mean fog-water yields of 2.9 and 3.3 L m⁻² day⁻¹ at two sites, showing that fog-fed soilless horticulture is technically possible in a hyper-arid region. Li et al. [14] estimated that an AWH installation of 25 kW with a water-uptake efficiency of 3.33 L kWh⁻¹ could meet substantial agricultural demand in suitable humid regions, underlining the role of climate. The techno-economic analysis by Gayoso et al. [9] reported a levelized cost of water of US\$0.17 L⁻¹ with grid power, US\$0.17 L⁻¹ with grid power, US\$0.40 L⁻¹ with newly purchased off-grid PV and US\$ 0.09 L⁻¹ with existing PV in an arid climate. These costs are orders of magnitude above conventional irrigation water and are only justifiable for high-value crops, nurseries or emergencies.

V. FOGPONICS: PRINCIPLES AND EVIDENCE

5.1 Concept

Aeroponics grows plants with roots suspended in a dark chamber and periodically sprayed with nutrient solution. Fogponics replaces the spray with a continuous or pulsed fog produced by ultrasonic transducers or high-pressure nozzles. Fog emitters generate droplets of about 5–30 μm , finer than the 30–100 μm droplets typical of high-pressure aeroponics [5, 15]. Very fine droplets remain suspended, coat fine roots and root hairs, and keep the root zone highly aerated. Liquid water use is minimal because nearly all the fog either contacts roots or condenses and drains back to the reservoir. The approach is independent of soil quality and weather, and has been coupled with IoT sensing and fuzzy-logic control of temperature, humidity and pH [5].

5.2 Crop evidence

Aeroponics is already commercial in Indian seed-potato production. ICAR–Central Potato Research Institute, Shimla, perfected an aeroponic minituber technology in 2011 and has licensed it to private firms [16, 17]. Elsewhere, optimised aeroponic systems have produced an average of 491 minitubers per plant [15]. In leafy vegetables, comparisons of aeroponic, hydroponic and substrate culture of lettuce indicate that aeroponics promotes root development and yields comparable to or higher than conventional soilless systems [18]. Dry-fog application has also been tested in strawberry under protected cultivation [19]. Reviews note fogponics studies on potato and system development for red chilli in aeroponic greenhouses [5]. Evidence for perennial fruit crops is restricted to propagation (rooting of cuttings, seedlings and micro-plants), where high humidity and root aeration are already routine.

5.3 Limitations specific to fogponics

- Fog is so fine that heavier nutrient ions and dissolved calcium may be delivered less efficiently than in coarser aeroponic sprays. Nutrient strength and fogging cycles must be calibrated.
- Ultrasonic transducers warm the solution and form mineral scale. Discs need regular cleaning or replacement, and condensate (low in minerals) reduces scaling.
- Roots have no water buffer. A fogger or power failure can desiccate roots within hours, so battery or UPS backup and humidity alarms are essential.
- Warm, humid chambers favour biofilm and pathogens. Disinfection (UV/ozone), tank shading and temperature control are mandatory.

VI. INTEGRATED SYSTEM DESIGN

Fig. 2 shows an integrated design. Solar PV with battery storage powers a refrigerative AWG, a sorbent harvester or both, chosen according to local humidity. Passive dew or fog collectors add free water where conditions allow. Condensate passes through sediment filtration and UV/ozone disinfection into an opaque, shaded tank. Because condensate is nearly free of minerals, a fertigation unit doses a complete nutrient solution including Ca, Mg and micronutrients, and controls EC and pH. Water is delivered either as nutrient fog to a fogponic root chamber (leafy greens, strawberry, orchids, minitubers, nursery) or by subsurface drip, wick or container systems (tomato, capsicum, cut flowers, fruit nurseries). The protected structure, whether a polyhouse, net house or container farm, contains a dehumidifier that recaptures transpired water and chamber run-off. An IoT controller monitors RH, temperature, vapour-pressure deficit (VPD), tank level, EC, pH and root-zone moisture, and schedules AWG operation for the most humid hours.

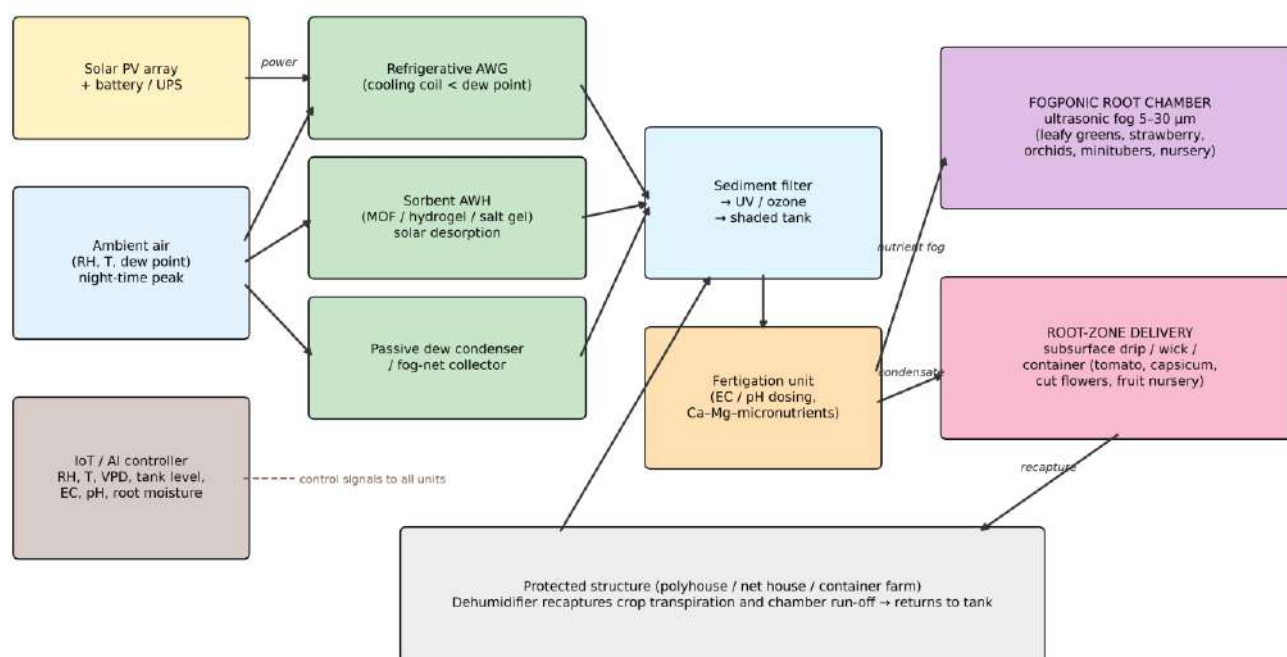


FIGURE 2: Schematic of a solar-powered air-to-water condensation and fogponic system for zero-watering protected horticulture (author's conceptual design).

TABLE 2
INDICATIVE NUTRIENT-SOLUTION AND ENVIRONMENTAL TARGETS FOR CONDENSATE-BASED SOILLESS CULTURE (TO BE CALIBRATED PER CULTIVAR AND LOCATION)

Parameter	Leafy vegetables & herbs	Strawberry	Tomato / capsicum / cucumber	Cut flowers (gerbera, carnation, rose)	Remarks
EC (dS m ⁻¹)	~1.0–1.8	~1.0–1.5	~2.0–3.5	~1.2–2.0	Condensate EC is near zero; all nutrients must be added
pH	5.5–6.5	5.5–6.2	5.5–6.5	5.5–6.2	Low buffering of condensate; monitor daily
Fog/spray cycle	Continuous low fog or short pulses	Pulsed	Drip / wick preferred	Drip or fog in propagation	Adjust to root-chamber RH
Root-zone temperature	Below ~25 °C	Below ~22–24 °C	Below ~26 °C	Below ~24 °C	Shading and evaporative cooling in Indian summers
Hygiene	UV/ozone; weekly cleaning	Same	Same	Same	Biofilm and Legionella risk in warm stagnant water

Note: Table 2 values are working ranges compiled from common soilless-culture practice, not from a single trial. They must be validated for Indian cultivars under condensate-fed systems.

VII. CROP SUITABILITY FOR INDIAN HORTICULTURE

Crop suitability depends on water demand per unit area, economic value per litre of water, root-zone tolerance of soilless culture and duration in the system. Table 3 synthesises the reviewed evidence into a suitability matrix for Indian conditions.

TABLE 3
SUITABILITY OF INDIAN HORTICULTURAL CROPS FOR AIR-TO-WATER CONDENSATION FARMING AND FOGPONICS (AUTHOR'S SYNTHESIS)

Crop group	Crops	Recommended mode	Suitability	Rationale / evidence
Leafy vegetables & herbs	Lettuce, spinach, amaranth, coriander, fenugreek, basil, mint, microgreens	Fogponics / aeroponics	★★★ High	Short cycle, small plants, high value per litre; aeroponic lettuce performs as well as or better than hydroponics [18]; atmospheric water adequate for leafy brassica [8]
Tuber seed production	Potato minitubers	Aeroponics / fogponics	★★★ High	Commercial ICAR–CPRI aeroponic technology [16, 17]; high minituber numbers per plant [15]
Fruiting vegetables	Cherry tomato, capsicum, cucumber, chilli	Condensate drip / wick in polyhouse; fog in nursery	★★ Moderate	Higher water demand and plant size; suited where AWG output is high (coastal/NE) or as drought back-up
Soft fruits	Strawberry (day-neutral)	Fogponics / vertical aeroponics; condensate drip	★★★ High	Compact, high-value; dry-fog strawberry trials [19]
Fruit crop propagation	Mango, citrus, guava, pomegranate, papaya, fig, dragon fruit, grapes (cuttings, seedlings, grafts)	Fog chamber for rooting and hardening; then drip	★★★ High (nursery stage)	High humidity and aeration accelerate rooting; small water volume per plant; adult trees not feasible
Orchard trees	Mango, citrus, guava, banana (adult)	Not recommended (only hydrogel establishment aid)	★ Low	Water demand far exceeds AWG output; aerogels can bridge transplant drought [10, 11]
Cut flowers	Gerbera, carnation, chrysanthemum, rose	Condensate drip in polyhouse; fog for propagation	★★ Moderate	High value per stem; established soilless protocols
Epiphytic and pot flowers	Orchids (Dendrobium, Phalaenopsis), anthurium, bedding plugs	Fogponics / fog-humidified benches	★★★ High	Aerial roots adapted to humid air; low water demand

VIII. AGRO-CLIMATIC DEPLOYMENT FRAMEWORK AND SIZING FOR INDIA

8.1 Zoning

Because energy per litre is governed mainly by absolute humidity [6], deployment should follow India's humidity gradients. Table 4 proposes a first-order zoning, which must be refined with at least one year of local hourly RH and temperature data from IMD or automatic weather stations before investment.

TABLE 4
PROPOSED AGRO-CLIMATIC DEPLOYMENT FRAMEWORK FOR AIR-TO-WATER HORTICULTURE IN INDIA
(AUTHOR'S PROPOSAL)

Zone (examples)	Humidity regime	Preferred technology	Priority crops / uses
Coastal belts (Kerala, Konkan, coastal Andhra Pradesh and Tamil Nadu, West Bengal); North-East	High RH most of the year	Refrigerative AWG on solar PV; closed-loop polyhouses	Leafy greens, strawberry, orchids, anthurium, nurseries
Western Ghats, Nilgiris, NE hill stations	Frequent seasonal fog	Fog nets + storage; AWG as back-up	Nurseries, cut flowers, potato minitubers
Deccan plateau (Telangana, interior Karnataka, Maharashtra, Andhra Pradesh)	Humid in monsoon, dry in summer	Hybrid: AWG + sorbent AWH + rainwater tank; transpiration recapture	Fruit-crop nurseries, vegetable seedlings, high-value protected crops during El Niño years
Arid north-west (Thar, Kutch) and cold arid Ladakh	Very low RH	Sorbent AWH, dew condensers, sealed container farms only	Microgreens, herbs and seedlings for local markets and defence/remote stations

8.2 Sizing procedure

A simple sizing chain is recommended: (1) daily water requirement W ($L \text{ day}^{-1}$) = per-plant water use $\times$ number of plants, reduced by the recapture fraction in sealed structures; (2) derated generator output = rated $L \text{ day}^{-1} \times$ local RH/temperature derating factor taken from the manufacturer's performance curve; (3) daily energy E (kWh) = $W \times$ specific energy ($kWh \text{ L}^{-1}$) at local conditions; (4) PV capacity (kWp) $\approx E \div$ (peak sun hours $\times$ system efficiency). As an illustration only, a system needing $200 L \text{ day}^{-1}$ at $0.5 kWh \text{ L}^{-1}$ requires $100 kWh \text{ day}^{-1}$. With 5 peak sun hours and 75% system efficiency, this needs about 27 kWp of PV. The same requirement at $3 kWh \text{ L}^{-1}$ (dry air) would need about 160 kWp , which shows why humid zones, closed-loop recapture and low-demand crops are essential.

IX. ROLE UNDER EL NIÑO AND CLIMATE CHANGE

El Niño typically weakens the south-west monsoon, reducing rainfall for rainfed kharif crops and increasing heat stress and irrigation demand [3]. As warming intensifies the ENSO–monsoon link [4], horticulture will face sharper and more frequent supply shocks. Air-to-water systems will not replace the monsoon for field horticulture. They can, however, serve as climate-insurance infrastructure in three ways: (i) keeping nurseries and planting-material production running in drought years, which protects the next season's orchard and vegetable establishment; (ii) sustaining high-value protected crops (leafy greens, strawberry, flowers) near urban markets; and (iii) producing disease-free seed potato and propagules in aeroponic/fogponic units. Because AWG output rises with humidity, these systems also complement rather than compete with rainwater harvesting. Tanks fill during monsoon surpluses, and AWGs add water during humid but rain-deficient spells, which are common in El Niño monsoons.

X. CONSTRAINTS AND CRITICAL APPRAISAL

- **Energy and cost:** $0.02\text{--}3.64 kWh \text{ L}^{-1}$ depending on humidity [6] and levelized costs of US\$ $0.09\text{--}0.40 \text{ L}^{-1}$ [9] restrict the approach to high-value, small-area systems.
- **Low output in hot, dry periods:** in Indian summers the demand for water peaks just when AWG output is lowest. Sorbent systems and night-time operation only partly mitigate this.
- **Capital and maintenance:** compressors, fans, filters, ultrasonic discs and sensors need skilled maintenance that is scarce in rural areas.
- **Water quality and hygiene:** condensate lacks minerals and can carry airborne contaminants. Warm tanks risk biofilm and Legionella, so filtration, UV/ozone and complete fertigation are mandatory.
- **Evidence gaps:** few replicated trials exist on Indian cultivars, and no long-term economic or life-cycle assessments for condensate-fed horticulture were found.

- **Terminology:** "zero watering" should be communicated as zero irrigation from surface or groundwater. The system still consumes water from the air and significant energy.

XI. RESEARCH AND POLICY ROADMAP

TABLE 5
RESEARCH AND POLICY PRIORITIES

Horizon	Research priorities	Policy and extension
Short term (1–3 years)	Replicated trials of condensate-fed leafy vegetables, strawberry and fruit nurseries in coastal, Deccan and arid zones; cultivar-specific EC/pH and fog-cycle protocols; humidity-mapping for AWG suitability	Pilot units at horticultural universities and KVKs; inclusion of solar AWG–fogponic units under protected-cultivation subsidies
Medium term (3–5 years)	Hybrid AWG–sorbent systems; transpiration-recapture greenhouses; AI scheduling for peak-humidity operation; life-cycle and economic analyses	Bundling with agrivoltaics and PM-KUSUM solar schemes; farmer-producer-organization-run nursery hubs
Long term (> 5 years)	Low-cost MOF/hydrogel sorbents made in India; drought-resilient nursery networks; integration with El Niño early-warning systems	National standards for condensate quality in horticulture; El Niño contingency plans that include protected nursery capacity

XII. CONCLUSION

Air-to-water condensation farming and fogponics together offer a technically proven way to grow selected horticultural crops without drawing on rainfall, rivers or groundwater. Crop-level evidence confirms that atmospheric water can sustain leafy vegetables, that fog collection can feed greenhouse hydroponics, and that aeroponic seed-potato production is commercially established in India. The decisive constraint is energy per litre, which depends strongly on humidity. Current deployment is therefore rational mainly for nurseries, propagation, seed potato, leafy greens, strawberry and flowers in humid or foggy zones, and as climate-insurance infrastructure during El Niño years. With closed-loop recapture, solar integration, India-specific trials and supportive policy, "zero-watering" protected horticulture can become a practical part of India's adaptation to declining water availability and a strengthening El Niño threat.

ACKNOWLEDGEMENT

The author thanks Sri Konda Laxman Telangana Horticultural University for institutional support.

CONFLICT OF INTEREST

The author declares no conflict of interest.

