ISBN: 978-81-992068-6-1

ADVANCES IN AGRICULTURE, HORTICULTURE AND ANIMAL HUSBANDRY

VOLUME II

Editors:
Dr. Mudasir Hassan Bhat
Prof. (Dr.) Sanjay Khajuria
Dr. Nandini Vithalrao
Dr. Sanhita Sengupta

Bhumi Publishing, India

First Edition: August 2025

Advances in Agriculture, Horticulture and Animal Husbandry Volume II

(ISBN: 978-81-992068-6-1)

DOI: https://doi.org/10.5281/zenodo.17063745

Editors

Dr. Mudasir Hassan Bhat

Department of Economics,

Lalit Narayan Mithila University,

Darbhanga, Bihar

Prof. (Dr.) Sanjay Khajuria

Chief Scientist & Head,

Krishi Vigyan Kendra Samba,

SKUAST, Jammu

Dr. Nandini Vithalrao

Department of Zoology,

Government (Autonomous) Degree College,

Kalaburagi, Karnataka

Dr. Sanhita Sengupta

Department of Physiotherapy,

Brainware University,

Kolkata, W. B.

Bhumi Publishing

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Published by Bhumi Publishing,

a publishing unit of Bhumi Gramin Vikas Sanstha

Bhumi Publishing

Nigave Khalasa, Tal – Karveer, Dist – Kolhapur, Maharashtra, INDIA 416 207

E-mail: bhumipublishing@gmail.com

PREFACE

Agriculture, horticulture, and animal husbandry form the foundation of human civilization and continue to play a pivotal role in ensuring food security, economic stability, and sustainable development across the globe. In recent decades, these sectors have witnessed rapid advancements driven by scientific research, technological innovation, and evolving socio-economic needs.

This book, "Advances in Agriculture, Horticulture and Animal Husbandry," aims to present a comprehensive overview of recent developments, challenges, and opportunities within these vital disciplines. It brings together contributions from experts, researchers, and practitioners who are at the forefront of innovation and practice in their respective fields.

The chapters cover a wide range of topics including sustainable farming practices, precision agriculture, plant breeding, pest management, modern irrigation techniques, post-harvest technologies, livestock nutrition, genetic improvement, and animal health management. Emphasis has been placed on integrating traditional knowledge with modern scientific approaches to address the pressing issues of climate change, resource conservation, and global food demand.

We hope that this volume will serve as a valuable resource for students, researchers, policymakers, extension workers, and all stakeholders involved in agricultural sciences. By fostering a deeper understanding of current trends and future directions, this book aspires to contribute meaningfully to the advancement and sustainability of agriculture, horticulture, and animal husbandry.

We extend our sincere gratitude to all the authors, reviewers, and contributors whose efforts have made this publication possible. Their dedication and expertise have significantly enriched the content and scope of this work.

- Editors

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(ISBN: 978-81-992068-6-1)

PERSPECTIVES TO MEASURING FOOD COMMMODITY MARKET INTEGRATION FOR IMPROVED AVAILABILITY AND ACCESSIBILITY OF FOOD IN NIGERIA: A REVIEW

B. L. Lamarana, B. Taru* and S. Y. Mohammed
Department of Agricultural Economics and Extension,
Federal University of Kashere, P.M.B 0182 Gombe State, Nigeria
*Corresponding author E-mail: balataru@fukashere.edu.ng

Abstract:

This paper analyses the state of the art research on food market integration in Nigeria, classified it and provided a comprehensive bibliography for researchers with interest in market integration. A thorough review of literature published between 2007 and 2025 on food market integration in Nigeria generated 35 articles for in-depth analysis. The articles were classified on the basis of econometric tools/methodology employed in data analysis, number of sample years, commodity considered for the studies, states considered in the studies, year of publication, type of data, recommendations from the studies. Findings showed that the majority of research have concentrated on identifying the degree of linkages among the markets with various recommendations made which if implemented will go a long way in improving market integration there by increasing income from food marketing activities. The paper also identified the following factors as very important in increasing/decreasing the degree of market integration: physical infrastructure, market institutions, information, competition, market power, trade, social capital, public/government intervention and export restrictions/ban. The paper further identified several areas for future research.

Keywords: Fluctuations, Integration, Market, Price, Perfectly Competitive, Volatility.

Introduction:

The role that market plays in allocating agricultural products over space is very important. Agricultural commodities move from surplus regions to deficit areas if a market is perfectly competitive. If markets are well integrated, it means that price changes in one location are consistently related to price changes in other locations and market participants are able to interact between different markets perfectly. Several authors define market integration in various ways. Earlier definition was based on price interdependence between different markets (Faminow *et al.,* 1990). Later Barrett (2001) defined it as the smooth flow of commodities from one place to another. Pan *et. al.* (2019) explains it in terms of the flow of both goods and price information between markets. However, a simple general definition relates it to the movement of commodities and information across space, time and form (González *et al.,* 2001). Price transmission, the core of market integration, occurs when a change in one price causes another price to change. Price volatility on the other hand, describes how quickly or widely prices can change (Ronald *et al.,* 2016). Price fluctuation is a common feature of well-functioning agricultural markets. Nevertheless, when it becomes large and unexpected, i.e. volatile, price fluctuation can have a negative impact on food security of consumers, farmers and the entire population (Ronald *et al.,* 2016; Taru, 2014).