REFERENCES

- [1] Ministry of Agriculture & Farmers Welfare, Government of India. (2025). *Area and production of horticulture crops for 2024–25 (3rd Advance Estimates)*. Department of Agriculture & Farmers Welfare. <https://agriwelfare.gov.in/en/StatHortEst>
- [2] Press Information Bureau, Ministry of Jal Shakti, Government of India. (2024). *Per capita water availability*. <https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=2002726>
- [3] USDA Foreign Agricultural Service. (2026). *Monsoon advances amid emerging El Niño concerns* (GAIN Report IN2026-0038, Mumbai, 25 June 2026).
- [4] Zhao, Y., Wang, T., Xu, C., Li, X., Piao, S., & Yao, T. (2026). Greenhouse warming exacerbates El Niño-induced Indian monsoon droughts. *Nature Communications*. <https://doi.org/10.1038/s41467-026-76049-7>
- [5] Suganob, N. J., Arroyo, C. L., & Concepcion II, R. (2024). Interplay of fogponics and artificial intelligence for potential application in controlled space farming. *AgriEngineering*, 6(3), 2144–2166. <https://doi.org/10.3390/agriengineering6030126>
- [6] Mohammed, M. S., et al. (2026). Atmospheric water harvesting: A comprehensive review of techniques, innovations, systems, and future prospects. *ScienceDirect (Elsevier)*. <https://www.sciencedirect.com/science/article/pii/S2949821X26002218>
- [7] Beithou, N., et al. Atmospheric water harvesting technology: Review and future prospects. *Journal of Ecological Engineering*. <https://www.jeeng.net/pdf-182814-104417>

- [8] Yang, K., Pan, T., Farhat, N., Ibarra Felix, A., Waller, R. E., Hong, P.-Y., Vrouwenvellder, J. S., Gan, Q., & Han, Y. (2024). Stand-alone, maintenance-free solar-driven atmospheric water extraction for off-grid irrigation. *Nature Communications*, 15, 6260. <https://doi.org/10.1038/s41467-024-50715-0>
- [9] Gayoso, N., Moylan, E., Noha, W., Wang, J., & Mulchandani, A. (2024). Techno-economic analysis of atmospheric water harvesting in arid, temperate, and tropical climates. *ACS ES&T Engineering*, 4. <https://doi.org/10.1021/acsestengg.4c00098>
- [10] Zhou, Z., Zhang, J., Liao, Y., Li, X., Pei, X., Zhou, L., & Xiao, H. (2025). Atmospheric water irrigation and plant growth promotion in sandy soil by polyacrylamide–chitosan–CaCl₂ aerogels. *Journal of Environmental Management*. <https://www.sciencedirect.com/science/article/abs/pii/S030147972502924X>
- [11] Zhou, X., et al. (2020). Super moisture absorbent gels for sustainable agriculture via atmospheric water irrigation. *ACS Materials Letters*, 2(11), 1419–1422. <https://pubs.acs.org/doi/10.1021/acsmaterialslett.0c00439>
- [12] Albornoz, F., del Río, C., Carter, V., Escobar, R., & Vásquez, L. (2023). Fog water collection for local greenhouse vegetable production in the Atacama Desert. *Sustainability*, 15(22), 15720. <https://www.mdpi.com/2071-1050/15/22/15720>
- [13] Frontiers. (2025, February 20). *Fog harvesting could provide water for drinking and agriculture in the world's driest regions*. <https://www.frontiersin.org/news/2025/02/20/fog-harvesting-water-drinking-agriculture-worlds-driest-regions>
- [14] Li, H. J., et al. (2023). Potential analysis of atmospheric water harvesting. *Water*, 15(5), 878. <https://www.mdpi.com/2073-4441/15/5/878>
- [15] da Silva Filho, J. B., et al. (2020). Yield of potato minitubers under aeroponics, optimized for nozzle type and spray direction. *HortScience*, 55(1), 14–22. <http://journals.ashs.org/view/journals/hortsci/55/1/article-p14.xml>
- [16] NITI Aayog Frontier Technologies. *Hi-tech tissue culture and aeroponics are modernising the foundation of India's potato economy*. <https://frontiertech.niti.gov.in/story/hi-tech-tissue-culture-and-aeroponics-are-modernising-the-foundation-of-indias-potato-economy/>
- [17] Agrinnovate India. *ICAR–CPRI aeroponic technology*. <https://www.agrinnovateindia.com/icar-cpri-aeroponic-technology.html>
- [18] Li, Q., Li, X., Tang, B., & Gu, M. (2018). Growth responses and root characteristics of lettuce grown in aeroponics, hydroponics, and substrate culture. *Horticulturae*, 4(4), 35. <https://www.mdpi.com/2311-7524/4/4/35>
- [19] Dry-fog application in protected strawberry cultivation. *Acta Horticulturae*, 1176. International Society for Horticultural Science. https://ishs.org/ishs-article/1176_6/

Indian Pomegranate Exports: Production, Residue Compliance, Quality and Market Constraints

Durgesh Kailas Narwade^{1*}; B V Deore²; Y S Saindane³; S A Hiray⁴; P E More⁵; S B Deore⁶

¹Department of Entomology, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra-413-722, India

²All India Network Project on Pesticide Residues and Contaminants, Department of Entomology, MPKV, Rahuri, Ahilyanagar, Maharashtra- 413-722, India

³AICRP on Forage Crops, Mahatma Phule Krishi Vidyapeeth Rahuri, Ahilyanagar, Maharashtra- 413-722, India.

⁴Pomegranate Research & Technology Transfer Center Lakhmapur, Malegaon, Maharashtra- 423-213, India.

⁵AICRP on Arid Zone Fruit, Department of Horticulture, Mahatma Phule Krishi Vidyapeeth Rahuri, Ahilyanagar, Maharashtra- 413-722, India.

⁶Department of Horticulture, Mahatma Phule Krishi Vidyapeeth, Rahuri, Ahilyanagar, Maharashtra-413-722, India

*Corresponding Author

Received:- 16 September 2026/ Revised:- 28 September 2026/ Accepted:- 07 October 2026/ Published: 15-10-2026

Copyright @ 2026 International Journal of Environmental and Agriculture Research

This is an Open-Access article distributed under the terms of the Creative Commons Attribution

Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted

Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— India is a major producer of pomegranate, yet only a small proportion of its production enters international markets, indicating a persistent gap between production capacity and export performance. This review synthesizes evidence on the production, fruit quality, pesticide use, residue, post-harvest, phytosanitary, and market factors that shape the exportability of Indian pomegranate. India produced about 3.16 million tonnes of pomegranate in 2022-23, while only around 2.5% was exported, despite substantial growth in export value over the past decade. The review shows that export constraints begin at the farm level, where pest and disease pressure and frequent pesticide application can affect fruit quality and compliance with residue requirements, while inadequate farm-level documentation can limit traceability. Residue studies from India demonstrate considerable variation among regions and sampling periods, with both compliant samples and samples exceeding applicable MRLs reported. Importantly, regulatory compliance with MRLs and dietary-health risk are distinct considerations and should not be interpreted interchangeably. Beyond production, inadequate pre-cooling, grading, packhouse capacity, integrated cold chains and processing infrastructure can reduce the quality achieved in the orchard, particularly for highly perishable arils. Market access is further influenced by destination-specific sanitary and phytosanitary requirements, certification, traceability, labelling, tariffs and other non-tariff measures. Exports remain concentrated in regional markets, whereas substantially higher price realizations have been reported for selected high-value destinations. The evidence indicates that increasing exports therefore requires a coordinated value-chain approach rather than greater production alone. Priority areas include export-oriented crop protection, residue-compliant production, farm-level traceability, cluster-based post-harvest infrastructure, value addition, market diversification and stronger alignment between production systems and destination-market requirements.

Keywords— Export competitiveness; Pesticide residues; Maximum residue limits; Traceability; Post-harvest management.

I. INTRODUCTION

Pomegranate (*Punica granatum* L.) is an important fruit crop of arid and semi-arid regions and has become an economically important horticultural commodity in India. The crop is valued for its nutritional properties, attractive fruit characteristics, and growing demand in domestic and international markets. India has a diverse range of pomegranate cultivars, although only a limited number are cultivated commercially. Among them, Bhagwa has emerged as an important commercial and export variety

because of its attractive rind and aril colour, sweetness, good keeping quality, and high yield (Prasad et al., 2013; Saroj and Sharma, 2017). Pomegranate cultivation is concentrated mainly in Maharashtra, Karnataka, Gujarat, and Andhra Pradesh, with Maharashtra being the leading producing state. India also has an important advantage in terms of fruit availability, as pomegranate can be produced throughout the year, while several competing countries have more restricted production seasons (Kahramanoglu, 2019).

Despite this production strength, only a small proportion of Indian pomegranate reaches international markets. In TE 2022-23, India produced about 3.16 million metric tonnes of pomegranate, while only about 2.5 per cent of the production was exported (Rao et al., 2026). Indian pomegranate exports have increased substantially over the years, with export value rising from USD 15.57 million in 2010-11 to USD 69.08 million in 2023-24 (Rao et al., 2026). However, a large share of exports continues to be directed towards a limited number of markets, particularly the United Arab Emirates, Bangladesh and Nepal (Rao et al., 2026). This difference between the scale of production and the quantity entering international trade raises an important question: why has India not been able to convert its large production base into a much larger and more diversified export presence?

Export performance in fresh fruit depends on more than production volume. Fruit intended for international markets must meet specific requirements related to size, colour, appearance, surface quality, variety, shelf life, and absence of pests and diseases. In pomegranate, these characteristics can be influenced by cultivar, agro-climatic conditions, nutrient and water management, pest and disease pressure, and harvesting practices. A diverse insect and non-insect pest complex has been reported on pomegranate, and damage caused by these pests can reduce yield, fruit quality, and marketability (Kulkarni et al., 2007; Balikai et al., 2011; Balikai et al., 2022). Diseases such as bacterial blight, wilt, anthracnose, and fruit rots also affect production and fruit quality, with bacterial blight being one of the major constraints in Indian pomegranate production (Doddaraju et al., 2019; Sharma et al., 2021). Recent assessments of the export sector have also identified fruit size, colour variation, bacterial blight, and varietal inconsistency among the factors that can reduce export readiness (Rao et al., 2026).

Crop protection practices are closely related to the quality and safety requirements of export-oriented production. Because pomegranate is affected by a diverse pest and disease complex, chemical pesticides remain an important component of crop protection in commercial orchards. Studies have reported considerable dependence on synthetic pesticides and frequent pesticide applications. In some production systems, spraying has been largely calendar-based rather than based on actual pest incidence (Elango and Sridharan, 2017). In addition, deficiencies in farmer awareness regarding pesticide residues, maximum residue limits (MRLs), pre-harvest intervals (PHIs), recommended dosages, and safe pesticide use have been reported in several agricultural production systems (Anbazhagan et al., 2022; Kumar et al., 2023; Prasad et al., 2023; Vallur et al., 2023). These practices are relevant to export production because decisions regarding pesticide selection, application rate, and timing are made at the farm level, whereas the harvested fruit must satisfy the residue requirements of the destination market.

Pesticide residues have consequently become an important consideration in the export of pomegranate. Residue-monitoring studies conducted in India have detected several insecticides and fungicides in pomegranate fruit, with considerable variation among regions, seasons and sampling sources. An early large-scale study of export-oriented pomegranate from Maharashtra and Karnataka detected residues belonging to several pesticide groups, and a proportion of the samples exceeded European Union MRLs (Kolekar et al., 2011). Subsequent studies have also reported pesticide residues in pomegranate from different parts of India (Kottadiyil et al., 2023; Aralimarad et al., 2024). These findings need to be interpreted carefully because the detection of a residue does not by itself indicate a dietary health risk. However, residues exceeding the MRL applicable to a particular pesticide-commodity combination can create a regulatory and commercial problem, particularly when the produce is intended for export markets (Dureja et al., 2015; Ambrus and Yang, 2016).

The issue becomes more important because residue standards and other regulatory requirements differ among importing countries. Pomegranate intended for export may therefore need to comply with requirements related to pesticide residues, phytosanitary measures, certification, traceability, labelling and food safety. Differences among Indian, Codex, and European Union requirements can influence pesticide selection, spray schedules, and PHI management in export-oriented orchards (Dureja et al., 2015; Ambrus and Yang, 2016; Pasupuleti et al., 2022). Residue studies have also shown that pesticide persistence in pomegranate varies with the pesticide used, dose, environmental conditions, and fruit characteristics, making crop-specific residue and dissipation information important for determining appropriate PHIs and maintaining residue compliance (Hem et al., 2010; Mohapatra and Lekha, 2016; Parmar et al., 2025).

The constraints to export do not end at the farm. Pomegranate is a perishable commodity and requires proper harvesting, grading, packing, storage, and transportation to retain its quality. Inadequate primary grading and collection facilities, limited pre-cooling and cold-storage infrastructure, fragmented cold-chain systems, and insufficient processing facilities can contribute to quality deterioration and post-harvest losses. These limitations are particularly important for minimally processed arils, which require rapid cooling and continuous temperature control. The development of cluster-based facilities, improved packhouses, cold-chain systems, traceability, and processing infrastructure has therefore been identified as important for strengthening the efficiency of the Indian pomegranate export value chain (Gulati et al., 2022). Market access also depends on sanitary and phytosanitary requirements, certification, traceability, labelling and other non-tariff measures. Countries such as those in the European Union and other high-value markets may impose stringent requirements related to pesticide residues, pests and diseases, and product certification. Compliance with these requirements can increase the cost and complexity of exporting fresh fruit, particularly for small and fragmented producers. Thus, export competitiveness depends on the ability to produce fruit that consistently meets the required quality and safety standards and to maintain these standards through the subsequent stages of the supply chain.

The available literature on Indian pomegranate is distributed across different areas, including production, pest and disease management, pesticide use, residue monitoring, food safety, post-harvest handling and international trade. However, these aspects have largely been examined separately. Bringing them together is important for understanding the gap between India's production potential and its export performance. In particular, farm-level crop protection practices, residue compliance, fruit quality, post-harvest handling and market-access requirements are interconnected parts of the same export chain rather than isolated issues.

The present review therefore examines the major factors influencing the export of Indian pomegranate, with particular emphasis on production and fruit-quality constraints, crop-protection practices and pesticide-residue compliance, post-harvest and value-chain limitations, phytosanitary and other market-access requirements, and the opportunities available for expanding India's presence in international markets. The review aims to bring these aspects together to identify the major points at which constraints arise and to discuss how improvements across the production-to-export chain could contribute to more consistent and competitive Indian pomegranate exports.

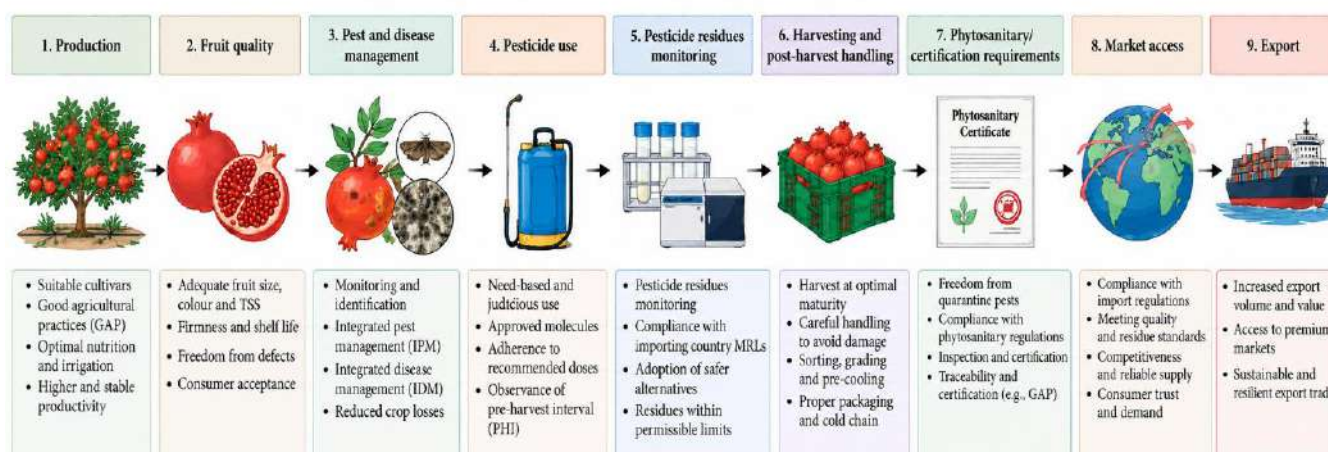


FIGURE 1: Conceptual framework of the major factors influencing the exportability of Indian pomegranate, from production and fruit quality through crop protection, pesticide-residue compliance, post-harvest handling, phytosanitary requirements, market access and export.

II. POMEGRANATE PRODUCTION AND EXPORT POSITION OF INDIA

India is among the major pomegranate-producing countries in the world. The crop is cultivated mainly in Maharashtra, Karnataka, Gujarat, and Andhra Pradesh, with Maharashtra accounting for the largest share of the country's production. The expansion of pomegranate cultivation in India has been associated with an increase in both cultivated area and productivity, particularly following the wider adoption of commercially preferred cultivars such as Bhagwa. The increase in production has also been supported by the suitability of pomegranate to arid and semi-arid agro-climatic conditions and by its relatively high economic returns compared with several other horticultural crops (Prasad et al., 2013; Saroj and Sharma, 2017).

According to Rao et al. (2026), India produced approximately 3.16 million metric tonnes of pomegranate in 2022-23 from about 0.3 million hectares of cultivated area. However, only about 2.5 per cent of the total production entered export markets. More recent production estimates reported by Rao et al. (2026) indicate continued growth in the country's pomegranate production, with approximately 2.9 million metric tonnes produced during 2023-24. Maharashtra remained the leading producing state, accounting for more than half of the country's production, followed by Gujarat, Karnataka, Rajasthan and Andhra Pradesh (Rao et al., 2026). The continued expansion of production indicates that availability of fruit is not, by itself, the major limitation to increasing exports.

Pomegranate also offers India an important seasonal advantage in international trade. Production in Maharashtra and Gujarat extends across the year, while several competing countries have more restricted harvesting periods. This provides an opportunity for India to supply international markets during periods when fruit availability from some other producing countries is relatively low (Kahramanoglu, 2019). The Bhagwa cultivar further strengthens this opportunity because of its attractive rind and aril colour, sweetness, keeping quality, and consumer acceptance. Bhagwa has therefore become the principal cultivar associated with Indian pomegranate exports, while cultivars such as Ganesh, Phule Arakta, Ruby and Mridula contribute to production and are exported to a more limited extent (Prasad et al., 2013; Saroj and Sharma, 2017).

Despite these advantages, the growth in production has not been accompanied by a proportionate increase in exports. Indian pomegranate export value increased from approximately USD 15.57 million in 2010-11 to USD 69.08 million in 2023-24, representing substantial growth over the period (Rao et al., 2026). However, the recent export trend has been less consistent than the earlier period of rapid expansion. The domestic market has remained an important destination for Indian pomegranate, and in some years, better domestic prices have reduced the incentive to send fruit to export markets (Rao et al., 2026). However, in recent years, heavy domestic supply has destabilized the market, and prices have dropped sharply. Thus, the export problem is not simply a question of producing more fruit; it also concerns the ability to consistently produce, handle, and market fruit that satisfies the requirements of international buyers as well as stabilize the domestic market.

Another important feature of India's export profile is the concentration of exports in a relatively small number of destinations. The United Arab Emirates, Bangladesh, and Nepal account for a substantial share of Indian pomegranate exports, while countries such as the Netherlands and Qatar also receive Indian fruit (Rao et al., 2026). This concentration provides established market channels for Indian producers but also indicates limited diversification into some high-value markets. Expanding into such markets requires fruit to meet more demanding requirements related to quality, residue compliance, traceability, phytosanitary measures, certification, and post-harvest handling.

Comparison with other producing countries also needs to be interpreted cautiously because internationally comparable pomegranate-specific trade data are limited. Pomegranates are included under the broader HS 081090 category in international trade statistics, together with several other fruits, making it difficult to obtain accurate country-wise comparisons of pomegranate exports and imports. Country-specific information is therefore often compiled from national statistical agencies and other sectoral sources rather than from a single internationally standardized database (Ergun, 2012).

The production-export gap therefore points to a broader issue in the Indian pomegranate sector. India possesses a substantial production base, a commercially established export cultivar, and a long production season, but these advantages do not automatically translate into access to all international markets. Fruit leaving the orchard must retain the required physical quality, comply with food-safety and residue standards, meet phytosanitary requirements, and remain commercially viable through packing, storage, and transportation. Therefore, the reasons for the limited conversion of production into exportable fruit need to be examined across the entire production and supply chain, not from the perspective of production volume alone.

This production-export gap forms the basis for examining the specific constraints affecting export readiness, beginning with fruit quality and crop protection at the farm level and extending to residue compliance, post-harvest handling, infrastructure and international market-access requirements.

III. PRODUCTION AND FRUIT QUALITY CONSTRAINTS AFFECTING EXPORTABILITY

The ability to export pomegranate depends first on the production of fruit that meets the physical and quality requirements of the target market. Although India has a strong production base and an established export cultivar in Bhagwa, differences in fruit size, colour, appearance, varietal consistency, and overall quality can reduce the proportion of fruit suitable for premium

export markets. Bhagwa is widely preferred because of its attractive rind and aril colour, sweetness, and good keeping quality, and it has gained strong acceptance in domestic as well as international markets (Prasad et al., 2013; Saroj and Sharma, 2017). However, the characteristics of fruit produced under different production conditions are not always uniform, which can affect their acceptance in demanding export markets.

Fruit size is one of the important quality attributes influencing export potential. The available assessment of the Indian pomegranate sector identified relatively small fruit size as a constraint, particularly in markets where larger fruits are preferred. Differences in fruit size can arise from cultivar characteristics as well as orchard management and growing conditions. The issue is particularly relevant for high-value markets where buyers often follow specific size and appearance specifications. Thus, increasing production without achieving the required fruit size may not substantially increase the quantity of fruit that can be marketed as premium export produce (Rao et al., 2026).

Colour and external appearance are also important because pomegranate is commonly marketed as a whole fresh fruit. The attractive rind colour and deep red arils of Bhagwa contribute to its market acceptance (Saroj and Sharma, 2017). However, colour development can be affected by growing conditions, particularly during periods of high temperature. Variation in colour, together with surface blemishes and other external defects, can reduce the market value of fruit even when the internal edible portion remains acceptable. Recent observations from the Indian export sector have identified summer colour variation and surface quality as important considerations for improving export-grade production (Rao et al., 2026).

Varietal consistency is another consideration for export-oriented production. Although Bhagwa has become the principal commercial and export cultivar, several other varieties are grown in different parts of the country. The characteristics of these cultivars differ in terms of fruit size, colour, seed softness, keeping quality, and other market-related traits (Prasad et al., 2013). Such variation can make it difficult to maintain a uniform supply when buyers require consistent fruit characteristics. The availability of suitable planting material and the development or selection of cultivars with desirable export attributes are therefore important for maintaining consistency in quality (Rao et al., 2026).

Pests and diseases add another layer to the quality problem. A diverse insect and non-insect pest complex has been reported on pomegranate, and infestation can affect different plant parts and reduce fruit yield, quality, and marketability (Kulkarni et al., 2007; Balikai et al., 2011; Balikai et al., 2022). Among diseases, bacterial blight caused by *Xanthomonas axonopodis* pv. *punicae* is considered one of the most destructive diseases of pomegranate in India, with severe outbreaks capable of causing substantial yield losses (Doddaraju et al., 2019). Other diseases, including wilt, anthracnose, fruit rots, Alternaria diseases, and Phytophthora-associated diseases, can also affect fruit production and quality (Sharma et al., 2021). Consequently, the production of export-grade fruit requires effective management of both insect pests and diseases throughout the crop season.

The relationship between pest management and export quality is particularly important because cosmetic damage can directly affect the marketability of fresh fruit. Insects that damage the rind or developing fruit may reduce the visual quality required by export markets. At the same time, the need to protect the crop from pests and diseases can increase dependence on pesticides. This creates an additional challenge for export-oriented production because crop protection measures must control the target problem without compromising residue compliance at harvest.

Production conditions can further influence the consistency of fruit quality. Pomegranate is cultivated across a range of agro-climatic regions in India, and differences in climate, orchard management, and cultivar performance contribute to variation in yield and fruit characteristics. Maharashtra remains the major production state, but differences in productivity among producing states indicate that there is further scope for improving production efficiency (Rao et al., 2026). The challenge for export-oriented production is therefore not simply to increase total production, but to improve the proportion of fruit that meets the required specifications of the intended market.

The available evidence suggests that production and quality constraints should be considered together with the requirements of the export market. Fruit that is produced in sufficient quantity but does not meet specifications for size, colour, appearance, disease freedom or consistency may have limited access to premium markets. This makes export-oriented production different from production aimed only at the domestic market. Improving the quantity of fruit suitable for export consequently requires attention to cultivar selection, orchard management, pest and disease management, and the maintenance of consistent quality from the field onwards.

IV. PESTICIDE USE PRACTICES AND THEIR IMPLICATIONS FOR EXPORT READINESS

Pesticide use is an important component of pomegranate production because the crop is affected by a wide range of insect pests and diseases that can reduce fruit yield and market quality. Studies from pomegranate-growing regions have reported the use of chemical insecticides for managing important pests, while the pattern of pesticide use is also influenced by farmers' access to technical information, local production practices, and advisory services (Chauhan and Gupta, 2024; Kambrekar et al., 2015a, 2015b). Thus, the way pesticides are selected and applied at the farm level has implications beyond pest control, particularly when the produce is intended for markets with strict food-safety requirements.

One of the important concerns reported in pomegranate cultivation is the continued use of calendar-based pesticide application rather than applications based on pest incidence. Elango and Sridharan (2017) reported that most pomegranate growers followed predetermined spray intervals, while only a small proportion based pesticide application on actual pest infestation. The same study indicated frequent insecticide applications during the cropping season. Such practices can increase the overall number of pesticide applications even when pest pressure does not justify repeated treatment. Field studies on important pomegranate pests have also demonstrated the continued role of insecticides in crop protection (Kambrekar et al., 2015a, 2015b), highlighting the need to integrate chemical control with more site-specific and need-based pest management.

The choice of pesticide is another important factor in export-oriented production. Farmers may obtain pesticide recommendations from different sources, including input dealers, farmer groups and extension agencies. Studies from different parts of India have shown that pesticide dealers often play an important role in farmers' decisions regarding product selection and application (Gaddanakeri et al., 2023; Ali et al., 2022; Vallur et al., 2023). At the same time, gaps in knowledge regarding pesticide residues, pre-harvest intervals (PHI), safe handling, and other aspects of pesticide use have been reported among farmers in several regions (Kumar et al., 2023; Prasad et al., 2023; Krishna et al., 2022). These observations are relevant to export production because farm-level pesticide decisions ultimately influence the chemical profile of harvested fruit.

The problem becomes more important when several pesticides are applied repeatedly or in combination. Farmers may also apply more than one pesticide in a single spray operation to address multiple pest and disease problems. Such practices require careful attention to label directions, compatibility, and dosage because inappropriate combinations can affect pesticide performance or cause unwanted effects. Repeated use of pesticides from limited chemical groups may also increase selection pressure on pest populations and contribute to resistance development. Therefore, effective export-oriented crop protection requires not simply a reduction in pesticide use, but more rational selection and application based on pest incidence, registered uses, recommended doses, and appropriate intervals.

From an export perspective, pesticide application must also be considered in relation to residue compliance and traceability. The recent assessment of the Indian pomegranate export sector identified pesticide compliance and traceability as important concerns raised by industry stakeholders. The report noted the need for stronger field-level documentation, residue management, and farmer-level capacity building to meet the requirements of high-value international markets (Rao et al., 2026). This indicates that export readiness begins at the production stage rather than only at the packhouse or export point.

The importance of this issue is also reflected in the limited awareness of residue-related requirements reported among pomegranate growers. In the Maharashtra survey, only 21.3 per cent of growers were aware of maximum residue limits (MRLs), while 78.7 per cent were unaware of them. Similarly, only a small proportion of growers reported using economic threshold level-based decisions for pesticide application, despite a relatively high proportion reporting use of recommended doses. These findings suggest that following the recommended dose alone does not necessarily ensure need-based pesticide application or compliance with residue requirements. The observations are consistent with earlier reports of gaps in farmers' knowledge regarding pesticide residues and PHI (Kumar et al., 2023; Prasad et al., 2023; Krishna et al., 2022).

Therefore, pesticide management in Indian pomegranate production needs to be viewed as a part of the export-quality system rather than solely as a pest-control practice. Appropriate pesticide selection, need-based application, adherence to PHI, proper record-keeping, and awareness of residue standards can help connect farm-level crop protection with the requirements of export markets. The relationship between pesticide use and export performance becomes particularly important because residues that remain within one regulatory system may not necessarily satisfy the requirements of another market. This provides the basis for examining pesticide residues and differences in MRL requirements as a separate factor influencing the international marketability of Indian pomegranates.

V. PESTICIDE RESIDUES AND MRL COMPLIANCE IN INDIAN POMEGRANATE

The presence of pesticide residues in harvested pomegranate has received increasing attention because residue compliance is closely linked with food safety and access to international markets. Pomegranate is produced under intensive crop-protection programmes, and residues may remain on or within the fruit depending on the pesticide used, application frequency, dose, and interval between the final application and harvest. Therefore, residue monitoring is an important part of assessing the suitability of pomegranate for markets where pesticide standards are strictly regulated (Kolekar et al., 2011; Kottadiyil et al., 2023; Aralimarad et al., 2024). Early monitoring studies in India indicated that residue compliance could be a significant concern in export-oriented pomegranate production. Kolekar et al. (2011) analysed 179 export-oriented samples collected from major pomegranate-growing areas of Maharashtra and Karnataka and screened them for 86 pesticide residues. About one-third of the samples had no detectable residues, while nearly half contained residues within the prescribed limits. However, approximately one-fifth of the samples exceeded the European Union MRLs, with the proportion of non-compliant samples increasing substantially between the two years of observation. Several fungicides, together with some organophosphate and neonicotinoid insecticides, contributed to the observed violations.

Findings from other Indian studies have also shown that residue occurrence varies considerably among production regions and sampling periods. Pujeri et al. (2011), while analysing only five composite samples from Bijapur, detected residues in four samples, with several pesticide concentrations exceeding the European Union MRLs. In contrast, a more recent market survey by Kottadiyil et al. (2023) reported that 88.8 per cent of the analysed pomegranate samples contained residues below the prescribed MRLs, although bifenthrin, fenvalerate and cypermethrin were frequently detected. Aralimarad et al. (2024) similarly detected several pesticide residues in pomegranate from Kalyana, Karnataka. Despite the occurrence of residues, their dietary risk assessment indicated that the detected concentrations did not result in significant acute or chronic health risks. These findings show that residue detection alone should not be interpreted as evidence of unacceptable consumer risk; the concentration of the residue and the applicable regulatory limit must also be considered. An important issue in export-oriented production is that MRLs are not necessarily identical across regulatory systems. Codex establishes international MRLs, while individual importing regions may apply their own regulatory requirements. In India, pesticide MRLs are prescribed by the Food Safety and Standards Authority of India (FSSAI), whereas the European Union follows its own harmonized regulatory framework. Consequently, a residue concentration that complies with one regulatory system may not necessarily comply with the requirements of an importing market (Ambrus and Yang, 2016; Dureja et al., 2015; Pasupuleti et al., 2022). Differences between Indian and European requirements have been specifically noted for certain pesticides in pomegranate, including carbendazim, creating additional challenges for export-oriented residue management (Mohapatra and Lekha, 2016).

This regulatory variation is particularly important for Indian pomegranate because export markets may impose stringent requirements on both pesticide residues and documentation of production practices. Recent stakeholder-based analysis of the Indian pomegranate export sector identified residue compliance and traceability as important concerns for exporters, particularly in relation to high-value markets. The same assessment highlighted the need for better field-level documentation, residue testing, and farmer training on Good Agricultural Practices and MRL management (Rao et al., 2026).

Thus, pesticide-residue compliance cannot be considered only as a post-harvest laboratory issue. It begins with pesticide selection at the farm level and is influenced by the choice of molecule, application frequency, dose, timing, and adherence to the pre-harvest interval. Regular monitoring of residues, together with proper farm records and awareness of the requirements of the intended export market, is therefore important for maintaining consistent compliance. The available literature indicates that residue occurrence in Indian pomegranate is well documented, but geographically broad and continuous monitoring remains necessary to understand changing residue patterns and their implications for export trade.

The residue issue also needs to be examined alongside the broader export chain. Even when fruit meets the required residue limits, export consignments must satisfy other quality, phytosanitary, traceability, and handling requirements. This indicates that residue compliance is one component of export readiness rather than an isolated factor, leading to the need to consider the analytical monitoring, regulatory standards and market-access requirements together.

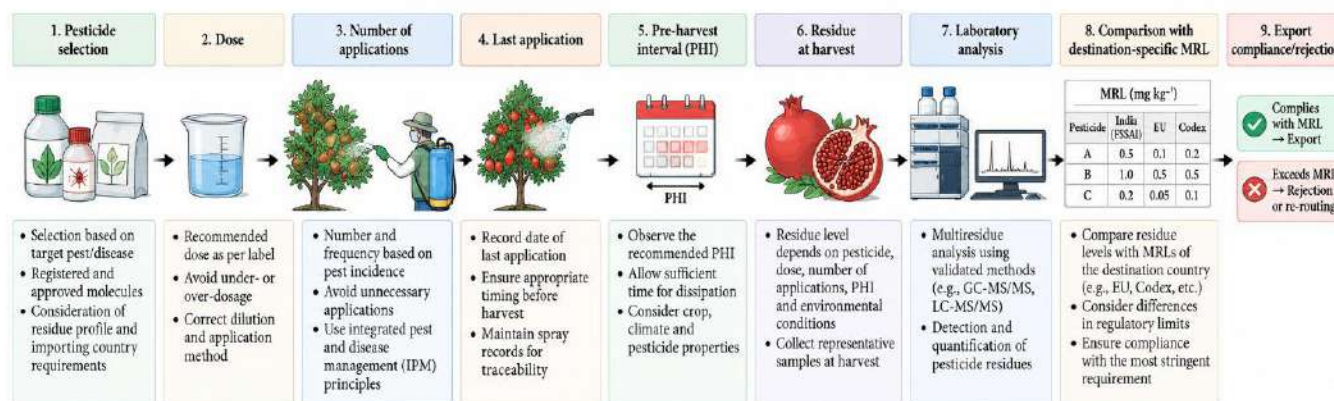


FIGURE 2: Pathway from farm-level pesticide use to residue monitoring, MRL compliance and export-market acceptance.

VI. ANALYTICAL APPROACHES FOR MONITORING PESTICIDE RESIDUES IN POMEGRANATE

Reliable residue monitoring depends on analytical methods capable of detecting a wide range of pesticides at low concentrations in a chemically complex fruit matrix. Pomegranate contains pigments, sugars, organic acids, and other matrix components that can interfere with extraction and instrumental determination. For this reason, residue analysis generally involves careful sample preparation followed by chromatographic separation and sensitive detection. The development of multiresidue methods has made it possible to examine several pesticide groups in a single analytical procedure, which is particularly useful for surveillance of commercially produced fruit (Banerjee et al., 2008; Satpathy et al., 2014).

The QuEChERS approach has become widely used for multiresidue analysis of fruits and vegetables because of its relatively simple extraction procedure, rapid processing and suitability for simultaneous determination of multiple compounds. The method generally involves homogenisation of the sample, extraction with acetonitrile, salt-assisted partitioning and subsequent clean-up, with modifications introduced where necessary to reduce matrix interference (Pszczolińska and Kociołek, 2022; Zhang et al., 2025). Its application to pomegranate has enabled the development of methods capable of detecting pesticides belonging to different chemical groups at concentrations relevant to regulatory monitoring.

Earlier analytical studies demonstrated the feasibility of multiresidue detection in pomegranate using gas chromatographic techniques. Banerjee et al. (2008) developed a method for the determination of 82 pesticides in pomegranate, apple and orange using ethyl acetate extraction, dispersive clean-up and liquid chromatography-tandem mass spectrometry. The method produced acceptable recoveries and reproducibility for most of the compounds examined. Savant et al. (2010) subsequently developed a GC-ion trap MS/MS method covering 50 pesticides in grapes, pomegranate and mango, demonstrating the capability of the approach to quantify residues at concentrations below relevant European Union MRLs.

With the increasing need to analyse pesticides having different physicochemical properties, both gas chromatography and liquid chromatography have become important complementary techniques. Satpathy et al. (2014) reported a QuEChERS-based GC-MS/MS method for simultaneous determination of 82 pesticides in grape and pomegranate. Other investigations have applied modified QuEChERS procedures with GC-MS or liquid chromatographic methods for specific pesticide groups in pomegranate (Mohapatra, 2014; Bilehal et al., 2014). These developments are important because no single instrumental platform is equally suitable for all pesticide classes.

More recent multiresidue analysis increasingly combines GC-MS/MS and LC-MS/MS to provide broader analytical coverage. Such approaches allow relatively non-polar and volatile compounds as well as polar and thermally less stable pesticides to be examined within the same monitoring programme. The importance of this combined approach is evident from recent pomegranate residue investigations in which large numbers of pesticides were screened using complementary chromatographic techniques (Kottadiyil et al., 2023; Aralimarad et al., 2024). Method validation is equally important because the analytical result forms the basis for judging whether a consignment complies with an applicable MRL. Validation generally considers parameters such as specificity, linearity, recovery, precision, matrix effects, and limits of detection and quantification. Validation against internationally accepted guidance, together with appropriate quality-control procedures, supports the reliability of residue results used for regulatory decision-making (Sharma et al., 2021).

The progress in analytical methodology has strengthened the ability to detect pesticide residues at trace concentrations, but analytical capacity alone cannot ensure export compliance. Sampling strategy, representativeness of the samples, selection of target pesticides and comparison with the correct regulatory standard are equally important. Differences in pesticide-use patterns between production regions can also result in different residue profiles. Therefore, continuous field and market surveillance using validated multiresidue methods is necessary to generate reliable information for residue management and to identify potential compliance problems before fruit enters export channels (Kolekar et al., 2011; Kottadiyil et al., 2023). Taken together, the literature shows that considerable progress has been made in the analytical detection of pesticide residues in pomegranate. The remaining challenge is to connect this analytical information with farm-level pesticide practices, regulatory requirements and export-market surveillance. Such integration is essential because the objective of residue analysis in an export system is not merely to detect chemicals, but to provide dependable evidence that the harvested fruit meets the requirements of the intended market.

VII. DIETARY RISK ASSESSMENT OF PESTICIDE RESIDUES: FOOD SAFETY AND EXPORT COMPLIANCE

The detection of pesticide residues in pomegranate does not by itself indicate an unacceptable risk to consumers. The significance of a detected residue depends on its concentration, the amount of fruit consumed, the toxicological reference value of the pesticide and the population group considered. Dietary risk assessment therefore provides a different perspective from MRL compliance, as it estimates the potential exposure of consumers under specified consumption conditions (Aralimarad et al., 2024; Parmar et al., 2025).

Recent studies on pomegranate have used approaches such as Estimated Daily Intake (EDI), Estimated Short-Term Intake (ESTI), Hazard Quotient (HQ) and Hazard Index (HI) to assess chronic, acute and cumulative dietary exposure. Aralimarad et al. (2024) reported that although pesticide residues were detected in pomegranate samples from Kalyana Karnataka, the estimated hazard quotient and hazard index values remained below one, indicating that the exposures considered in that assessment were below the corresponding toxicological reference values. Similar findings have been reported by Parmar et al. (2025), where residue occurrence and regulatory exceedance did not necessarily translate into a corresponding increase in estimated dietary risk.