The degree of market integration, which is assessed through price transmission and volatility, determines the strength and effectiveness of price mechanism in resource allocation. If food markets are not integrated, price signals will not be transmitted from supply deficit regions to surplus markets. Spatial price relationship has been used to analyze how price changes are transmitted from one market to the other and how markets are link together by trade (Ronald *et al.,* 2016; Sunga, 2017 & Taru, 2014). In the past 2 to 3 decades, there has been an increase in the evolution of literatures on tools to measure markets integration, especially those of agricultural markets (Ronald *et al.,* 2016; Sunga, 2017; Traore & Diop, 2021). However, the transition from the conceptual approach to markets integration measurement is very complex which can be reflected by the diversity of approaches and measurement tools employed over the years (Ronald *et al.,* 2016).

While reviewing literature on food market integration, we noticed that the most widely used approach to analyze markets integration is the price transmission mechanism of geographically distant areas (Ronald *et al.,* 2016 & Sunga, 2017). Recent studies have applied econometric techniques such as Ravallion/Timmer models, Co-integration, Johansen Co-integration, Engel and Granger test, Granger-causality, Error Correction Models, Parity Bounds Model, Autoregression, Threshold Autoregression (TAR) to test for integration hypothesis (Minten *et al.,* 2014; Ronald *et al.,* 2016; Sunga, 2017; Kyari, 2018; Bor, 2020; Traore & Diop, 2021).

This paper evaluates and systematically arranges past literatures by reviewing it thoroughly so that researchers in the area of food market integration can find it useful. Specifically, the study analyzed the state of the art research on food market integration, classified them and provided a perspective for future research. The literatures reviewed covers articles on vertical and spatial market integration, symmetric and asymmetric price transmission and price volatility published in high quality journals as well as unpublished M.Sc. and Ph.D. thesis between 2007 and 2025.

Rationale of the Study

Markets determine to a large extend the availability and accessibility of food. The extent to which markets make food available, accessible and keep prices stable depends on whether or not they are integrated, if markets are well-integrated, it is assumed that market forces are working properly (Ronald *et al.,* 2016). For markets that are integrated, food commodities will flow from surplus to deficit areas. High prices in deficit areas provide an incentive to traders to bring food commodities from surplus to deficit areas, as a result, food prices should decline in deficit areas, making it available and accessible.

Bearing in mind the importance of food commodity market integration, a lot of work have been done to test integration of food markets in various states of Nigeria. Some of these studies found weak or strong integration in food markets whereas others did not find any. Some studies rejected the integration hypothesis while others failed to reject the integration hypothesis. This paper reviews these literatures and identify questions that require more research. The paper also brings together and analyses various methodologies which have been used in various states for studying food market integration. Finally, the review also identifies the recommendations from these studies as well as several issues that future research on market integration should address.

Methodology

A range of sources were searched to review past researches on food commodity market integration across Nigeria. Out of hundreds of papers, thirty five (35) papers formed the sample for this study. All the reviewed papers were published between 2007 and 2025 in peer reviewed journals while two were from unpublished M.Sc. and Ph.D. thesis. Appendix 1 shows the basis for classification of the literature; year of publication, source of study, state and crop considered for the study, data sample used, type of data, methodology employed for analysis as well as findings and recommendations from the reviewed literatures.

The search for literatures was based on the keyword descriptor "food or commodity market integration/price transmission/price volatility/spatial price difference" from selected databases and websites. The databases selected were searched for the keywords in titles, abstracts, keywords list and full text. The full text of the papers was then reviewed subject to relevance, in order to select the ones related to this study. Based on relevance and consideration of the time period for this study, we finally obtained thirty five (35) articles on which we based to write this review.

The entire literature on food market integration was classified using a systematic model presented in Figure 1 (Ronald *et al.,* 2016), that is;

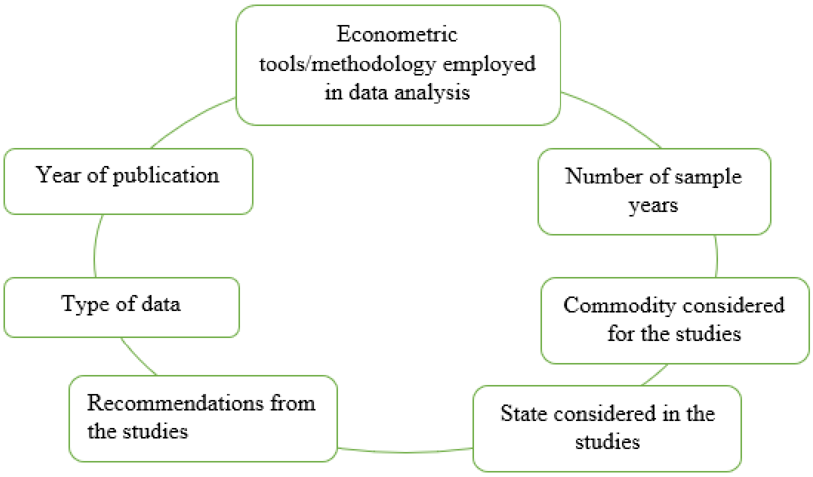

Figure 1: Basis for classification of literature on food market integration (modified from Ronald *et al.*, 2016).

Results and Discussion:

A comprehensive bibliography of the literature on food market integration is presented in appendix 1, classified on the basis of the variables mentioned in Figure 1. Each of the variable and the results obtained from the review is discussed in this section.

Econometric Tools/Methodology Used in Data Analysis

The frequency of various econometric tools adopted for data analyses in the papers reviewed is presented in Table 1.

Table 1: Methodology used in data analysis (*Multiple responses exist)

Variable	Frequency	Percentage
Correlation	4	3.23
Johansen cointegration	25	20.16
Vector Error correction model (VECM)	10	8.06
Augmented Dickey-Fuller (ADF) Unit root test	26	20.97
Granger Causality Test,	23	18.55
Engel and Granger cointegration	5	4.03
Error correction model (ECM)	7	5.65
Index of Market Concentration	5	4.03
Variance Decomposition	4	3.23
Autoregressive Distributive Lag (ARDL) model	2	1.61
Phillips–Perron (PP) Unit root test	2	1.61
Regression	2	1.61
Ravallion	2	1.61
Vector Autoregression	3	2.42
Coefficient of Variation	1	0.81
Impulse Response Function	3	2.42
Total	**109**	**100**

The majority of the studies used Augmented Dickey-Fuller (ADF) unit root test (20.97%), followed by Johansen cointegration analysis (20.16%), Granger Causality Test (18.55%), Vector Error Correction Model (VECM) (8.06%) and Error Correction Model (ECM), (5.65%) to test food market integration. Others used Engel and Granger Cointegration and Index of Market Concentration (IMC) with (4.03%) each. Correlation, and Variance Decomposition (VD) had (3.23%) each. Less popular econometric tools are also shown in Table 1; they include Impulse Response Function (IRF) (2.42%), Vector Autoregression (2.42%) while Autoregressive Distributive Lag (ARDL) model, (Phillips–Perron (PP) Unit root test, Regression, Ravallion, had (1.61%) each and the least used econometric tool was Coefficient of Variation with (0.81%).

Year of Publication wise Classification of Studies

Although the trend in food market integration has been fluctuating, with least researches recorded between 2005 to 2010, there has been a general increase in research in this field since mid 2010. It can be observed from Table 2 that 28.71% of the reviewed work was done between the period 2020 to 2022, 25.71 was carried out between 2017-2019 while non was recorded between 2008 to 2010.

Table 2: Year of publication wise classification of studies

Year	Frequency	Percentage
2005-2007	2	5.71
2008-2010	0	0
2011-2013	4	11.43
2014-2016	6	17.14
2017-2019	9	25.71
2020-2022	10	28.57
2023-2025	4	11.43
Total	**35**	**100**

Source; Author's computation, 2024

State Considered in the Studies

State wise distribution of the studies is shown in Table 3. Out of the 35 papers, 9 were conducted in Oyo, 6 from Abia, Adamawa, Enugu and Niger each. Gombe and Lagos had 5 papers each, Kano had 4 while Benue, Borno, Cross River, Jigawa and Taraba had 3 papers each. States that had two studies each are Bauchi, Ekiti, Imo, Kwara, Ondo, Rivers and Sokoto. The rest of the states (Akwa Ibom, Kaduna, Katsina, Kebbi, Nasarawa and Ogun) under the category of others, had only one study, respectively.

Table 3: States considered in the studies

State	Frequency	Percentage
Abia	6	7.32
Adamawa	6	7.32
Bauchi	2	2.44
Benue	3	3.66
Borno	3	3.66
Cross River	3	3.66
Ekiti	2	2.44
Enugu	6	7.32
Gombe	5	6.10
Imo	2	2.44
Jigawa	3	3.66
Kano	4	4.88
Kwara	2	2.44
Lagos	5	6.10
Niger	6	7.32
Ondo	2	2.44
Oyo	9	10.98
Rivers	2	2.44
Sokoto	2	2.44
Taraba	3	3.66
Other state*	6	7.32
Total	82	100

*Other states include; Akwa Ibom, Bauchi, Ekiti, Imo, Kaduna, Katsina, Kebbi, Kwara, Ogun, Rivers and Sokoto

*Multiple responses exist

Source; Author's computation, 2024

Number of Years Taken as Sample

Table 4 further described the number of years considered as sample for each study. Most studies, 15 (42.86%) had a sample size of 6 to 10 years. Out of the 35 studies, 13 (37.14%) had datasets with time frame between 1 – 5 years and 4 (11.43%) had datasets falling between 11 – 15 years. Two (2) studies (5.71%) had datasets falling between 16 – 20 years while only one study had dataset of 26 – 30 years.

Table 4: Classification of studies base on years taken as sample

Number of sample years	Frequency	Percentage
1 – 5	13	37.14
6 – 10	15	42.86
11 – 15	4	11.43
16 – 20	2	5.71
21 – 25	0	0.00
26 – 30	1	2.86
Total	**35**	**100**

Source; Author's computation, 2024

Type of Data Employed for the Studies

The results of the type of data employed for each study are presented in table 5. The result showed that, majority (86.11%) employed secondary data in form of monthly retail prices, while five employed primary data in the form of; weekly retail prices (8.33%), weekly whole sale prices (2.78%) and monthly retail prices (2.78%).