The distinction between residue compliance and dietary risk is particularly important for export-oriented pomegranate production. An MRL is a regulatory limit established for a specific pesticide and commodity under a particular regulatory system, whereas an HQ or HI compares estimated dietary exposure with a toxicological reference value. Therefore, a sample may exceed the MRL established by an importing country even when the estimated dietary exposure remains below the relevant toxicological reference value. Conversely, compliance with an MRL should not be interpreted as evidence that residue monitoring is unnecessary, because the MRL primarily serves a regulatory and food-production control function (Ambrus and Yang, 2016; Dureja et al., 2015; Pasupuleti et al., 2022).

This distinction becomes more relevant when multiple pesticide residues occur in the same fruit sample. Multi-residue occurrence has been reported in pomegranate monitoring studies, with different pesticides occurring simultaneously in individual samples (Kolekar et al., 2011; Kottadiyil et al., 2023). Such findings indicate that assessment based on a single pesticide may not fully describe overall exposure, particularly where several compounds are detected in the same commodity. The use of cumulative indices such as the Hazard Index provides one approach for examining combined exposure under defined assumptions.

These findings should nevertheless be interpreted within the limitations of dietary risk assessment. The calculated exposure depends on the residue concentrations measured in the sampled fruit, the consumption assumptions, body weight and the toxicological reference values used. Consequently, results from one region or sampling period cannot automatically be generalized to all pomegranate-producing areas. Continuous monitoring and periodic reassessment are therefore necessary, particularly when pesticide-use patterns and residue profiles change over time.

From an export perspective, the practical importance of dietary risk assessment lies in its ability to complement, rather than replace, regulatory residue monitoring. Export markets may impose specific MRL requirements, documentation procedures and testing arrangements irrespective of whether a measured residue concentration represents a significant dietary risk. Recent analysis of the Indian pomegranate export sector has therefore emphasized the need to strengthen residue management and field-level compliance in order to satisfy demanding international markets (Rao et al., 2026).

Overall, the available evidence indicates that the presence of pesticide residues and the assessment of consumer dietary risk are related but distinct aspects of pomegranate safety. For India to supply a wider range of international markets, residue management must address both consumer protection and compliance with the regulatory requirements of the destination country. This brings the discussion beyond pesticide residues alone to the wider phytosanitary, certification, traceability and market-access requirements that determine whether produce can successfully enter international markets.

VIII. POST-HARVEST MANAGEMENT, COLD CHAIN AND VALUE-CHAIN CONSTRAINTS

Meeting pesticide and quality requirements at the farm level does not by itself ensure that pomegranate reaches the international market in acceptable condition. After harvest, the fruit passes through several stages involving collection, transportation, cleaning, sorting, grading, packing and storage. Weaknesses at any of these stages can result in physical damage, moisture loss, deterioration in appearance and reduction in shelf life. Therefore, post-harvest handling is an important link between production quality and export quality.

Pomegranate requires careful harvesting and handling because damaged or diseased fruits are generally unsuitable for export. In the export value chain described for Indian pomegranate, fruits are manually harvested and transported in crates to registered packing houses, where they undergo quality inspection, cleaning, sorting and grading. Fruits are then classified according to characteristics such as size, weight, colour and external appearance before packing. Traceability information associated with the farm, plot, packing house and harvest or packing date is also maintained in export-oriented systems.

A major limitation in the present value chain is the inadequate availability of post-harvest infrastructure close to production areas. The recent assessment of the Indian pomegranate sector identified insufficient pre-cooling, grading and washing facilities at the farm or cluster level, along with inadequate cold storage and integrated cold-chain infrastructure. Sorting and grading are still largely manual in many parts of the chain. These limitations can increase the time between harvest and proper handling and may contribute to quality deterioration before the fruit reaches export facilities (Rao et al., 2026).

The lack of coordinated collection and processing infrastructure is another important issue. Production is often connected to markets through pre-harvest contractors or village-level aggregators, while primary grading and packing facilities are not uniformly distributed across production clusters. The 2026 export-sector assessment identified the absence of adequate primary grading and collection centres, limited warehousing and cold-storage capacity, and gaps in transportation and marketing infrastructure as important constraints in the domestic value chain (Rao et al., 2026).

Cold-chain management becomes even more critical when pomegranate is processed into arils. Unlike whole fruit, arils are highly perishable and require rapid cooling and controlled-temperature handling. The export assessment reported that the processing and export of arils require continuous cold-chain facilities from the point of processing through international transport. Limited access to suitable processing, pre-cooling and refrigerated infrastructure can therefore restrict the expansion of this higher-value segment (Gulati et al., 2022; Rao et al., 2026).

The development of value-added products nevertheless provides an additional avenue for improving the utilization of pomegranate production. Arils, juice and other processed products can provide alternatives to dependence on fresh whole-fruit exports. However, value addition also introduces additional requirements related to hygiene, temperature control, packaging and traceability. The sector therefore needs infrastructure that can maintain product quality consistently from production clusters to processing and export points (Gulati et al., 2022; Rao et al., 2026).

Taken together, the available evidence suggests that post-harvest limitations are not simply issues of storage or transportation; they affect the ability to preserve the quality achieved in the orchard. A fruit meeting export specifications at harvest may still lose market value through rough handling, delayed cooling, inadequate grading or breaks in the cold chain. Strengthening packhouse facilities, pre-cooling, refrigerated transport, cluster-level processing and traceability can therefore help connect farm-level production with export-market requirements.

Thus, the relatively small share of Indian pomegranate entering international markets needs to be understood in the context of the entire value chain. Production volume alone does not determine export performance; the ability to consistently preserve quality, document production practices and deliver the fruit in suitable condition is equally important.

IX. PHYTOSANITARY REQUIREMENTS, CERTIFICATION AND MARKET-ACCESS BARRIERS

Even when pomegranate fruit satisfies the required physical and residue standards, entry into an international market depends on compliance with the phytosanitary and import regulations of the destination country. These requirements are intended to reduce the risk of introducing pests and diseases and to ensure that imported produce meets specified safety and quality conditions. For Indian pomegranate, such requirements can become an important barrier when production, documentation, treatment and inspection systems are not sufficiently aligned with those of the importing market (Rao et al., 2026).

Sanitary and phytosanitary (SPS) measures are particularly important for fresh fruit because importing countries may examine both pesticide residues and the possible introduction of economically important pests and diseases. The recent assessment of Indian pomegranate exports reported that stringent SPS requirements in markets such as the European Union and the United States include controls related to pesticide residues, pests and diseases. Non-compliance may result in delays, additional inspection or rejection of consignments (Rao et al., 2026).

Phytosanitary procedures can also differ substantially among destination countries. The recent export assessment highlighted continuing market-access requirements associated with pest-risk analysis, pest-free areas and other phytosanitary conditions for markets including China, Indonesia, Russia and Japan. Such requirements mean that market access depends not only on the quality of the fruit itself but also on whether the exporting country can demonstrate compliance with the specific pest-management and certification conditions established by the importing country (Rao et al., 2026).

Certification is another component of export readiness. Good Agricultural Practices (GAP) provide a framework covering production practices, food safety and other aspects of responsible agricultural production. Certification can therefore provide evidence that the crop has been produced and handled according to defined requirements. However, the cost and technical requirements associated with certification may create difficulties for small and fragmented growers, particularly when access to higher-value markets depends on documented compliance (Rao et al., 2026).

Traceability is closely connected with certification and phytosanitary compliance. Export-oriented supply chains require information that can link the harvested produce with its production and handling history. The recent assessment identified farm-level documentation and traceability as important areas for improvement in Indian pomegranate production, particularly in relation to pesticide management and export-market compliance (Rao et al., 2026).

Packaging and labelling requirements add another layer of compliance. Export markets may prescribe specific information regarding product origin, packaging and other characteristics, while environmental requirements associated with packaging materials can further increase the cost and complexity of export operations. These requirements become more demanding as exporters attempt to enter high-value markets with more detailed quality and traceability expectations (Rao et al., 2026).

The combination of phytosanitary requirements, residue standards, certification, labelling and tariffs therefore creates a broader market-access challenge than any single technical requirement. The 2026 assessment noted that Indian pomegranate exports remain concentrated in a limited number of neighbouring markets, while entry into several higher-value destinations is affected by regulatory and other trade barriers (Rao et al., 2026).

Importantly, these barriers operate across different stages of the supply chain. Farm-level pesticide and pest-management practices influence residue and phytosanitary compliance; packing houses are involved in inspection, grading and documentation; and exporters must coordinate testing, certification, transport and destination-specific requirements. Consequently, strengthening market access requires coordination between growers, producer organisations, packhouses, laboratories, exporters and regulatory agencies rather than addressing each requirement independently (Rao et al., 2026).

Overall, the literature indicates that India's limited export presence cannot be explained only by production or fruit availability. Compliance with destination-specific phytosanitary and certification requirements is an additional stage between producing export-quality fruit and successfully entering the international market.

X. EXPORT DESTINATIONS, MARKET CONCENTRATION AND INTERNATIONAL COMPETITIVENESS

The export performance of Indian pomegranate shows an important difference between the availability of fruit for export and the markets in which that fruit is actually sold. Although India has developed a substantial export trade over the past decade, exports remain concentrated in a limited number of destinations. This concentration is important because different markets offer different levels of price realization and impose different quality, safety and phytosanitary requirements (Rao et al., 2026).

India's pomegranate exports increased from USD 15.57 million in 2010-11 to USD 69.08 million in 2023–24, corresponding to an average annual growth rate of 16.3 per cent over the period. However, export growth slowed during the later years, and the volume exported in 2022–23 declined as the domestic market offered attractive prices to producers. This suggests that the domestic market can compete with exports for available fruit, particularly when international markets involve greater compliance and logistical costs (Rao et al., 2026).

The geographical distribution of exports further illustrates this pattern. During the period reported by the export analysis, the UAE, Bangladesh, Nepal, the Netherlands and Qatar accounted for major shares of India's pomegranate exports, with the UAE and Bangladesh together representing a substantial proportion of export volume. These destinations have helped India develop and maintain export volumes, but the distribution also indicates considerable dependence on a relatively small group of markets (Rao et al., 2026).

At the same time, substantial differences exist in the price realized across destination markets. The country-wise export data for 2023–24 reported realizations of about INR 702 per kg in Switzerland and INR 628 per kg in the United States, compared with approximately INR 126 per kg in the UAE, INR 47 per kg in Nepal and INR 32 per kg in Bangladesh. These differences indicate that destination choice is associated with markedly different levels of value realization, although the higher-priced markets also require compliance with more demanding quality, safety, certification and phytosanitary conditions (Rao et al., 2026).

The present export structure therefore reflects two distinct market segments for Indian pomegranate. Neighbouring and regional markets provide an established outlet for larger export volumes, supported partly by geographical proximity and relatively shorter supply chains. In contrast, distant high-value markets require greater attention to fruit quality, residue compliance, certification, traceability, cold-chain management and destination-specific phytosanitary conditions. The recent export assessment suggests that strengthening these capabilities could support greater participation in high-value markets while retaining existing regional destinations as part of the export base (Rao et al., 2026).

India also shows evidence of international competitiveness in pomegranate exports. The recent ICRIER–APEDA assessment reported a Revealed Comparative Advantage (RCA) greater than one and identified a competitive price position for India. However, the same analysis noted that trade remains constrained by non-tariff measures, including SPS and labelling requirements, tariff disadvantages in some markets and limited product differentiation and branding (Rao et al., 2026). Thus, production capacity and comparative advantage do not automatically result in broad international market penetration.

Another difficulty in assessing the global position of pomegranate is the availability of reliable trade statistics. At the international level, pomegranate is included under the broader HS code 081090, which also covers several other fruits. This prevents direct separation of pomegranate from all commodities classified under the same code and makes detailed country-wise comparison of global pomegranate trade more difficult (Ergun, 2012; Rao et al., 2026).

Market diversification therefore appears closely connected with the broader quality and compliance issues discussed in earlier sections. Access to higher-value destinations depends on producing fruit with consistent size, colour and appearance, maintaining acceptable residue profiles, fulfilling phytosanitary requirements and preserving quality through the supply chain. In this sense, diversification is not simply a matter of identifying new buyers; it requires the production and export system to meet the technical requirements of those markets (Rao et al., 2026).

Overall, the export evidence shows that India has built a growing pomegranate export sector, but much of the trade remains concentrated in regional markets, while higher-value destinations account for relatively smaller quantities. The difference in destination-wise price realization, together with the requirements associated with premium markets, highlights the importance

of improving quality, compliance, traceability and supply-chain performance. These factors provide the basis for examining the major opportunities and strategies for expanding Indian pomegranate exports, including value addition, export-oriented production clusters, market diversification and stronger integration of growers with export supply chains.

Export requirement	Farm Production and crop management	Packhouse Sorting, grading, packing and storage	Laboratory Residue analysis and testing	Exporter Market access and compliance
 Pesticide use and pre-harvest interval (PHI)	✓	—	—	—
 Residue testing	—	✓	✓	✓
 Traceability (farm to export)	✓	✓	—	✓
 Phytosanitary compliance (pests and diseases)	✓	✓	—	✓
 Certification (e.g., GAP and other schemes)	✓	✓	—	✓
 Packaging and labelling	—	✓	—	✓

 Indicates key responsibility/requirement at this stage
 — Not a primary responsibility at this stage

FIGURE 3: Destination-specific export requirements and the distribution of key compliance responsibilities across farm, packhouse, laboratory and exporter stages of the pomegranate export chain.

XI. OPPORTUNITIES FOR EXPANDING INDIAN POMEGRANATE EXPORTS

The constraints affecting Indian pomegranate exports also indicate several opportunities for improving the position of the crop in international markets. India already has important production advantages, including a large production base, the widely accepted Bhagwa cultivar and the ability to produce fruit across different cropping seasons. The challenge is to convert these production advantages into consistent export-quality supply through better integration of cultivation, post-harvest handling, compliance and marketing (Prasad et al., 2013; Saroj and Sharma, 2017; Rao et al., 2026).

One important opportunity lies in the expansion of value-added pomegranate products, particularly arils. The available evidence indicates that international demand exists for ready-to-eat arils and other processed products such as juice concentrates, dried products and seed oil. Compared with whole fruit, these products can provide additional avenues for value realization, although their expansion depends on appropriate processing, hygiene, packaging, cold storage and traceability systems (Gulati et al., 2022; Rao et al., 2026).

The development of production-cluster-based export infrastructure could help address several of these requirements simultaneously. Establishing packhouses and processing facilities close to major production areas can reduce unnecessary movement of fruit before primary handling and provide facilities for cleaning, grading, pre-cooling, packaging and storage. The recent export assessment has proposed strengthening such infrastructure through cluster-based systems and improved connections between farms, processing centres and exporters (Rao et al., 2026).

Such an approach may be particularly useful for pomegranate-growing regions of Maharashtra, where large production clusters already exist. The export assessment identified areas such as Solapur and specifically highlighted Sangola as a location with substantial Bhagwa cultivation and experience in export-oriented production. Cluster-level facilities could therefore provide a practical link between growers and export markets by combining primary processing, quality assessment, residue testing and logistics within the production region (Rao et al., 2026).

Market diversification represents another area of opportunity. Current exports are concentrated in a limited number of regional markets, while smaller quantities are shipped to destinations where the reported price realization is considerably higher. Expanding into such markets would require consistent compliance with quality, residue, certification and phytosanitary standards, but diversification could reduce dependence on a small group of destinations and create opportunities for higher-value trade (Rao et al., 2026).

Branding and traceability can support this process by distinguishing Indian pomegranate from competing origins. The recent export assessment noted the importance of certification, traceability and targeted branding, particularly for premium retail markets. Experiences involving traceable and certified Indian aril products suggest that market identity may be strengthened when product quality can be linked with documented production and handling practices (Gulati et al., 2022; Rao et al., 2026).

Varietal improvement is also relevant to long-term export development. Although Bhagwa is widely accepted in international trade, concerns regarding fruit size, uniformity and suitability for different market segments have been reported. The development or selection of clones with stable fruit characteristics suited to particular agro-climatic conditions and export requirements may therefore complement improvements in crop management and post-harvest handling (Prasad et al., 2013; Saroj and Sharma, 2017; Rao et al., 2026).

Crop protection also has a role within this export-oriented approach. Better integration of pest and disease management with residue management can help reduce unnecessary pesticide applications while maintaining fruit quality. Farmer training in Good Agricultural Practices, pesticide selection, MRL requirements and record keeping can strengthen the connection between orchard management and export compliance. The recent export assessment specifically identified farmer training, integrated pest and disease management and stronger field-level compliance as areas requiring continued attention (Rao et al., 2026).

Taken together, these opportunities suggest that expansion of Indian pomegranate exports depends on improvements across the entire supply chain rather than on increasing production alone. Higher export participation will require coordinated progress in fruit quality, residue compliance, traceability, packhouse infrastructure, cold-chain management, value addition, varietal improvement and market development. Such an integrated approach can help convert India's existing production capacity into a more consistent and diversified export supply.

XII. RESEARCH GAPS AND FUTURE DIRECTIONS FOR INDIAN POMEGRANATE EXPORTS

The literature reviewed above shows that India has a strong production base and an established export trade, but the available research is distributed across separate areas such as production, pesticide use, residue monitoring, post-harvest handling and market access. These studies provide useful information on individual constraints, but relatively few studies examine how these factors interact along the complete pomegranate supply chain. The recent ICRIER–APEDA assessment also identified the need to consider production, compliance, infrastructure, processing and market access together when examining India's export potential (Rao et al., 2026).

One important research gap concerns the relationship between farm-level pesticide practices and export compliance. Previous studies have documented pesticide-use patterns and residue occurrence in different pomegranate-growing regions, but these investigations are often limited to specific locations or sampling periods (Elango and Sridharan, 2017; Kolekar et al., 2011; Kottadiyil et al., 2023). There is a need for more systematic studies linking the pesticides actually used by growers with residue levels detected at harvest and, where possible, with the requirements of specific export destinations. Such studies could help identify which production practices contribute most to residue-related non-compliance.

Geographically representative residue surveillance is another area requiring attention. Earlier investigations have provided valuable evidence from Maharashtra, Karnataka, Gujarat and other regions, but the available information remains fragmented with respect to sampling location, season, pesticide coverage and source of fruit (Kolekar et al., 2011; Pujeri et al., 2011; Kottadiyil et al., 2023; Aralimarad et al., 2024). Continued multiresidue monitoring of both field-produced and market-available pomegranate could provide a better understanding of changes in residue profiles over time. Such datasets would also be useful for distinguishing persistent production-related problems from isolated residue findings.

A related gap exists in the integration of residue data with dietary risk assessment and export compliance. Studies have shown that pesticide residues may be detected, and in some cases exceed particular MRLs, while estimated dietary exposure remains below the corresponding toxicological reference values (Aralimarad et al., 2024; Parmar et al., 2025). Further work should therefore continue to distinguish regulatory compliance from dietary-health risk and should examine both aspects when

interpreting residue findings. Comparative studies using Indian regulatory limits alongside the requirements of major importing markets could provide more practical information for export-oriented production (Dureja et al., 2015; Pasupuleti et al., 2022).

Traceability and farm-level documentation also deserve greater research attention. The recent export-sector assessment identified gaps in documentation, pesticide management and compliance capacity in parts of the production system (Rao et al., 2026). However, there is limited published evidence on how farm records, pesticide application histories, residue testing and traceability systems can be integrated into a practical and economically feasible system for small and medium growers. Research on digital or cluster-based traceability models could therefore contribute to improving continuity between farm production, packhouse operations and export certification.

Post-harvest research also needs to move beyond individual technologies and examine the complete chain from harvest to export. Existing evidence identifies shortcomings in pre-cooling, grading, cold storage, transportation and processing infrastructure, while aril products require particularly careful temperature and hygiene management (Gulati et al., 2022; Rao et al., 2026). Further studies could evaluate integrated packhouse and cold-chain models at major production clusters and quantify their effects on fruit quality, post-harvest loss, rejection rates and export value.

Market-specific research is another important need. India's export destinations differ substantially in their price realization, phytosanitary conditions, certification requirements and consumer preferences (Rao et al., 2026). More detailed studies comparing destination markets could help identify the production and supply-chain characteristics required for entry into particular markets rather than treating the international market as a single category. Such research would also help clarify whether the major constraints to market expansion arise at the farm, processing, logistics or policy level.

Finally, greater attention is needed to the potential of value-added products such as arils, juice and other processed forms. The literature and recent sector assessment indicate that these products provide opportunities for diversification, but their expansion is constrained by processing capacity, cold-chain requirements, packaging technology and quality control (Gulati et al., 2022; Rao et al., 2026). Research combining product quality, processing economics, food safety, shelf life and export-market requirements could help determine where value addition can be integrated most effectively into the Indian pomegranate supply chain.

Overall, future research should move towards a more integrated framework in which production practices, fruit quality, pest and disease management, pesticide residues, traceability, post-harvest handling and destination-market requirements are studied as connected components of export readiness. The evidence currently available provides a strong foundation, but greater integration of these research areas is needed to understand why a large production base has not yet translated into a proportionately broader international market presence.

XIII. CONCLUSION

India has a strong foundation for pomegranate export through its large production base, widespread cultivation of Bhagwa, long production season and established access to overseas markets. Yet the relatively small share of production entering international trade shows that production volume alone does not determine export performance. The exportable share of the crop depends on whether fruit consistently meets market requirements for size, colour, appearance, disease freedom, residue compliance, shelf life, traceability and phytosanitary safety. The evidence reviewed in this article indicates that export constraints are interconnected. Pest and disease pressure can increase dependence on pesticides; pesticide selection and application practices influence residue profiles; residue non-compliance can restrict access to particular markets; and inadequate post-harvest handling can reduce the quality of fruit that has already met farm-level requirements. At the same time, certification, traceability, phytosanitary procedures, logistics and market-specific standards influence the cost and feasibility of reaching higher-value destinations. Improving exports therefore requires an integrated production-to-market approach rather than a single intervention. Priority areas include export-oriented crop and pest management, better control of pesticide residues, systematic residue surveillance, stronger farm-level documentation and traceability, improved packhouses and cold-chain infrastructure, expansion of value-added products such as arils, and diversification into markets with sustainable demand. Research should increasingly examine these factors together so that farm practices, food safety, post-harvest management and destination-market requirements can be considered within a common framework. The central challenge for India is not simply to produce more pomegranate, but to increase the proportion of fruit that can move efficiently and consistently from the orchard to compliant, higher-value international markets. Strengthening this connection across the entire value chain can provide a more practical basis for expanding Indian pomegranate exports.

AUTHOR(S) CONTRIBUTION STATEMENT

Durgesh Kailas Narwade: Conceptualization, Methodology, Investigation, Formal analysis, Writing-original draft, Visualization, Writing-review & editing. B. V. Deore: Writing-review & editing, Data curation, Investigation. S. B. Deore: Review & editing.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION PROCESS

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with language editing, grammar correction, and improvement of clarity and readability. The final manuscript was critically reviewed and verified by the authors, who take full responsibility for its content.

ACKNOWLEDGEMENTS

The authors would like to thank the All India Network Project on Pesticide Residues and Contaminants, Mahatma Phule Krishi Vidyapeeth, Rahuri, for their support during the preparation of this manuscript.

REFERENCES

- [1] Ali, I., Rahman, S. Z., Qamar, A., & Khan, M. S. (2022). Survey-based study on farmers' knowledge and pattern of using insecticide on different crops in Aligarh District of Uttar Pradesh, India. *International Journal of Human and Health Sciences*, *6*(2), 193-199. <https://doi.org/10.31344/ijhhs.v6i2.445>
- [2] Ambrus, Á., & Yang, Y. Z. (2016). Global harmonization of maximum residue limits for pesticides. *Journal of Agricultural and Food Chemistry*, *64*(1), 30-35. <https://doi.org/10.1021/jf505347z>
- [3] Anbazhagan, P., Wilson, A., Nallasamy, V., & Ramanathan, S. (2022). Assessment on knowledge and perception regarding health risks of pesticide usage among farmers. *International Journal of Public Health Science*, *11*(4), 1424. <https://doi.org/10.11591/ijphs.v11i4.21230>
- [4] APEDA. (2023). *Agricultural and Processed Food Products Export Development*. <https://apeda.gov.in/>
- [5] Aralimarad, P., Bedar, J., Mahato, S., Hanchinal, S. G., Naik, N., Shwetha, U., Pavankumar, K., Naveenkumar, P., Gavai, A., Rat, R. S., & Patil, M. (2024). Simultaneous determination of multi-class pesticide residues in solanaceous vegetables and selected fruits using LC-MS/MS and potential impact on consumer health with measurement uncertainty. *Research Square*. <https://doi.org/10.21203/rs.3.rs-5199827/v1>
- [6] Balikai, R. A., Kotikal, Y. K., & Mani, M. (2022). Pests and their management in pomegranate. In M. Mani (Ed.), *Trends in horticultural entomology*. Springer. https://doi.org/10.1007/978-981-19-0343-4_29
- [7] Balikai, R. A., Kotikal, Y. K., & Prasanna, P. M. (2011). Status of pomegranate pests and their management strategies in India. *Acta Horticulturae*, *890*, 569-583. <https://doi.org/10.17660/ActaHortic.2011.890.81>
- [8] Banerjee, K., Patil, S. B., Patil, S. H., Dasgupta, S., Savant, R., & Adsule, P. G. (2008). Single-laboratory validation and uncertainty analysis of 82 pesticides determined in pomegranate, apple, and orange by ethyl acetate extraction and liquid chromatography/tandem mass spectrometry. *Journal of AOAC International*, *91*(6), 1435-1445. <https://doi.org/10.1093/JAOAC/91.6.1435>
- [9] Bilehal, D., Chetti, M. B., Sung, D. D., & Goroji, P. T. (2014). Reversed-phase UPLC method for the determination of monocrotophos, thiram, carbendazim, carbaryl, and imidacloprid pesticides in mango and pomegranate by QuEChERS method. *Journal of Liquid Chromatography & Related Technologies*, *37*(12), 1633-1643. <https://doi.org/10.1080/10826076.2013.803205>
- [10] Chauhan, N. N., & Gupta, D. (2024). Evaluation of IPM modules against pomegranate fruit borer *Deudorix epijarbas* (Moore). *Indian Journal of Entomology*, *86*(2), 557-561. <https://doi.org/10.55446/IJE.2023.815>
- [11] Directorate General of Foreign Trade Ministry of Commerce and Industry Government of India. (2025). Dgft.gov.in. <https://www.dgft.gov.in/CP/index.jsp>
- [12] Doddaraju, P., Kumar, P., Gunnaiah, R., Gowda, A. A., Lokesh, V., Pujer, P., & Manjunatha, G. (2019). Reliable and early diagnosis of bacterial blight in pomegranate caused by *Xanthomonas axonopodis* pv. *punicae* using sensitive PCR techniques. *Scientific Reports*, *9*, 10097. <https://doi.org/10.1038/s41598-019-46588-9>
- [13] Dureja, P., Singh, S. B., & Parmar, B. S. (2015). Pesticide maximum residue limit (MRL): Background, Indian scenario. *Pesticide Research Journal*, *27*(1), 4-22.
- [14] Elango, K., & Sridharan, S. (2017). Assessment of farmer's perception on pesticides usage pattern and knowledge of pest management in pomegranate under high-density planting at major pomegranate growing districts of Tamil Nadu. *Trends in Biosciences*, *10*(45), 9260-9263.
- [15] Ergun, M. (2012). Pomegranates. In M. Siddiq (Ed.), *Tropical & subtropical fruits: Postharvest physiology, processing and packaging* (1st ed., pp. 529-548). John Wiley & Sons Inc.

- [16] Gaddanakeri, S., Pradeep, S., Deshmukh, S., Shivanna, B. K., Sridhara, S., Thippesha, D., & Fakrudin, B. (2023). Insecticide usage pattern and knowledge level of farmers on insecticides handling to manage *Leucinodes orbonalis* Guenee in brinjal across different localities. *International Journal of Environment and Climate Change*, *13*(8), 777-784. <https://doi.org/10.9734/ijec/2023/v13i82010>
- [17] Gulati, A., Ganguly, K., & Harsh Wardhan. (2022). *Agricultural value chains in India*. Springer Nature.
- [18] Hem, L., Park, J.-H., & Shim, J.-H. (2010). Residual analysis of insecticides (lambda-cyhalothrin, lufenuron, thiamethoxam and clothianidin) in pomegranate using GC- μ ECD or HPLC-UV. *Korean Journal of Environmental Agriculture*, *29*(3), 257-265. <https://doi.org/10.5338/KJEA.2010.29.3.257>
- [19] Kahramanoglu, I. (2019). Trends in pomegranate sector: Production, postharvest handling and marketing. *International Journal of Agriculture, Forestry and Life Sciences*.
- [20] Kambrekar, D. N., & Biradar, A. P. (2015a). Field efficacy of insecticides in the management of pomegranate aphid, *Aphis punicae* (Passerini). *Acta Horticulturae*, *1089*, 153-159. <https://doi.org/10.17660/ActaHortic.2015.1089.17>
- [21] Kambrekar, D. N., Biradar, A. P., & Karabhantanal, S. S. (2015b). New insecticides for the management of pomegranate fruit borer, *Deudorix isocrates* (F.). *Indian Journal of Entomology*, *77*(3), 240-244. <https://doi.org/10.5958/0974-8172.2015.00050.4>
- [22] Kolekar, V. S., Wakure, D. D., Raut, P. N., & Utture, S. C. (2011). Monitoring of pesticide residues in exportable pomegranate fruits. *Acta Horticulturae*, *890*, 547-555. <https://doi.org/10.17660/ActaHortic.2011.890.77>
- [23] Kottadiyil, D., Mehta, T., Thasale, R., & Sivaperumal, P. (2023). Determination and dietary risk assessment of 52 pesticide residues in vegetable and fruit samples by GC-MS/MS and UHPLC-QTOF/MS from Gujarat, India. *Journal of Food Composition and Analysis*, *115*, 104957. <https://doi.org/10.1016/j.jfca.2022.104957>
- [24] Krishna, T. M., Devaki, K., Kumar, K. K., & Prasanthi, L. (2022). Dissipation kinetics and the pre-harvest residue of chlorantraniliprole in pigeon pea (*Cajanus cajan* L.) succulent pods using ultra-high-performance liquid chromatography with photodiode array detector (UHPLC-PDA). *Open Journal of Analytical and Bioanalytical Chemistry*, *6*(1), 013-017. <https://doi.org/10.17352/ojabc.000025>
- [25] Kulkarni, S. R., Kadam, J. R., & Chavan, A. P. (2007). Preliminary studies on the efficacy of *Verticillium lecanii* (Zimmermann) against mixed populations of mealy bugs on pomegranate. *Pest Management in Horticultural Ecosystems*, *13*(1).
- [26] Kumar, P., LNU, D., & Singh, R. P. (2023). *Farmer's attitudes on pesticide-use and pest-management practices: A case study of vegetable-cultivators in the vicinity of Lucknow, India*. <https://doi.org/10.52679/bi.e202312002>
- [27] Mohapatra, S. (2014). Residue dynamics of chlorpyrifos and cypermethrin in/on pomegranate (*Punica granatum* L.) fruits and soil. *International Journal of Environmental Analytical Chemistry*, *94*, 1394-1406. <https://doi.org/10.1080/03067319.2014.954564>
- [28] Mohapatra, S., & Lekha, S. (2016). Residue level and dissipation of carbendazim in/on pomegranate fruits and soil. *Environmental Monitoring and Assessment*, *188*(7), 406. <https://doi.org/10.1007/s10661-016-5404-2>
- [29] Parmar, K. D., Rathod, P. H., Kalasariya, R. L., Pandya, M. J., Patel, M. R., Chawla, S., & Patel, M. P. (2025). Dissipation and risk assessment of a combination product of chlorantraniliprole + abamectin and spirotetramat in pomegranate fruit and juice. *Biomedical Chromatography*, *39*(9), e70174. <https://doi.org/10.1002/bmc.70174>
- [30] Pasupuleti, V. V., Majji, K. R., Bagade, P., & Kachireddy, V. N. S. R. (2022). Study on existence of pesticides in Indian grapes and their compliance for export to EU nations through advanced analytical instrumentation. *Research Journal of Chemistry and Environment*, *26*(10), 75-88. <https://doi.org/10.25303/2610rjce075088>
- [31] Pienaar, L., & Boonzaaij, J. (2018). *Drought policy brief: Western Cape agriculture*. Bureau for Food and Agricultural Policy, Western Cape Department of Agriculture.
- [32] Prasad, A., Nagda, G., Syed, N., & Kumar, A. (2023). A detailed survey on awareness, knowledge and practice of pesticides used against various vegetables, fruits and cereal crops grown in and around Udaipur region of South Rajasthan, India. *Bulletin of Pure and Applied Sciences—Zoology*, *42*(1), 43-63. <https://doi.org/10.48165/bpas.2023.42A.1.6>
- [33] Prasad, K. S., Mukunda, G., Mohankumar, A., & Yathiraj, K. (2013). Bhagwa a promising variety of pomegranate for dry. *International Journal of Agricultural Sciences*.
- [34] Pszczolińska, K., & Kociołek, B. (2022). The pesticide residue analysis in commodities with high content of chlorophyll based on the quick, easy, cheap, effective, rugged, and safe method: A review. *Journal of Separation Science*, *45*(1), 149-165. <https://doi.org/10.1002/jssc.202100304>
- [35] Pujeri, U. S., Yadawe, M., Hiremath, S. C., & Pujar, A. S. (2011). Monitoring of pesticide residues in pomegranate of Bijapur District, Karnataka. *Research Journal of Chemistry and Environment*, *15*(2), 355-358.
- [36] Rao, S., Bhargava, A., Rohtagi, A., & Gulati, A. (2026). *Strategies to boost India's pomegranate exports*. Indian Council for Research on International Economic Relations (ICRIER).
- [37] Saroj, & Sharma, B. D. (2017). *Cultivar Bhagwa: Revolutionizing*. ICAR-Central Institute for Arid Horticulture.
- [38] Satpathy, G., Tyagi, Y. K., & Gupta, R. K. (2014). Development and validation of multi-residue analysis of 82 pesticides in grapes and pomegranate as per the requirements of the European Union (EU) and Codex Alimentarius using GC-MS/MS with compound-based screening. *American Journal of Food Science and Technology*, *2*(2), 53-61. <https://doi.org/10.12691/ajfst-2-2-2>
- [39] Sharma, A. K., Dubey, J., Katna, S., Shandil, D., Brar, G. S., & Singh, S. (2021). Validation of analytical methods used for pesticide residue detection in fruits and vegetables. *Food Analytical Methods*, *14*(9), 1919-1926. <https://doi.org/10.1007/s12161-021-02027-y>
- [40] UN Comtrade. (2024). *UN Comtrade*. <https://comtradeplus.un.org/>
- [41] Vallur, J. H. V., Cherukuri, S. R., Chiranjeevi, Ch., Varma, P. K., & Rao, V. S. (2023). Knowledge, attitude and behaviour of paddy growers towards use and handling of pesticides in Krishna Western Delta area of Guntur District of Andhra Pradesh, India. *Ecology, Environment & Conservation*, *29*(3), 1055-1060. <https://doi.org/10.53550/eec.2023.v29i03.020>
- [42] Zhang, X., Wang, X., Chen, J., Zhang, Z., Ding, H., Du, X.-Z., & Lu, X.-Q. (2025). Simultaneous detection of 34 pesticide and metabolite residues in vegetables and fruits using improved QuEChERS-gas chromatography-tandem mass spectrometry with carboxylated multi-walled carbon nanotubes. *Chinese Journal of Chromatography*, *43*(10), 1145-1153. <https://doi.org/10.3724/sp.j.1123.2025.02001>

Optimization of Mineral Fertilization of Cotton (*Gossypium hirsutum* L.) under Late Sowing Conditions in the Countries of the Regional Program for Integrated Cotton Production in Africa (PR-PICA)

Traoré Amadou^{1*}; Ouattara Adama²; Amonmidé Isidore³; Diop Assane⁴; N'Goran Kouadio Emanuel⁵; Koffi Kokou Zovodu⁶; Djinodji Renougal⁷; Kobenan Koffi Christophe⁸; Kamga Dimitri⁹; Takpa O'Nel¹⁰; Séidou Moudjaidou¹¹; Koulibaly Bazoumana¹²

¹Institut d'Economie Rurale (IER) Mali,

^{2,12}Institut de l'Environnement et de Recherches Agricoles (INERA) Burkina Faso,

^{3,10,11}Institut de Recherche sur le Coton (IRC) Bénin,

⁴Institut Sénégalais de Recherche Agricole (ISRA) Sénégal,

^{5,8}Centre National de Recherche Agronomique (CNRA) Côte d'Ivoire,

⁶Institut Togolais de Recherche Agronomique (ITRA) Togo,

⁷Institut Tchadien de Recherche Agronomique pour le Développement (ITRAD) Tchad,

⁹Institut de Recherche Agricole pour le Développement (IRAD) Cameroun.