Table 5: Type of data employed for the studies

Primary Data	Frequency	Percentage
Weekly Retail Prices	3	8.33
Weekly Whole Sale Prices	1	2.78
Monthly Retail Prices	1	2.78
Secondary Data		
Monthly Retail Prices	**31**	86.11
Total	**36**	**100**

*Multiple responses exist

Source; Author's computation, 2024

Commodity Considered for the Studies

The type of food commodity considered in the various studies reviewed are presented on Table 6. It can be seen that most of the studies (19) were conducted on Cowpea, followed by Maize (9), Rice (6), Cassava (5) and Yam (4). Two of the papers reviewed were on Fish, Onion, Tomato and sweat pepper each. The rest of the commodities that fall under the category of others (millet, poultry meat, chile pepper and fresh pepper were considered by one research each.

Table 6: Commodity considered for the studies

Commodity	Frequency	Percentage
Cowpea	19	32.76
Rice	6	10.34
Maize	9	15.52
Yam	4	6.90
Sorghum	3	5.17
Cassava	5	8.62
Fish	2	3.45
Onion	2	3.45
Tomato	2	3.45
Sweat pepper	2	3.45
Other crops*	4	6.90
Total	**58**	**100**

*Other crops include: Millet, Poultry meat, Tomato, Chille pepper, Sweat pepper, Fresh pepper

*Multiple responses exist

Source; Author's computation, 2024

Recommendations Identified in the Studies (Multiple Response)

Table 1 also contained the recommendations which are identified in the papers reviewed. The recommendation with the highest percentage was better infrastructure (26.32%), followed by better price information flow (23.68%), better market and price policy (15.97%), provision of credit facilities (9.21%), better supervision of market participants (6.58%), provision of extension services (3.95%). Membership of cooperative and stabilization of weight and measures had (2.63%) each while each of the recommendation under the category of others (promotion of competition, stable fuel price, better security, improve insurance institution, strengthening the value chain) had (6.18%) each.

Better infrastructures as recommended by various researches include provision of good road networks and transportation facilities, adequate processing and storage facilities, functional communication services. One of the most important factors to achieving market integration of food commodities is the quality of roads and other physical infrastructure. Poor roads lead to an increase in transportation costs in the following ways: higher fuel consumption, higher maintenance costs, faster depreciation of vehicles, tyre replacement costs, and loss of time due to lower speeds (Taravaninthorn and Raballand, 2009). Road improvement project reduced the price differences between two markets and increased the correlation of their prices over time

(Loveridge, 1991). Minten and Kyle (1999) found that transportation cost was twice as high on poor roads as on paved roads.

Better price information flows are very important determinants of transaction costs and market integration (Ronald *et al.,* 2016). Market information is essential for location of buyers and sellers. In recent past, information flow in rural areas of developing countries, was by word of mouth and through informal channels or by personal contact. Currently, the importance of radios, televisions, newspapers and telephones is increasing. Because of high illiteracy levels, the radio is the most important mechanism for farming communities to obtain information on agricultural markets. There is also a rapid expansion in the use of mobile phones among farming communities and traders (Abraham, 2006, Muto & Yamano, 2009). With the popularity of mobile phones in agriculture, there is no doubt that information on prices is exchanged faster than it used to be sometime back. Some studies have been conducted on mobile phone usage in food markets (Abraham, 2006, Muto and Yamano, 2009). However, more research is still needed on how mobile phone popularity has affected the degree of integration of food markets.

Table 7: Recommendations identified in the studies

Recommendation	Frequency	Percentage
Better market and price policy	12	15.79
Reduction in externality cost	2	2.63
Provision of credit facilities	7	9.21
Better infrastructure	20	26.32
Better price information flow	18	23.68
Membership of cooperative	2	2.63
Provision of extension services	3	3.95
Stabilization of weight and measures	2	2.63
Better supervision of market participants	5	6.58
Other recommendations*	5	6.58
Total	**76**	**100**

*Other recommendations include: promotion of competition, stable fuel prices, better security, improved insurance institutions, strengthening the value chain.

*Multiple responses exist

Source; Author's computation, 2024

Better market and price policies directly or indirectly affect food markets. Examples of public policies include public/government intervention in food markets and export/import restrictions. Typically, intervention by governments is aimed at maintaining grain stocks for emergency use. It is also an attempt to stabilize grain prices and provide grain to remote deficit areas. Depending on the motive, government intervention may either improve or hinder the integration of food markets. Government intervention may have both positive and negative effects on market integration. In the presence of export or import restrictions, food markets do not operate freely within and between countries. Even market information does not move freely, which affects market integration. Generally, export/import restrictions may reduce the degree of market integration. This needs to be proved further by research. The relationship between government intervention and price transmission still needs further research. More issues that need research include effect of export/import restrictions on price volatility and price transmission in food markets.

From this analysis, the work that has so far been done on market integration is well appreciated. However, we have also found out that there is still a lot that needs to be done in order to address and improve market integration in Nigeria.

Conclusions and Future Research:

The objectives of this review were to: analyze the state of the art research on food market integration; classify it; and provide a perspective for future research. The contribution of research work in food market integration during the period under study, that is, 2007 to 2025, has been increasing continuously. This is especially evident from 2017 to 2022. Much of the works have concentrated in south east and north east states on cowpea, maize and rice. However, there are many states and food commodities which have not caught the attention of researchers in this field. Future research should therefore include states and other commodities which have not been covered. Sample data, sampled commodity and sample states considered for future research should be altered to notice any variation in research results.