*Corresponding Author

Received:- 12 September 2026/ Revised:- 28 September 2026/ Accepted:- 08 October 2026/ Published: 15-10-2026

Copyright © 2026 International Journal of Environmental and Agriculture Research

This is an Open-Access article distributed under the terms of the Creative Commons Attribution

Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted

Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— Late sowing of cotton is an increasing constraint in West and Central African countries due to irregular rainfall, which reduces the length of the growing cycle and limits the effectiveness of mineral fertilization. This study aimed to determine the most efficient and cost-effective mineral fertilization strategy for cotton cultivation under late-sowing conditions in the countries of the Regional Integrated Cotton Production Program in Africa (PR-PICA). Trials were conducted during the 2023 and 2024 cropping seasons at ten experimental sites in Benin, Burkina Faso, Mali, and Senegal using a randomized complete block design with four replications. Four treatments were compared including a control with no fertilization (0% FMR), the recommended dose (100% FMR: 200 kg ha⁻¹ of NPKSB + 50 kg ha⁻¹ of urea), 75%, and 50% of this dose. Agro-morphological parameters, yield components, seed cotton yield, and the benefit/cost ratio were evaluated. The results show that application of mineral fertilization significantly improves plant growth, the number of bolls per hectare, and seed cotton yield compared to the unfertilized control. However, no significant difference was observed between doses of 100%, 75%, and 50% of the recommended mineral fertilizer for seed cotton yield. Country and year effects were significant for most of the variables studied, reflecting the influence of soil and climate conditions on crop performance. The economic analysis indicates that 50% of the recommended mineral fertilizer dose offers the best economic efficiency by reducing the fertilization costs with no significant effect on seed cotton yield. These results show that under late sowing conditions, applying 50% of the recommended mineral fertilizer is an agronomically effective and economically advantageous strategy. This mineral fertilization dose represents a relevant option to improve the profitability of cotton cultivation while limiting input costs under late sowing conditions in PR-PICA member countries.

Keywords— Cotton, late sowing, mineral fertilization, yield, economic profitability, PR-PICA.

I. INTRODUCTION

Cotton (*Gossypium hirsutum* L.) cultivation is one of the main drivers of agricultural and economic development in the member countries of the Regional Integrated Cotton Production Program in Africa (PR-PICA), namely Benin, Burkina Faso, Cameroon, Côte d'Ivoire, Mali, Senegal, Chad, and Togo. This sector represents a vital source of income for millions of producers, contributes to the supply of textile industries, and makes a significant contribution to these countries' export earnings (FAO, 2022; Renaudin, 2010). However, the sustainability of cotton production is currently facing several major constraints, including the progressive decline in soil fertility and the increasing effects of climate variability, resulting in an irregular rainy season, more erratic rainfall distribution, and an increased frequency of droughts (PR-PICA, 2024; Traoré et al., 2021; Ndour et al., 2018).

The most significant consequence of this climate variability is the increased frequency of late sowing of cotton. In rainfed cotton production systems, the delayed onset of rainfall forces farmers to postpone sowing, thus reducing the effective duration of the crop cycle. This shortening of the cycle exposes the sensitive flowering, fruiting, and boll-filling phases to less favorable water availability and high temperatures at the end of the season, which generally leads to reduced vegetative growth, boll production, and seed cotton yield (Amonmidé et al., 2020; Sêkloka et al., 2015).

In the cotton-growing areas of the PR-PICA region, the lixisols generally have low nutrient reserves, making mineral fertilization essential to maintain crop productivity. Current recommendations are based on the application of 200 kg ha⁻¹ of NPKSB fertilizer supplemented by 50 kg ha⁻¹ of urea (PR-PICA, 2024). However, these recommendations were developed under normal sowing conditions, and their relevance in late-sowing situations remains insufficiently documented. Indeed, when the growing cycle is shortened, the cotton plant's capacity to absorb and utilize nutrients, particularly nitrogen and potassium, can be limited, which is likely to reduce the agronomic and economic efficiency of fertilization (Sêkloka et al., 2015).

Faced with this situation, farmers sometimes adopt empirical strategies such as reducing fertilizer doses or even completely eliminating urea application during very late sowing of cotton (Amonmidé et al., 2020). Although these practices aim to limit production costs, they are still based on few validated experimental references at the regional level. In a context where farm profitability is becoming a major issue, it appears necessary to determine the fertilization doses that reconcile agronomic performance and economic efficiency under late sowing conditions.

We hypothesized that under late sowing conditions, a reduction in the recommended mineral fertilization dose would maintain a yield level comparable to that obtained with the full dose, while improving the economic profitability of the crop. The objective of this study is therefore to evaluate the effects of different mineral fertilization doses on growth, yield components, seed cotton yield, and the economic profitability of cotton under late sowing conditions in several PR-PICA member countries.

II. MATERIALS AND METHODS

2.1 Study Sites

The experiments were conducted during the 2023 and 2024 cropping seasons in four member countries of the Regional Integrated Cotton Production Program in Africa (PR-PICA): Benin, Burkina Faso, Mali, and Senegal. The trials were established at research stations representative of the main cotton-producing areas in each country to cover a diversity of soil and climate conditions.

In Benin, trials were conducted at the Permanent Experimental Centers (CPEs) of Angaradébou (3°1'00"E, 11°19'50"N) and Okpara (9°20'49"E, 2°41'3"N), belonging to the Cotton and Fiber Agricultural Research Center (CRA-CF) of the National Institute of Agricultural Research of Benin (INRAB). These two sites represent the northern and north-central zones of the Beninese cotton basin, respectively, and concentrate a significant portion of national production of seed cotton.

In Burkina Faso, experiments were conducted at the Farako-Bâ (N 11°05' and W 04°19'), Houndé (N 11°32' and W 03°26'), and Kouaré (N 11°58'4 and E 00°18') stations. The soils at these sites are lixisols characterized by low organic matter content, low nitrogen and phosphorus reserves, limited cation exchange capacity, and a slightly to moderately acidic reaction. Rainfall recorded during the 2023 growing season varied across the sites, reflecting significant climatic variability.

In Mali, trials were conducted at Farako/Finkolo (-5°48'W, 11°21'N) and N'Tarla (12.6193°N, -5.689°W) research stations, both part of the Sikasso Regional Agricultural Research Center. The soils, with a sandy-loam texture, have a high sand content,

low nutrient retention capacity, and moderate acidity. Rainfall totals recorded over the two years of experimentation indicate contrasting water conditions between growing seasons.

In Senegal, the study was carried out in three Multi-Local Experimental Units (AMEX) in the Senegalese cotton-growing region:

- AMEX of Koussanar (Tambacounda Region): located in the northern/dry zone of the cotton-growing basin, approximately 7 km from the town of Koussanar. The soil is primarily of a slightly leached tropical ferruginous type. The climate is Sudano-Sahelian, characterized by an average annual rainfall of between 600 and 800 mm.
- AMEX of Kolda (Kolda Region): located in the middle zone of the cotton-growing basin, near the border with the Vélingara department. The soils there are tropical ferruginous (moderately to heavily leached). The climate is Sudanian, with annual rainfall generally varying between 800 and 1,000 mm.
- AMEX of Kédougou (Kédougou Region): located in the southern/humid zone of the cotton basin. The soils are predominantly ferrallitic and gravelly. The climate is of the Sudanian-Guinean type, characterized by high annual rainfall between 1,000 and 1,300 mm.

2.2 Experimental Setup

The trials were conducted using a randomized complete block design (blocks of Fisher) with four treatments and four replications. Each elementary plot consisted of six 10-m-long rows spaced 0.80 m apart, corresponding to an area of 48 m². After eliminating edge effects, observations and harvests were carried out on a usable plot composed of the four central 8-m-long rows, for a total area of 25.6 m². The total area of one trial was 768 m², excluding access paths.

2.3 Treatments Studied

In this experiment, four levels of mineral fertilization were compared:

- T1: control without fertilization (0% of the recommended mineral fertilizer);
- T2: 100% of the recommended mineral fertilizer (200 kg ha⁻¹ of NPKSB + 50 kg ha⁻¹ of urea);
- T3: 75% of the recommended mineral fertilizer;
- T4: 50% of the recommended mineral fertilizer.

Cotton fertilizer 14N-18P-18K+6S+1B was applied 10 days after emergence, while urea 46% N was applied between 20 to 30 days after emergence, these application periods being specific to late sowing.

2.4 General Cotton Crop Management

The cotton cultivation operations were carried out according to the technical guidelines recommended in each country. Soil preparation was performed by mechanical plowing or animal traction, depending on the site. Sowing of cotton was carried out at a rate of three to five seeds per hill, followed by thinning to two plants per hill before the fifteenth day after emergence. Weed control was carried out according to the practices recommended in each country. With regard to the phytosanitary protection of cotton plants against pests and diseases, the first two treatments (30 and 44 days after emergence) were carried out using alternative products to pyrethroids, and the others using binary products against caterpillars and sucking pests, in compliance with current recommendations.

2.5 Measured Variables and Economic Analysis

The observations focused on the main growth and agronomic parameters of cotton, including plant height at harvest, plant density, number of bolls per plant, average weight of boll (AWB), and seed cotton yield. Yields were determined from harvests carried out on usable plots according to the harmonized PR-PICA procedures.

The profitability of different fertilization strategies was evaluated using the partial budget method, considering only the costs and revenues associated with the treatments. The calculated indicators included gross revenue, net profit, gross margin, and

the benefit/cost ratio (BCR), obtained by dividing profits by production costs. The following formula was therefore used: $BCR = \text{present value of benefits} / \text{present value of costs}$. A BCR value greater than 1 indicates that the strategy is economically viable. Fertilizer and seed cotton prices for each country were used for these economic calculations.

2.6 Statistical Analyses

The data were subjected to analysis of variance (ANOVA) using R software (version 4.0.1) after verifying the model's application conditions (normality of the distribution). When the effect of the treatments was significant at the 5% level, the means were separated using Duncan's test.

III. RESULTS

3.1 Effects of Mineral Fertilization Doses on Cotton Growth Parameters

Mineral fertilization had no significant effect on plant density at harvest ($p = 0.77$), indicating that the different fertilizer doses applied did not influence stand maintenance under late sowing conditions (Table 1). However, plant density differed significantly between countries ($p < 0.001$) and the growing seasons ($p < 0.001$). The highest densities of cotton plants were observed in Mali and Senegal, while Benin recorded the lowest values. Similarly, the 2024 growing season had a higher average density than that of 2023. The significant interaction between countries and years reflects a variation in stand maintenance conditions depending on the study environments.

TABLE 1
COTTON PLANT DENSITY PER HECTARE UNDER LATE SOWING CONDITIONS IN FOUR COUNTRIES OF THE REGIONAL PROGRAM FOR INTEGRATED COTTON PRODUCTION IN AFRICA (PR-PICA)

Factors	Level	Number of plants/ha	p-value	Coefficient of variation (CV%)
Treatments	T1	46705 a	0.77	1.98
	T2	48293 a		
	T3	46088 a		
	T4	46974 a		
Countries	Mali	51854 a	2.2e-16 ***	14.8
	Burkina Faso	47853 b		
	Benin	36911 c		
	Senegal	51441 a		
Years	2023	44724 b	0.00235 **	6.89
	2024	49306 a		
Countries x Years			0.0011 **	
Overall Average		47015		

Legend: T1: no mineral fertilizer application; T2: application of 100% of the recommended mineral fertilizer, FMR (200 kg/ha of NPK+S+B and 50 kg/ha of urea), T3 = application of 75% of the FMR, T4: application of 50% of the FMR; CV: coefficient of variation; significant differences ($P < 0.05$) between treatments are indicated by stars and letters indicate homogeneous groups.

Conversely, plant height at harvest in Table 2 was significantly influenced by fertilization treatments ($p < 0.001$). Unfertilized plants exhibited the shortest cotton plant heights, while all the three other fertilization levels (100%, 75%, and 50% of the recommended mineral fertilizer) promoted comparable vegetative growth. These results show that under late sowing conditions, reducing the fertilization dose to 50% of the recommended dose did not compromise cotton plant height growth. Cotton plant heights were also affected by countries and planting years ($p < 0.001$), with the highest values observed in Mali and during the 2024 growing season. The significant interaction between countries and years highlights a differentiated response in cotton plant growth according to the soil quality and climate conditions encountered in the different experimental environments.

TABLE 2
HEIGHT OF COTTON PLANTS UNDER LATE SOWING CONDITIONS IN FOUR COUNTRIES OF PR-PICA

Factors	Level	Heights (cm)	Probability	Coefficient of variation (CV%)
Treatments	T1	89.21 b	0.0003 ***	9.82
	T2	108.34 a		
	T3	111.81 a		
	T4	108.15 a		
Countries	Mali	115.71 a	0.0001 ***	10.14
	Burkina Faso	97.62 bc		
	Benin	111.37 ab		
	Senegal	92.81 c		
Years	2023	92.32 b	1.9e-09 ***	16.2
	2024	116.34 a		
Countries x Years			1.9e-08 ***	
Overall Average		104.38		

Legend: T1: no mineral fertilizer application; T2: application of 100% of the recommended mineral fertilizer, FMR (200 kg/ha of NPK+S+B and 50 kg/ha of urea), T3 = application of 75% of the FMR, T4: application of 50% of the FMR; CV: coefficient of variation; significant differences ($P < 0.05$) between treatments are indicated by stars and letters indicate homogeneous groups.

3.2 Effects of Mineral Fertilization Doses on Total Number of Bolls and Bolls Load per Plant

The total number of bolls harvested per hectare was significantly influenced by fertilization treatments ($p < 0.001$) (Table 3). Fertilized plots produced a significantly higher number of bolls than the unfertilized control, confirming the positive effect of mineral fertilization on cotton fruiting under late-sowing conditions. In contrast, no significant difference was observed between treatments receiving 100%, 75%, and 50% of the recommended mineral fertilizer (FMR), indicating that halving the dose of fertilizers did not limit statistically the boll formation. The number of bolls also differed significantly between countries and growing seasons ($p < 0.001$), reflecting the influence of soil properties and climate conditions on the expression of this trait. The significant interactions observed between countries and cropping years show that the fruiting response differs according to the experimental environments.

TABLE 3
NUMBER OF BOLLS PER HECTARE UNDER LATE SOWING CONDITIONS IN FOUR COUNTRIES OF PR-PICA

Factors	Level	Total bolls/ha	Probability	Coefficient of variation (CV%)
Treatments	T1	182245 b	0.004 **	10.4
	T2	233054 a		
	T3	217156 a		
	T4	224519 a		
Countries	Mali	205345 b	6.123e-15 ***	21.4
	Burkina Faso	214383 b		
	Benin	163118 c		
	Senegal	274129 a		
Years	2023	216583	0.6655	1.54
	2024	211904		
Countries x Years			3.347e-06 ***	
Overall Average		214244		

Legend: T1: no mineral fertilizer application; T2: application of 100% of the recommended mineral fertilizer, FMR (200 kg/ha of NPK+S+B and 50 kg/ha of urea), T3 = application of 75% of the FMR, T4: application of 50% of the FMR; CV: coefficient of variation; significant differences ($P < 0.05$) between treatments are indicated by stars and letters indicate homogeneous groups.

The boll load per plant followed a similar trend as total bolls number (Table 4). Fertilized treatments resulted in significantly higher boll loads than the control, while doses of 100%, 75%, and 50% of the recommended mineral fertilizer showed statistically comparable performance. This response reflects the capability of cotton plants to maintain their fruiting potential despite a reduction in the fertilizer dose under the late-sowing conditions studied. Furthermore, the boll load was significantly affected by countries and cropping years, with variations reflecting differences in growing conditions between experimental sites. The significant interactions between these factors confirm that the environment plays a crucial role in the expression of this yield component.

TABLE 4
BOLLS LOAD PER COTTON PLANT UNDER LATE SOWING CONDITIONS IN FOUR COUNTRIES OF PR-PICA

Factors	Level	bolls/plant	Probability	Coefficient of variation (CV%)
Treatments	T1	6.12 a	0.27	10.05
	T2	7.78 a		
	T3	7.56 a		
	T4	7.56 a		
Countries	Mali	12.09 a	2.2e-16 ***	46.6
	Burkina Faso	4.75 c		
	Benin	5.09 c		
	Senegal	7.09 b		
Years	2023	8.01 a	0.02	14.8
	2024	6.50 b		
Countries x Years				
Overall Average		7.25		

Legend: T1: no mineral fertilizer application; T2: application of 100% of the recommended mineral fertilizer, FMR (200 kg/ha of NPK+S+B and 50 kg/ha of urea), T3 = application of 75% of the FMR, T4: application of 50% of the FMR; CV: coefficient of variation; significant differences ($P < 0.05$) between treatments are indicated by stars and letters indicate homogeneous groups.

3.3 Effects of Mineral Fertilization Doses on Average Weight of Boll (AWB) and Seed Cotton Yield

Table 5 indicates that the mean average weight of boll was significantly influenced by fertilization treatments ($p < 0.05$). Plants receiving mineral fertilization produced heavier bolls than the unfertilized control, indicating a beneficial effect of nutrient application on capsule filling. However, no statistically significant difference was observed between treatments receiving 100%, 75%, and 50% of the recommended mineral fertilizer, suggesting that reducing the fertilization dose did not alter the mean AWB under late-sowing conditions. The AWB value also varied significantly across countries and growing seasons, reflecting the influence of soil fertility and climate conditions on this yield component. The significant interactions observed between countries and years confirm that the treatment response depended on the environmental context.

TABLE 5
AVERAGE WEIGHT OF BOLLS (AWB) UNDER LATE SOWING CONDITIONS IN FOUR COUNTRIES OF PR-PICA

Factors	Level	AWB (g)	Probability	Coefficient of variation (CV%)
Treatments	T1	3.71 a	0.57	2.77
	T2	3.90 a		
	T3	3.84 a		
	T4	3.96 a		
Countries	Mali	3.96 b	4.269e-12 ***	13.3
	Burkina Faso	3.12 c		
	Benin	4.31 a		
	Senegal	4.03 ab		
Years	2023	3.92 a	0.34	2.29
	2024	3.79 a		
Countries x Years			0.001386 **	
Overall Average		3.85		

Legend: T1: no mineral fertilizer application; T2: application of 100% of the recommended mineral fertilizer, FMR (200 kg/ha of NPK+S+B and 50 kg/ha of urea), T3 = application of 75% of the FMR, T4: application of 50% of the FMR; CV: coefficient of variation; significant differences ($P<0.05$) between treatments are indicated by stars and letters indicate homogeneous groups.

Seed cotton yield was strongly influenced by mineral fertilization ($p < 0.001$). The three fertilized treatments showed significantly higher yields than the unfertilized control, demonstrating the importance of fertilization for maintaining cotton productivity under late-sowing conditions (Table 6). In contrast, yields obtained with 100%, 75%, and 50% of the recommended mineral fertilization did not differ significantly, indicating that reducing the fertilization dose maintains a production level comparable to that obtained with the full dose. The effects of countries and years were also highly significant, highlighting variability in cotton performance across experimental environments. The significant interactions between country and year indicate that soil and climate conditions modulated yield expression, without altering significantly the overall trend observed between treatments.

TABLE 6
SEED COTTON YIELD (kg/ha) OF COTTON PLANTS UNDER LATE SOWING CONDITIONS IN FOUR COUNTRIES OF PR-PICA

Factors	Level	Seed cotton yields (kg/ha)	Probability	Coefficient of variation (CV%)
Treatments	T1	880 b	0.0002708 ***	15.3
	T2	1263 a		
	T3	1216 a		
	T4	1185 a		
Countries	Mali	1184 a	1.16e-11 ***	24.1
	Burkina Faso	737 b		
	Benin	1327 a		
	Senegal	1297 a		
Years	2023	1265 a	0.000214 ***	16
	2024	1008 b		
Countries x Years			5.32e-07 ***	
Overall Average		1136		

Legend: T1: no mineral fertilizer application; T2: application of 100% of the recommended mineral fertilizer, FMR (200 kg/ha of NPK+S+B and 50 kg/ha of urea), T3 = application of 75% of the FMR, T4: application of 50% of the FMR; CV: coefficient of variation; significant differences ($P<0.05$) between treatments are indicated by stars and letters indicate homogeneous groups.

3.4 Evaluation of the Benefit-to-Cost Ratio (BCR) of Fertilizer Treatments

Table 7 below presents the effects of the different treatments and the benefit-cost ratio (BCR) by country. It shows that the different doses applied did not significantly influence ($p = 0.17$) the benefit-cost ratio. However, a significant difference ($p < 0.001$) was observed between countries, with Senegal having the highest benefit-cost ratio (4.61), followed by Mali with 3.24, while Burkina Faso and Benin had the lowest benefit-cost ratios at 1.60 and 2.56, respectively. The countries $\times$ treatments interactions were not significant. The countries $\times$ years interaction was also not significant, implying that the variation between countries did not depend on the cropping year.

TABLE 7
BENEFIT-TO-COST RATIO (BCR) OF PRODUCTION AS A PERCENTAGE UNDER LATE SOWING CONDITIONS IN FOUR COUNTRIES OF PR-PICA

Factors	Level	Profit-to-cost ratio	Probability	Coefficient of variation (CV%)
Treatments	T2	2.41 a	0.17	22.3
	T3	2.95 a		
	T4	3.76 a		
Countries	Mali	3.24 ab	0.0006 ***	42.2
	Burkina Faso	1.60 b		
	Benin	2.56 b		
	Senegal	4.61 a		
Treatments * Countries			0.96	
Countries * Years			0.11	
Overall Average		3.04		

Legend: T1: no mineral fertilizer application; T2: application of 100% of the recommended mineral fertilizer, FMR (200 kg/ha of NPK+S+B and 50 kg/ha of urea), T3 = application of 75% of the FMR, T4: application of 50% of the FMR; CV: coefficient of variation; significant differences ($P < 0.05$) between treatments are indicated by stars and letters indicate homogeneous groups.

IV. DISCUSSION

This study evaluated the effects of different doses of mineral fertilizer on the agronomic and economic performance of cotton grown under late-sowing conditions in four PR-PICA member countries. The results showed that mineral fertilization significantly improves cotton plant growth, boll number, and seed cotton yield compared to the unfertilized control. However, no significant difference was observed between the treatments receiving 100%, 75%, and 50% of the recommended mineral fertilizer, indicating that a substantial reduction in the doses did not compromise cotton performance under these study conditions.

The increase in plant height observed in the fertilized treatments confirms the crucial role of mineral nutrition in the vegetative and reproductive development of cotton. The response to fertilizer application even at reduced doses highlights the increase in cotton plant height and collar diameter, which was reported by Amonmidé et al. (2020) and Balogoun et al. (2024). Complete or reduced doses of nitrogen, phosphorus, and potassium applications respectively promote vegetative growth, root development, flowering, and boll filling, resulting in improved productivity under late sowing conditions. These observations are consistent with previous work such as Sanfo (2003) and Sêkloka et al. (2015), which report a positive response of cotton to balanced fertilization when nutrients are a limiting factor.

One of the main findings of this study is that reducing the recommended mineral fertilizer dose by 50% did not lead to a significant decrease in seed cotton yield compared to the full dose. This result can be explained by the specific conditions of late sowing. The shortened growing cycle reduces the duration of vegetative growth and limits overall nutrient requirements (Amonmidé et al., 2020). Under these conditions, some of the nutrients applied with the full dose may not be efficiently utilized by the crop. Thus, reducing the fertilizer dose allows for better alignment of inputs with the actual needs of the cotton plant,

while maintaining a comparable level of production. However, contrasting results were found in normal sowing periods by Kouyaté et al. (2023), indicating that the efficacy of cotton fertilization is proportional to the amount of nutrients applied, highlighting that any reduction in the nutrient dose leads to a decrease in yield. Kassambara et al. (2024) revealed that seed cotton yield was 1263 kg/ha for early planting versus 361 kg/ha for late planting, indicating depressive efficacy with late sowing. Delayed planting dates led to reduced water availability for the crops and induced lower yields.

The yield trend observed was also similar to that observed for height, i.e., $T1 > T2 > T3 > T4$, with differences between countries and between years, which constitutes a major agronomic conclusion. The low yield of the control without fertilizer (T1) confirms the absolute necessity of fertilizing cotton, even under late sowing conditions, to meet the plant's needs. The soils in the study areas are often characterized by negative nutrient balances (Koulibaly et al., 2009; Kanté et al., 2005; Van der Pol & Traore, 1993), with P and K levels well below critical thresholds (Van der Pol & Traore, 1993). Hence the need to fertilize the cotton plant even under late sowing conditions.

The significant effects of the "country" and "year" factors highlight the influence of soil and climate conditions on crop performance. Differences in soil fertility, rainfall, and precipitation distribution among the experimental sites explain the observed variations in growth and yield parameters. Despite this environmental variability, the overall response to treatments remained remarkably stable, reinforcing the robustness of the conclusions and suggesting that the results are applicable across a wide range of conditions representative of the cotton-growing areas of the PR-PICA.

Economic analysis confirms the agronomic results. Although doses of 100%, 75%, and 50% of the recommended mineral fertilizer yields were comparable, reducing the dose to 50% lowered fertilization costs and improved the cost-benefit ratio. This observation shows that the most effective strategy is not necessarily the one that maximizes fertilizer inputs, but rather the one that simultaneously optimizes agronomic performance and economic profitability. In a context marked by rising input costs and the pursuit of more efficient agriculture, this strategy represents a particularly attractive option for producers.

Overall, this study makes an original contribution to knowledge on cotton fertilization management under late-sowing conditions. Contrary to conventional recommendations established for sowing at the normal time, the results obtained show that a reduction in the fertilization dose can be considered without significantly compromising yield. These results provide a scientific basis that can contribute to updating technical recommendations in PR-PICA member countries. However, further studies incorporating a larger number of growing seasons, production environments, and analyses of nutrient use efficiency would help to strengthen these recommendations.

V. CONCLUSION

This study evaluated the agronomic and economic performance of different doses of mineral fertilizer applied to cotton under late-sowing conditions in several PR-PICA member countries. The results show that fertilization significantly improves plant growth, boll production, and seed cotton yield compared to the unfertilized control. However, no significant difference was observed between doses corresponding to 100%, 75%, and 50% of the recommended mineral fertilizer for the main production parameters.

Economic analysis shows that the half-dose of mineral fertilizer recommended (50% of the recommended mineral content) represents the best compromise between productivity and profitability. This strategy allows for maintaining a yield comparable to that obtained with the full dose while reducing input costs, thus improving the benefit/cost ratio.

These results suggest that, under late sowing conditions, current fertilization recommendations could be adapted to better account for the reduced growing cycle length and the actual crop requirements. Adopting this strategy would help improve the profitability of cotton farms and optimize fertilizer use in PR-PICA member countries.

Further work conducted over a greater number of years, in contrasting environments and with different cotton genotypes will confirm the robustness of these results and refine fertilization recommendations adapted to late sowing conditions.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- [1] Amonmidé, I., Fayalo, G. D., & Dagbenonbakin, G. D. (2020). Effet de la période et densité de semis sur la croissance et le rendement du cotonnier au Bénin. *Journal of Applied Biosciences*, *152*(1), 15676-15697.

- [2] Balogoun, I., Zoundji, C. C., Ogoudjobi, S. L., Bero, E. O., Ayiayite, C. R.-M., Azongbe, R. J., & Adandonon, A. (2024). Effect of fertilization and weeding type on the cotton production in Benin. *AGBIR*, *40*(3), 1033-1036. <https://doi.org/10.35248/0970-1907.24.40.1033-1036>
- [3] FAO. (2022). *Les pays du Coton-4 (C-4) dans le cadre du marché mondial du coton : Situation et perspectives à court et moyen termes* (p. 40) [Rapport technique]. FAO. <https://www.fao.org/faostat/en/#data/TCL>
- [4] Kanté, S., Smaling, E., Keulen, & Sanogo, Z. J. L. (2005). Bilans des éléments nutritifs dans les systèmes de production de la zone cotonnière du Mali-Sud. *Science et Technique, Sciences Naturelles et Agronomie*, *1*.
- [5] Kassambara, E. M., Loison, R., Sissoko, S., Traoré, A., & Bretaudeau, A. (2024). Effects of planting date and density on cotton cultivars in sub-Saharan Africa rainfed conditions: A case study in Mali. *Agronomy Journal*, 1-12. <https://doi.org/10.1002/agj2.21672>
- [6] Koulibaly, B., Traoré, O., Dakuo, D., & Zombré, P. N. (2009). Effets des amendements locaux sur les rendements, les indices de nutrition et les bilans culturaux dans un système de rotation coton-maïs dans l'ouest du Burkina Faso. *BASE*. <https://popups.uliege.be/1780-4507/index.php?id=3586>
- [7] Kouyaté, A. B., Koné, S., Dembélé, S. G., & Famanta, M. (2023). Effets de différentes doses d'engrais inorganiques sur le rendement et la performance économique du cotonnier. *International Journal of Biological and Chemical Sciences*, *17*(7), 2971-2983. <https://doi.org/10.4314/ijbcs.v17i7.28>
- [8] Pol, F., & Traore, B. (1993). Soil nutrient depletion by agricultural production in Southern Mali. *Fertilizer Research*, *36*(1), 79-90. <https://doi.org/10.1007/BF00749951>
- [9] PR-PICA. (2024). *Sixième réunion bilan annuelle du Programme Régional de Production Intégrée du Coton en Afrique (PR-PICA)*.
- [10] Renaudin, C. (2010). Les riches heures et l'avenir incertain de la culture cotonnière en Afrique de l'Ouest et du Centre. *EchoGeo*, (14). <https://journals.openedition.org/echogeo/11955>
- [11] Sanfo, D. (2003). *Influence des dates de semis sur la précocité de floraison du cotonnier (Gossypium hirsutum L.) à la station de Farako-Bâ* [Mémoire de D.E.A., Université de Ouagadougou].
- [12] Sêkloka, E., Lançon, J., Batamoussi, M., & Thomas, G. (2015). La réduction de la croissance végétative à forte densité de semis comme stratégie d'adaptation variétale aux semis tardifs en culture cotonnière pluviale au Bénin. *Tropicultura*, *33*(4), 299.
- [13] Ndour, A., Clouvel, P., Goze, E., Martin, P., Leroux, L., Dieng, A., & Loison, R. (2018). L'expertise pour prédire la production cotonnière en Afrique de l'Ouest : Est-elle une solution face aux aléas climatiques émergents? *Biotechnologie, Agronomie, Société et Environnement*, *22*(4), 252-266.
- [14] Traoré, A., Sarr, M., Loison, R., Diouf, L., & Ndiaye, S. (2021). Contraintes et perspectives de la culture du coton en Afrique de l'Ouest dans un contexte de changement climatique : Cas du Sénégal. Synthèse bibliographique. *Journal of Applied Biosciences*, *166*, 17168-17179. <https://doi.org/10.35759/JABs.166.2>

Utilization of the Stingless Bee (*Trigona* sp.) as a Natural Pollinator in Rubber (*Hevea brasiliensis*) Agroforestry Program of PT Pertamina EP Sangatta Field, East Kalimantan, Indonesia

Annisa Nurjanah¹; Maulita Dwi Hariyanti²; Sofian Cahyo Aji³; Luisa Febrina Amalo^{4*}; Luluk Dwi Wulan Handayani⁵

^{1,2,3}Department of Environmental, HSSE Division, PT Pertamina EP Sangatta Field, Indonesia

^{4,5}Center for Environmental Research, IPB University, Indonesia

*Corresponding Author

Received:- 14 September 2026/ Revised:- 27 September 2026/ Accepted:- 06 October 2026/ Published: 15-10-2026

Copyright @ 2026 International Journal of Environmental and Agriculture Research

This is an Open-Access article distributed under the terms of the Creative Commons Attribution

Non-Commercial License (<https://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted

Non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Abstract— Rubber (*Hevea brasiliensis*) is an agroforestry commodity that provides ecological services, such as carbon uptake, erosion control, and habitat provision. However, its small, densely clustered flowers limit effective pollination by wild insects, so seed set and latex productivity often remain below their potential levels. This study reports a biodiversity conservation program carried out by PT Pertamina EP Sangatta Field, East Kalimantan, Indonesia, which introduced stingless bee (*Trigona* sp.) colonies in collaboration with partner farmer group, Trigona Reborn Group, as a natural pollinator for rubber trees grown under an agroforestry system together with citrus, mango, and papaya as companion crops. A suction-based honey-harvesting tool (Bee-Sap) was introduced to collect honey without damaging the comb, thereby allowing the colony to function as a pollinator. Monitoring conducted from January to June 2025 recorded the conservation of 250 rubber trees, an estimated colony population of 13,000 *Trigona* sp. individuals, and a program biodiversity index (H') of 0.90. The results indicate that the small body size and floral constancy behavior of *Trigona* sp. allow it to effectively reach the small rubber flowers, supporting cross-pollination, while the partnership also provides an additional income source for the farmer group through honey and propolis production.

Keywords— Agroforestry, Biodiversity conservation, *Hevea brasiliensis*, Natural pollinator, Stingless bee, *Trigona* sp.

I. INTRODUCTION

PT Pertamina EP Sangatta Field is a company engaged in oil and gas exploration and production that is committed to environmental conservation and community empowerment in its operational area. As part of this commitment, the company manages a conservation area for rubber (*Hevea brasiliensis*) developed under an agroforestry system, in which forestry species are combined with agricultural crops on the same land unit to increase land productivity, maintain ecosystem sustainability, and generate economic, ecological, and social benefits. Rubber-based agroforestry provides broader ecosystem services than rubber monoculture, including higher carbon storage and stronger support for biodiversity indicators (Perdomo Diaz et al., 2025).

Globally, *Hevea brasiliensis* is listed as Least Concern on the IUCN Red List (Fabriani & Hills, 2020). However, this status does not automatically guarantee the long-term sustainability of rubber populations, as regeneration still depends on the quality of the surrounding ecosystem, including the availability of effective pollinators. As a long-lived tree species, rubber also provides important ecological functions, such as carbon absorption, reduction of greenhouse gas emissions, prevention of soil erosion, maintenance of microclimate humidity, and provision of habitat for various flora and fauna (Singh et al., 2021; Liu et al., 2016).

Rubber is a cross-pollinated plant, and fruit and seed formation depend strongly on the presence of an effective pollinator (Li et al., 2022). In practice, however, natural pollination of *Hevea brasiliensis* by wild insects tends to be nonoptimal because the flowers are small, densely arranged, and clustered, which limits the ability of larger insects to reach the stigma. A study on insect pollinators in oil palm, rubber, and jungle-rubber land uses in Sumatra also found that pollinator communities in rubber plantations are commonly dominated by small carpenter bees rather than large-bodied bees, and that a *Trigona* sp. nest was found inside a rubber tree trunk (Siregar et al., 2016). Nonoptimal pollination reduces the number of seeds available for generative propagation and constrains natural regeneration, which increases the risk that a rubber stand becomes dominated by older, less productive trees.

At the same time, the company's CSR partner group in Sangkima Selatan Village, Trigona Reborn Group, maintains stingless bee (*Trigona* sp.) colonies, but has faced declining colony productivity because the number and variety of flowers available around the settlement area are limited. Honey harvesting that is still performed manually also tends to damage the comb, which disturbs the colony and reduces its long-term sustainability (Md Zaki & Abd Razak, 2018).

Pollinators play an important economic and ecological role. Approximately 75% of global food crops depend at least partly on animal pollination (Potts et al., 2016). Among insect pollinators, stingless bees have been reported as effective pollinators for various crops because of their small body size and floral constancy behavior, which increases the efficiency of cross-pollination and improves fruit and seed formation (Atmowidi et al., 2022; Wongsu et al., 2023). Due to these conditions, PT Pertamina EP Sangatta Field has proposed a solution by employing *Trigona* sp. colonies from the partner group as natural pollinators for rubber flowers. The program design was complemented by a honey-harvesting device that was specifically engineered to maintain the sustainability of the colonies. This study aims to evaluate the effectiveness of the stingless bee (*Trigona* sp.) colonies as natural pollinators within rubber (*Hevea brasiliensis*) agroforestry systems, assessed based on: (1) the number of rubber trees and bee colonies successfully conserved, (2) the biodiversity index of the conservation area, and (3) a comparison of pollination conditions before and after the intervention.

II. MATERIAL AND METHODS

2.1 Study Area and Program Design

This program was conducted in 2025 in the rubber (*Hevea brasiliensis*) agroforestry conservation area of PT Pertamina EP Sangatta Field in East Kalimantan, Indonesia. Within the agroforestry system, rubber trees are planted together with other crops, namely citrus (*Citrus sinensis*), mango (*Mangifera indica*), and papaya (*Carica papaya* L.), which serve as additional food sources for pollinating insects and help maintain a more balanced micro-ecosystem. The program was conducted in partnership with Trigona Reborn Group, a community group from the company's CSR-assisted village that cultivates *Trigona* sp. colonies.

2.2 Program Intervention

The main intervention was the introduction of *Trigona* sp. colonies belonging to the partner farmer group into the rubber agroforestry area to act as a natural pollinator. This approach makes use of the bee's small body size, which corresponds to the small and clustered morphology of the rubber flower, together with its floral constancy behavior, that is, the tendency to visit flowers of the same species within a single foraging trip, which increases the probability of effective cross-pollination. As a complementary intervention, a honey-harvesting tool (Bee-Sap) that works on a suction principle was applied so that nectar and honey could be extracted without damaging the comb. This tool was intended to reduce colony stress during harvesting and maintain colony population so that the bees could continue functioning as pollinators.

2.3 Data Collection

Monitoring was conducted from January to June 2025. An absolute counting method was used to record the cumulative number of rubber trees benefiting from *Trigona* sp. pollination and successfully conserved, together with the cumulative colony population and the number of companion-crop individuals in the conservation area. The biodiversity condition of the conservation area was calculated using the Shannon-Wiener diversity index (H'), which accounts for both the number of species present and the evenness of individuals among those species (Shannon & Weaver, 1949). The index was calculated separately for the flora and fauna recorded in the reclamation/conservation area using Equation (1).

$$H' = -\sum (p_i \ln p_i) \quad (1)$$

where p_i is the proportional abundance of species i , calculated as $p_i = n_i / N$, where n_i is the number of individuals of species i , and N is the total number of individuals of all species recorded in the conservation area (Shannon & Weaver, 1949).

Following this framework, an H' value below 1 is generally interpreted as low diversity dominated by very few species, a value between 1 and 3 as moderate diversity, and a value above 3 as high diversity. The overall program biodiversity index was obtained by combining the flora and fauna index values for the same monitoring period, providing a single indicator of the ecological condition of the conservation area that can be tracked from one monitoring period to the next.