We have also noted the growth in research in food market integration. However, little has been done regarding application and/or implementation of the recommendations from these researches. The majority of the researches have concentrated relatively more on identifying the degree of price transmission or linkages among markets.

We also appreciate the recommendations from the works that have been done on market integration and, hence, identified the following factors as very important: better infrastructure, better price information flow, better market and price policy, provision of credit facilities, better supervision of market participants, provision of extension services. Notwithstanding there is still much that needs to be done. Future research on food market integration should address the following questions; how does the quality of physical infrastructure (roads, processing, storage) affect the speed of adjustment of markets in case of a shock? How has the popularity of mobile phone use among the farming communities affected the degree of food market integration? How does trust and networking among farmers and traders influence price transmission and market integration? What is the effect of export/import restrictions on price volatility and price transmission in food markets?

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FROM SOIL TO SHELF: EMERGING TRENDS IN AGRICULTURE, HORTICULTURE AND ALLIED SCIENCES

Aditi Vohra
Dronacharya Degree College,
Kurukshetra (Haryana) India
Corresponding author E-mail: aditikap09@gmail.com

Abstract:

The chapter examines the pivotal role of modernization and sustainability in transforming food systems. Agriculture and horticulture remain the backbone of food and nutritional security, livelihoods and rural economies, while allied sciences such as livestock, aquaculture, and integrated farming systems contribute to resilience and resource efficiency. The chapter highlights how emerging technologies, sustainable practices, and digital tools are reshaping production, postharvest management, and supply chains. Advances in agriculture focus on precision farming, smart technologies and genome editing tools such as CRISPR to enhance productivity, stress tolerance, and sustainability. Horticulture has been revolutionized by protected cultivation, biotechnology, and postharvest innovations, which improve quality, reduce losses, and expand opportunities in high-value crops and exports. Allied sciences have introduced genetic improvements in livestock, biofloc and recirculating systems in aquaculture, and integrated farming models that diversify income and conserve resources.

Digital and AI-based interventions including ICT tools, mobile apps, IoT, blockchain and smart marketplaces, are enabling real-time decision-making, transparency, and equitable farmer-to-consumer linkages. These tools enhance productivity and efficiency but face barriers of high costs, digital literacy, and infrastructure.

The chapter also underscores the challenges of climate change, resource constraints, and socio-economic barriers. Climate-smart agriculture, sustainable intensification, and farmer empowerment are identified as critical strategies for resilience. Policy support, inclusive investments, and holistic approaches integrating environmental, economic, and social considerations are essential for widespread adoption.

In conclusion, integrating modern technologies with sustainable practices provides a roadmap for resilient food systems. Collaboration across governments, businesses, and communities, alongside innovation and investment, is crucial to ensure food security, environmental sustainability, and socio-economic prosperity from soil to shelf.

Keywords: Precision Farming, Sustainable Agriculture, Horticultural Innovations, Digital Interventions, Resilient Food Systems.

1. Introduction:

Agriculture, horticulture and allied sciences are central to addressing the dual challenges of a growing global population and environmental change. This chapter emphasizes the importance of modernization and sustainability to enhance productivity while minimizing ecological impact. It further outlines the objectives and scope, focusing on the integration of advanced technologies and sustainable practices that can revolutionize these sectors.

Importance of Agriculture, Horticulture, and Allied Sciences

Agriculture and horticulture are vital for global food and nutritional security while also serving as the backbone of livelihoods and economic prosperity (Janbandhu *et al.,* 2024; Parmar & Pandey, 2024). Horticulture, in particular, offers higher productivity per unit of land and contributes significantly to rural income and employment (Parmar & Pandey, 2024). Within horticulture, floriculture plays an important role in the ornamental and decorative sectors, where emphasis on sustainability and efficient resource use is growing (Rabiya, 2024).

Need for Modernization and Sustainability

Modern agriculture and horticulture are increasingly shaped by technologies such as precision farming, automation, and artificial intelligence, which are crucial for improving efficiency and profitability (Shamkuwar *et al.,* 2024; Janbandhu *et al.,* 2024). Alongside modernization, sustainable practices like climate-smart agriculture, organic farming, and integrated pest management are essential to address environmental concerns and ensure long-term food security (Sani *et al.,* 2024; Kumar & Ahmad, 2023). The adoption of emerging tools, including geoinformatics and nanotechnology, further enhances productivity and supports sustainable resource management (Singh *et al.,* 2024; Parmar & Pandey, 2024).

Objectives of the Paper

1. To analyze the role of digital and AI-based technologies in transforming the agricultural sector.
2. To identify key tools such as ICT applications, Artificial Intelligence, Internet of Things, Blockchain, and Smart Marketplaces, and examine their agricultural applications.
3. To evaluate the benefits of these technologies in improving productivity, efficiency, sustainability, and farmer empowerment.
4. To highlight the challenges, including digital divide, infrastructure limitations, technical expertise gaps, and data security concerns.
5. To provide insights that can guide policymakers, researchers, and practitioners toward effective integration of digital and AI-driven solutions in agriculture.

Scope of the Paper

This chapter reviews and synthesizes existing literature on the applications of digital and AI-based interventions in agriculture with a focus on their transformative potential. It covers a range of emerging technologies, including ICT tools, Artificial Intelligence, IoT, Blockchain, and digital marketplaces, to showcase how these innovations are reshaping agricultural practices. The scope is limited to examining technological benefits, real-world applications, and implementation challenges within the agricultural context. While the paper highlights global advancements, its discussion emphasizes the relevance for developing economies like India, where digital adoption can bridge productivity gaps and ensure sustainable agricultural development.

2. Advances in Agriculture

Advancements in agriculture have been shaped by precision farming, smart technologies, crop improvement techniques, and sustainable practices. These innovations aim to enhance productivity, efficiency, and sustainability, addressing the challenges of population growth and environmental concerns. Precision farming and smart tools have transformed traditional methods by integrating data-driven approaches to optimize resource use and improve yields. At the same time, crop improvement through genomics and CRISPR provides new opportunities for developing resilient, high-yielding varieties. Sustainable practices, including organic farming and conservation agriculture, remain central to soil health and ecological balance (Mahanto *et al.,* 2024). The following subsections highlight these key areas of progress.

Precision Farming and Smart Technologies

- Precision farming employs GPS, GIS, and IoT tools for site-specific management, reducing input waste and promoting sustainability (Mahanto *et al.,* 2024; Khan & Babar, 2024).
- Smart technologies such as AI, sensors, and data analytics provide real-time information for crop monitoring, soil health analysis, and automated irrigation (Meena *et al.,* 2024).
- Drones and UAVs equipped with sensors enable early detection of crop health issues and soil stress, ensuring timely interventions (Somashekar *et al.,* 2024).

Crop Improvement (Genomics, CRISPR, Hybrids)

- CRISPR offers precise genome editing for crops with improved yield, disease resistance and stress tolerance, making it more efficient and cost-effective than traditional breeding (Sampath *et al.,* 2023).
- Genomic tools and advanced breeding approaches support the development of stress-resilient, high-yielding varieties that align with sustainability goals (Naresh *et al.,* 2024).
- Practical applications include CRISPR-modified crops such as disease-resistant wheat and drought-tolerant rice, demonstrating its potential in strengthening ecological sustainability (Sampath *et al.,* 2023).

Sustainable Farming Practices

- Sustainable agriculture integrates technology with traditional practices, emphasizing organic farming, conservation agriculture, and agroecological systems (Sulochna *et al.,* 2023).
- Conservation agriculture enhances soil health through crop rotation, reduced tillage, and reduced reliance on synthetic inputs (Nemade *et al.,* 2023).
- Use of renewable energy and local resources further strengthens environmental conservation and food security (Saikanth *et al.,* 2023).

Challenges and Considerations

While these innovations hold great promise, adoption faces hurdles. Regulatory restrictions, public perception, and technical limitations can slow the use of technologies such as CRISPR (Sampath *et al.,* 2023). Similarly, transitioning to sustainable practices requires strong policy support, farmer training, and awareness programs to encourage adoption (Saikanth *et al.,* 2023). Despite these challenges, responsible implementation of modern technologies and sustainable approaches remains essential for achieving a secure and resilient agricultural future.

3. Advances in Horticulture

Advances in horticulture have significantly transformed the landscape of agricultural production, focusing on protected and controlled cultivation, biotechnological interventions, post-harvest management, and high-value crop production for export opportunities. These innovations aim to enhance productivity, sustainability, and economic viability in the horticultural sector. The integration of advanced technologies and practices is pivotal in addressing global food security challenges while ensuring environmental sustainability (Jain, 2023).

Protected and Controlled Cultivation

Protected cultivation techniques, such as greenhouses, high tunnels, and shade houses, offer numerous benefits including increased yield, enhanced quality, and protection against adverse climatic conditions and pests (Singh, 2024). Advanced methods like hydroponics, aeroponics, and vertical farming maximize productivity while minimizing resource consumption (Jain, 2023). The use of smart farming technologies, artificial intelligence, and precision agriculture further optimizes resource utilization and improves crop monitoring and management (Banjare, 2024).

Biotechnological Interventions

Biotechnology and genetic engineering are redefining crop development by creating resilient and high-yielding varieties crucial for sustainable food production (Sharma, 2023). Techniques such as tissue culture and genome editing are used to develop new cultivars with improved traits, leading to higher productivity and better quality (Janbandhu, 2024).

Post-Harvest Management and Value Addition

Post-harvest management practices are essential for maintaining quality and extending the shelf life of horticultural products, thereby reducing losses and increasing market value. Additionally, value addition through processing and packaging enhances the competitiveness of horticultural produce in domestic and international markets (Verma, 2023).

High-Value Crops and Export Opportunities

The cultivation of high-value crops such as fruits, vegetables, and ornamentals significantly contributes to the agricultural economy, particularly in developing countries where horticulture plays a vital role in GDP and employment. A strong export market for horticultural products not only boosts economic growth but also provides farmers with opportunities to access global markets (Ahmad, 2023).

Sustainability Challenges and Future Prospects

Despite these advancements, challenges such as high initial costs, energy requirements, and the need for skilled labor persist. To address these concerns, sustainable approaches like renewable energy use, organic farming, and integration of digital technologies are being explored to promote ecological balance and long-term productivity (Banjare, 2024; Jain, 2023).