III. RESULT AND DISCUSSION

3.1 Results

3.1.1 Individuals Conserved in the Agroforestry Area

Field documentation of the conservation area is presented in Figure 1, showing the physical condition of the components summarized in Table 1. The *Hevea brasiliensis* stand was recorded as a mature rubber planting arranged under the agroforestry pattern together with the companion crops described above. The *Trigona* sp. colony belonging to Trigona Reborn Group was documented in its hive box positioned within the rubber stand to allow direct foraging access to the surrounding flowers.



FIGURE 1: Field documentation of the rubber agroforestry conservation program at PT Pertamina EP Sangatta Field: (a) *Hevea brasiliensis* stand under the agroforestry system; (b) *Trigona* sp. colony housed in a wooden hive box; (c) application of the Bee-Sap non-destructive honey-harvesting tool.

Table 1 presents the cumulative number of individuals conserved in the agroforestry area up to June 2025, the target rubber trees, companion crops used for ecological support, and the introduced *Trigona* sp. colony. Table 1 shows that the target species of the program, rubber (*Hevea brasiliensis*), reached a cumulative total of 250 conserved trees, the largest single count among all plant species recorded and equivalent to approximately 71.6% of the 349 total plant individuals monitored across the five plant categories in the table. The companion crops occupied the remaining share, led by the grass/cover crop category with 54 individuals (15.5% of the plant total), followed by papaya with 30 individuals (8.6%), citrus with 10 individuals (2.9%), and mango with 5 individuals (1.4%). This distribution indicates that, in terms of individual count, the area is still dominated by the rubber stand itself, while the companion crops function as a smaller, supporting layer rather than an equally large component of the planting. The *Trigona* sp. colony was reported with a cumulative population of 13,000 individuals as of June 2025.

TABLE 1
CUMULATIVE NUMBER OF INDIVIDUALS CONSERVED IN THE AGROFORESTRY AREA (JUNE 2025)

No.	Local Name	Scientific Name	Total (2025)	Unit
1	Rubber	<i>Hevea brasiliensis</i>	250	Trees
2	Grass (cover crop)	<i>Panicum</i> sp.	54	Individuals
3	Citrus	<i>Citrus sinensis</i>	10	Trees
4	Mango	<i>Mangifera indica</i>	5	Trees
5	Papaya	<i>Carica papaya</i>	30	Trees
6	Stingless bee (kelulut)	<i>Trigona</i> sp.	13,000	Individuals

3.1.2 Biodiversity Index of the Conservation Area

Table 2 shows a flora diversity index of $H' = 0.90$. This value is classified as a low-diversity condition, consistent with a planting scheme that is still dominated by a single species (rubber) rather than an evenly distributed mix of species. The fauna diversity index for the same monitoring period was reported as $H' = 0.00$, reflecting that fauna monitoring in this cycle centered on the single introduced pollinator taxon, *Trigona* sp., rather than a multi-species fauna survey.

TABLE 2
BIODIVERSITY INDEX OF THE CONSERVATION AREA (2025)

IKH – Reclamation Area	2025
Flora Diversity Index (H')	0.9
Fauna Diversity Index (H')	0
Program Biodiversity Index	0.9

3.1.3 Condition Observed Before and After the Program

Prior to the program, field observations revealed that the pollination of *Hevea brasiliensis* in the conservation area was carried out only by wild insects without a managed pollinator. The flowers of the rubber tree were observed to be small, densely arranged, and clustered, a morphology that restricted the ability of these insects to contact the stigma. As rubber is a cross-pollinated plant, this constraint was reflected in seedlings with lower vigor, which were more susceptible to disease, and latex yields that remained below their potential. Field records from Trigona Reborn Group showed a less productive *Trigona* sp. colony prior to the program, a condition linked to the limited availability of flowers in the settlement area that served as the main source of nectar and pollen for bees. Honey harvesting is still carried out manually, which damages the comb and further weakens the sustainability of the colonies in the surrounding areas (Figure 2).

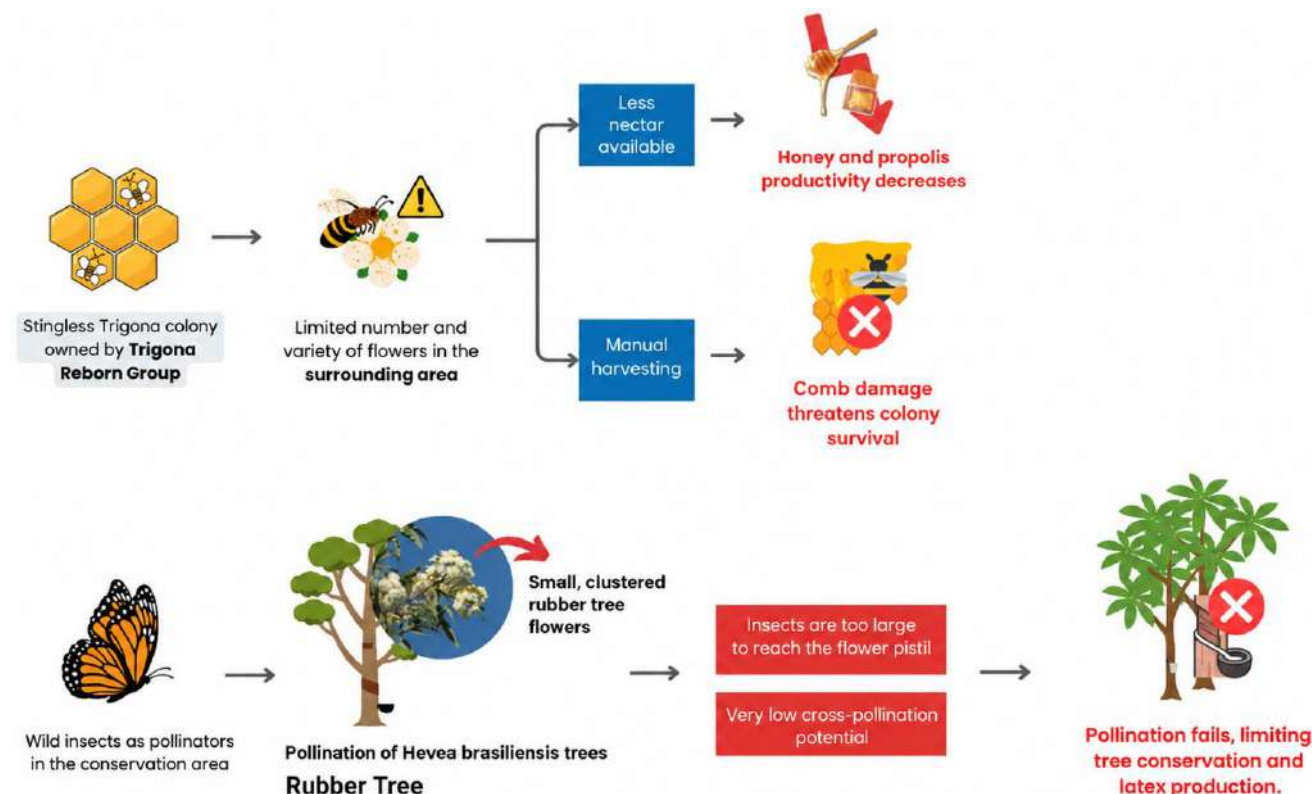


FIGURE 2: Schematic conditions before the program included limited floral resources and manual harvesting constraining the partner colony, and small, clustered rubber flowers limiting wild insect pollination.

After the program was implemented, *Trigona* sp. colonies belonging to Trigona Reborn Group were introduced into the rubber agroforestry area, and the Bee-Sap harvesting tool was put into use. Field monitoring recorded a cumulative conservation of 250 rubber trees, together with a *Trigona* sp. population of 13,000 individuals (Table 1), and a program biodiversity index of 0.90 (Table 2) for the January–June 2025 period. Figure 3 summarizes the post-program conditions, including the pathway from colony introduction to increased honey and propolis production, and the pathway from improved cross-pollination to tree conservation.

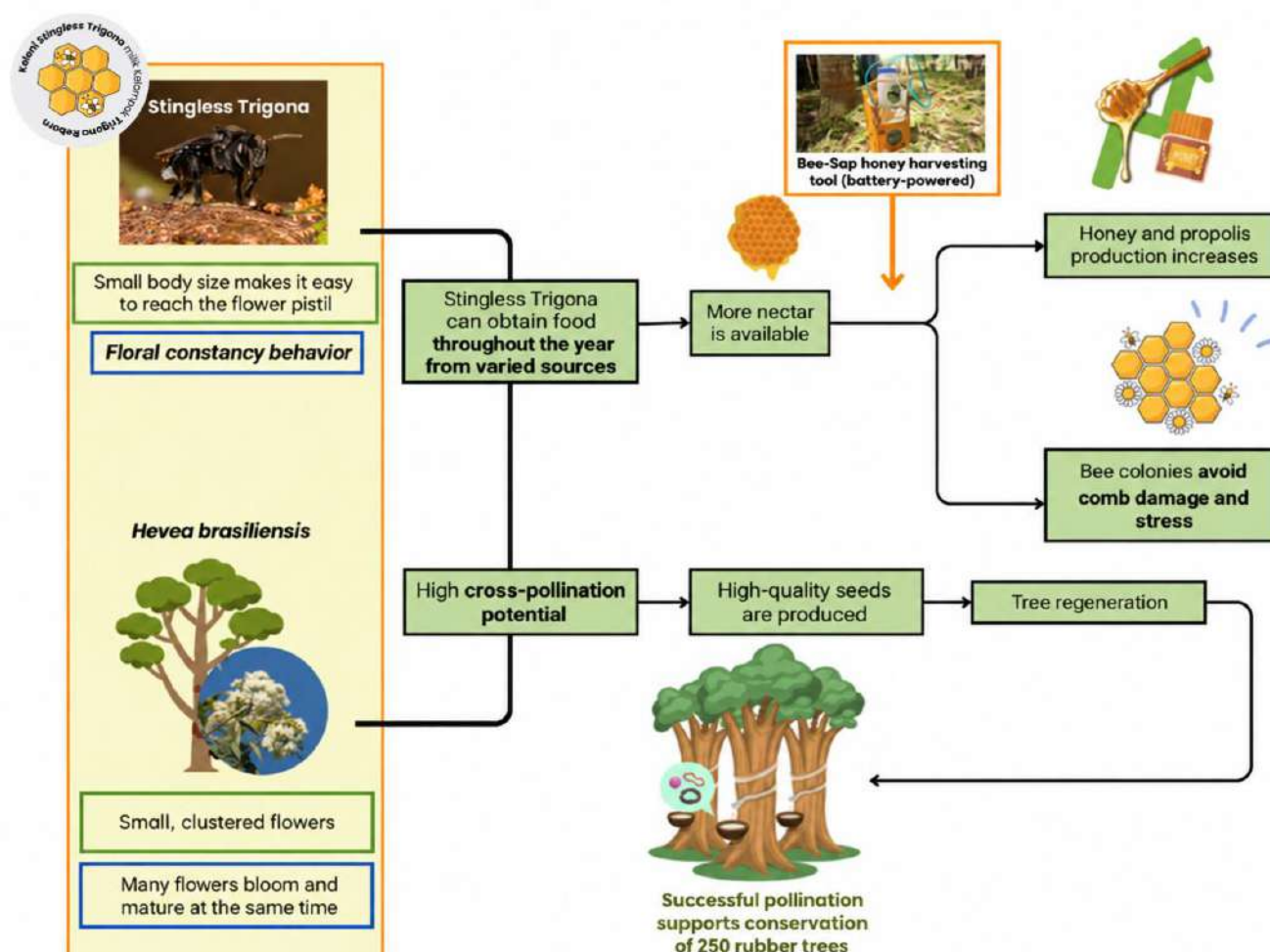


FIGURE 3: Schematic conditions after the program: *Trigona* sp. gains wider access to floral resources and is harvested non-destructively, whereas improved cross-pollination supports seed quality, tree regeneration, and conservation of 250 rubber trees.

3.2 Discussion

3.2.1 Mechanism of *Trigona* sp. as a Natural Pollinator of *Hevea brasiliensis*

The 250 conserved rubber trees and 13,000-individual *Trigona* sp. colony reported in Table 1 can be explained by the match between the bee's morphology and the rubber flower's structure. *Trigona* sp. was selected as the natural pollinator because its small body size matches the morphology of the *Hevea brasiliensis* flower. This allows the bee to enter the narrow floral opening, make contact with the anther and stigma, and carry pollen between flowers effectively (Ramadani et al., 2021; Md Zaki & Abd Razak, 2018). The abundant pollen produced by rubber flowers is then used by *Trigona* sp. as a main food resource for larval growth, colony health, and honey reserves, which is consistent with the increase in colony population implied by the program's monitoring data.

Trigona sp. also shows floral constancy, in which there is a tendency to visit flowers of the same species within one foraging period. This behavior increases the likelihood of cross-pollination between rubber flowers, producing higher-quality seeds and

supporting tree regeneration, and is consistent with reports that stingless bees improve fruit and seed formation in other crops through the same mechanism (Atmowidi et al., 2022; Wongsu et al., 2023). Because rubber is a cross-pollinated species, this mechanism offers a plausible biological pathway from pollinator intervention to improved seed set and tree conservation, as shown in Figure 2, although the present monitoring design, being an applied field program rather than a controlled experiment, does not itself isolate pollination from other contributing factors.

3.2.2 Role of Companion Planting in Supporting the Agroforestry System

The comparatively small share of companion crop individuals shown in Table 1 (citrus, mango, and papaya together making up less than 13% of the total plant) is consistent with their intended role as a supporting rather than a dominant planting layer. PT Pertamina EP Sangatta Field planted these companion crops to support the agroforestry system, help balance the ecosystem, and protect the soil, providing supplementary nectar and pollen sources alongside rubber flowers. With this combination, rubber productivity is supported both ecologically and economically, while a more sustainable agroforestry ecosystem is established, a pattern broadly consistent with reports that diversified rubber-based agroforestry systems support stronger biodiversity outcomes than rubber grown as a monoculture (Perdomo Diaz et al., 2025).

This program represents a sub-system-level change with an environmental impact classified as species protection through ecological engineering. The 250 conserved rubber trees, 13,000-individual *Trigona* sp. colony, and program biodiversity index of 0.90 (Tables 1 and 2) indicate that the program supports the preservation of the native habitat around the working area and contributes to the conservation of other flora and fauna in the surrounding landscape, including habitat within the Kutai National Park ecosystem, even though the flora index value is low. The PT Pertamina EP Sangatta Field conservation program was conducted in collaboration with Trigona Reborn Group and Kutai National Park. Trigona Reborn Group was responsible for bee cultivation and the commercial use of honey as an economically valuable product, while Kutai National Park supported biodiversity conservation and the preservation of stingless bee habitat. This collaboration not only increased rubber productivity through natural pollination but also strengthened conservation efforts and community empowerment around the working area, consistent with the broader recognition that pollinator-dependent economic value extends well beyond the immediate crop being pollinated (Potts et al., 2016).

IV. CONCLUSION

The integration of *Trigona* sp. stingless bee colonies as natural pollinators, proposed by the PT Pertamina EP Sangatta Field conservation program in collaboration with Trigona Reborn Group, supported the conservation of 250 rubber trees and an estimated colony of 13,000 individuals, with a program biodiversity index of 0.90. The small body size and floral constancy behavior of *Trigona* sp. allowed it to effectively access the small, clustered rubber flowers, while the non-destructive harvesting tool helped maintain colony sustainability. The program also generated economic benefits for the partner farmer group through increased honey and propolis production. As this program was implemented as an applied field intervention rather than a controlled experiment, further systematic monitoring, such as direct measurement of seed set, latex yield, colony population dynamics, and a multi-species fauna survey to complement the current flora-based index, is recommended to strengthen the quantitative evidence for the pollination effect reported here.

ACKNOWLEDGEMENT

The authors thank Trigona Reborn Group and Kutai National Park for their support and collaboration throughout the study.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- [1] Atmowidi, T., Prawasti, T. S., Rianti, P., Prasajo, F. A., & Pradipta, N. B. (2022). Stingless bees pollination increases fruit formation of strawberry (*Fragaria x ananassa* Duch) and melon (*Cucumis melo* L.). *Tropical Life Sciences Research*, 33(1), 41-58.
- [2] Fabriani, F., & Hills, R. (2020). *Hevea brasiliensis*. The IUCN Red List of Threatened Species 2020: e.T62003521A62003529.
- [3] Li, H.-L., Wang, Y., Guo, D., Zhu, J.-H., & Peng, S.-Q. (2022). Differential expression of lncRNAs and miRNAs between self-rooting juvenile and donor clones unveils novel insight into the molecular regulation of rubber biosynthesis in *Hevea brasiliensis*. *Frontiers in Plant Science*, 12, 740597.
- [4] Liu, H., Blagodatsky, S., Giese, M., Liu, F., Xu, J., & Cadisch, G. (2016). Impact of herbicide application on soil erosion and induced carbon loss in a rubber plantation of Southwest China. *Catena*, 145, 180-192.

- [5] Md Zaki, N. N., & Abd Razak, S. B. (2018). Pollen profile by stingless bee (*Heterotrigona itama*) reared in rubber smallholding environment at Tepoh, Terengganu. *Malaysian Journal of Microscopy*, 14, 38-54.
- [6] Perdomo Diaz, D., et al. (2025). Agroforestry with *Hevea brasiliensis*: A landscape-based strategy for carbon sequestration and biodiversity in post-conflict Colombia. Preprints.org, 2025051124.
- [7] Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., Garibaldi, L. A., Hill, R., Settele, J., & Vanbergen, A. J. (Eds.). (2016). *The assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production*. IPBES Secretariat.
- [8] Ramadani, R. F., Raffiudin, R., Ariyanti, N. S., Biagioni, S., Treanore, E., & Behling, H. (2021). Stingless bee foraging behavior and pollen resource use in oil palm and rubber plantations in Sumatra. *Jurnal Entomologi Indonesia*, 18(2), 81-92.
- [9] Shannon, C. E., & Weaver, W. (1949). *The mathematical theory of communication*. University of Illinois Press.
- [10] Singh, A. K., Liu, W., Zakari, S., Wu, J., Yang, B., Jiang, X. J., Zhu, X., Zou, X., Zhang, W., Chen, C., Singh, R., & Nath, A. J. (2021). A global review of rubber plantations: Impacts on ecosystem functions, mitigations, future directions, and policies for sustainable cultivation. *Science of the Total Environment*, 796, 148948.
- [11] Siregar, E. H., Atmowidi, T., & Kahono, S. (2016). Diversity and abundance of insect pollinators in different agricultural lands in Jambi, Sumatera. *HAYATI Journal of Biosciences*, 23(1), 13-17.
- [12] Wongsa, K., Duangphakdee, O., & Rattanawanee, A. (2023). Pollination efficacy of stingless bees, *Tetragonula pagdeni* Schwarz (Apidae: Meliponini), on greenhouse tomatoes (*Solanum lycopersicum* Linnaeus). *PeerJ*, 11, e15367.



International Journal of Environmental & Agriculture Research



Published by
AD Publications