4. Advances in Allied Sciences

Advances in allied sciences have significantly influenced livestock, dairy, fisheries, aquaculture, and integrated farming systems. These innovations are driving productivity, sustainability, and resilience while addressing pressing global challenges such as climate change, food security, and environmental protection. By integrating diverse agricultural practices into cohesive systems, allied sciences are improving resource efficiency, reducing environmental footprints, and enhancing economic viability (Bhattacharyya *et al.,* 2020). The following sections highlight key innovations in these domains.

Livestock and Dairy Innovations

- **Breeding and Genetics:** Modern breeding techniques are improving livestock resilience to climate change by enhancing heat tolerance, disease resistance, and nutritional efficiency, ensuring sustained productivity under adverse conditions (Bhattacharyya *et al.,* 2020).
- **Nutritional Advancements:** Feed innovations, including organic waste-based diets, have enhanced animal health and productivity while simultaneously lowering environmental impacts (Zulkifli, 2024).
- **Health Management:** The use of information and communication technology (ICT) in livestock systems enables real-time health monitoring, supports better decision-making, and reduces labor costs (Zulkifli, 2024).

- **Environmental Sustainability:** Precision farming, efficient waste management, and other sustainable practices in dairy farming are minimizing environmental footprints while boosting efficiency (Gheorghe-Irimia *et al.,* 2023).

Fisheries and Aquaculture Innovations

- **Biofloc Technology:** This approach improves water quality and fish health by fostering beneficial microbial communities, thereby reducing water exchange needs and increasing feed efficiency.
- **Recirculating Aquaculture Systems (RAS):** RAS enhances sustainability by optimizing water and space use, making aquaculture adaptable to climate change.
- **Integrated Aquaculture:** Incorporating multiple species such as fish and shellfish within the same system optimizes resources and strengthens ecosystem health, contributing to sustainable aquaculture (Choudhury *et al.,* 2023).

Integrated Farming Systems (IFS)

- **Crop-Livestock-Horticulture Linkages:** By integrating crops, livestock, and horticulture, IFS maximizes resource utilization, enriches soil health, reduces chemical inputs, and diversifies income (Singh *et al.,* 2024; Bahadur *et al.,* 2024).
- **Agroforestry:** Incorporating trees into farms enhances biodiversity conservation, carbon sequestration, and microclimatic regulation for both crops and livestock (Walia & Kaur, 2023).
- **Socio-Economic Benefits:** IFS increases employment opportunities, strengthens food security, and yields higher net returns than conventional farming while meeting socio-economic and ecological needs, making it a strong model for sustainable rural development (Seth *et al.,* 2023; Tiwari, 2023).

Challenges and Way Forward

Despite these advancements, challenges such as high initial costs, labor shortages, and inadequate policy support hinder adoption. Overcoming these barriers is crucial for scaling up sustainable innovations. Integrating technology with eco-friendly principles in livestock and aquaculture management will not only enhance productivity but also minimize environmental burdens, ensuring the long-term sustainability of these sectors (Zulkifli, 2024).

5. Digital and AI-Based Interventions

The integration of digital and AI-based interventions is reshaping agriculture by revolutionizing farm management, supply chains, and marketplaces. Technologies such as Information and Communication Technology (ICT), Artificial Intelligence (AI), the Internet of Things (IoT), and blockchain are enhancing efficiency, transparency, and sustainability in farming. These tools enable precision agriculture, improve resource management, and create more resilient food systems.

- **ICT Tools, Mobile Apps, and E-Extension Services:** ICT tools, including mobile apps and e-extension services, play a key role in delivering knowledge and resources to farmers. Platforms like India's *mKisan* and Africa's *e-Agriculture* provide real-time, location-specific updates on weather, pests, and markets, thereby supporting productivity and resilience. However, challenges such as the digital divide, limited access, and low digital literacy persist, highlighting the need for rural connectivity and capacity-building initiatives (Khatri *et al.,* 2024).
- **AI, IoT, and Blockchain in Farm Management and Supply Chains:** AI optimizes resource use and predicts outcomes, while IoT supplies real-time data for precision farming and livestock monitoring. Blockchain ensures transparency and security in supply chains, improves traceability, and facilitates farmer-to-consumer linkages. Together, these technologies address critical concerns such as climate change adaptation, food safety, and resource efficiency, though challenges like high implementation costs and data protection remain (Mahalle & Dongre, 2024; Pathak *et al.,* 2024).
- **Smart Marketplaces and E-Commerce in Agriculture:** Digital innovations are also transforming agricultural marketplaces. E-commerce platforms supported by AI and blockchain enable direct farmer-consumer transactions, reduce fraud, and promote fair pricing. By ensuring traceability and monitoring sustainable practices, these platforms enhance equity and environmental responsibility (Mishra & Raghuvanshi, 2024).

In summary, digital and AI-based interventions hold immense promise for advancing agricultural sustainability and food security. Yet, their effective implementation requires supportive infrastructure, digital literacy, and policy frameworks to overcome existing barriers.

6. Role of Digital and AI-Based Tools in Agriculture

Table 1 highlights the emerging digital and AI-based interventions revolutionizing agriculture by improving productivity, efficiency, and transparency. ICT tools and mobile apps such as *mKisan* and e-extension services are increasingly used to deliver real-time, location-specific information related to weather, pests, and market prices, thereby strengthening farmer knowledge and resilience. Artificial Intelligence (AI) supports predictive analytics, crop yield estimation, resource allocation, and precision farming, offering significant benefits in reducing costs and optimizing inputs, although high implementation costs and the need for technical expertise remain major challenges. The Internet of Things (IoT) facilitates real-time data collection in precision agriculture, livestock monitoring, and soil and water management, enabling informed decision-making, though infrastructure limitations often restrict adoption. Similarly, blockchain technology plays a key role in ensuring supply chain transparency, food safety traceability, and fair farmer compensation through decentralized marketplaces, despite facing barriers such as data protection concerns and high adoption costs. Smart marketplaces and e-commerce platforms also empower farmers by promoting direct farmer-to-consumer transactions, fair pricing, and sustainable practices, though they require strong digital literacy and secure platforms for effective functioning.

Table 1: Digital and AI-Based Interventions in Agriculture

Technology/Tool	Applications in Agriculture	Benefits	Challenges
ICT Tools & Mobile Apps (mKisan, e-Agriculture, E-extension services)	Dissemination of real-time, location-specific information (weather, pests, market prices).	Enhances productivity, resilience, and knowledge dissemination.	Digital divide, limited rural connectivity, low digital literacy (Khatri *et al.,* 2024).
Artificial Intelligence (AI)	Predictive analytics, crop yield estimation, resource allocation, precision farming.	Optimizes inputs, reduces costs, increases efficiency.	High implementation costs, need for technical expertise (Mahalle & Dongre, 2024; Pathak *et al.,* 2024).
Internet of Things (IoT)	Real-time data collection for precision agriculture, livestock monitoring, soil & water management.	Improved decision-making, better resource management.	Infrastructure and connectivity issues (Pathak *et al.,* 2024).
Blockchain	Supply chain transparency, food safety traceability, decentralized marketplaces.	Reduces fraud, enhances trust, ensures fair farmer compensation.	Data protection issues, adoption challenges, high costs (Mishra & Raghuvanshi, 2024; Radhika *et al.,* 2024).
Smart Marketplaces & E-Commerce	Direct farmer-to-consumer transactions, integration with AI & blockchain for sustainable practices.	Promotes equity, reduces intermediaries, ensures fair prices, supports sustainability.	Requires digital literacy, secure digital platforms (Mishra & Raghuvanshi, 2024)

Conclusion:

From Soil to Shelf underscores that the future of food systems hinges on integrating modernization with sustainability across agriculture, horticulture, and allied sciences. Evidence from the chapter shows how precision farming, smart tools, and genome editing in agriculture; protected cultivation, biotechnology, and robust postharvest management in horticulture; and innovations in livestock, aquaculture, and integrated farming systems collectively lift productivity, resource-use efficiency, and resilience. Digital and AI-based interventions- ICT, IoT, AI, blockchain and smart marketplaces further enable real-time decisions, transparency, and fairer farmer–consumer linkages, as summarized in Table 1.

Yet, scaling these advances requires confronting systemic constraints. Climate change, water and land pressures, and socio-economic barriers high upfront costs, limited finance, insecure land tenure, and skills gaps can slow adoption. Digital divides, infrastructure deficits, and data protection concerns add new layers of risk. Without enabling policies, targeted investments, and capacity building, the benefits of innovation may remain unevenly distributed.

The chapter identifies practical pathways to close this implementation gap. Climate-smart agriculture aligns productivity, adaptation, and mitigation, strengthened by digital tools, optimized cropping choices, and risk-transfer instruments. Sustainable intensification including conservation practices, integrated systems, and ecological approaches raises output without expanding land while safeguarding soil, biodiversity, and water. Farmer empowerment through education, producer collectives, and improved market access ensures that smallholders can participate in and benefit from technological change.

Operationalizing this agenda calls for coordinated action: data-driven management across the value chain; investment in rural connectivity, extension, and skills; supportive credit and incentives for sustainable practices; and governance that builds trust, ensures traceability, and protects privacy. Equally important is weaving traditional knowledge with modern science to fit local ecologies and cultures.

In sum, transforming food systems "from soil to shelf" is achievable when technological innovation and sustainability move together, and when policies, markets, and communities align. With collaboration among governments, businesses, and consumers and sustained investment in people and place the sector can deliver secure, equitable, and environmentally responsible food systems for the future.

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SUSTAINABLE VEGETABLE PRODUCTION THROUGH KITCHEN GARDENING

Satyendra Kumar*[1], Chandra Jeet Yadav[2] and Krishan Pal[3]

[1]Department of Vegetable Science,

Chandra Shekhar Azad University of Agriculture & Technology, Kanpur, Uttar Praesh

[2]Sam Hingginbottom University of Agriculture Technology and Sciences, Prayagraj

[3]College of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab

*Corresponding author E-mail: drskraja9@gmail.com

Introduction:

Kitchen gardening, also known as home gardening, is a sustainable practice of growing vegetables, herbs, and sometimes fruits in residential spaces for household consumption. It encourages environmental sustainability, food security, and self-reliance. Kitchen gardening becomes a vital component of sustainable living as urbanization rises and food supply systems are strained by population expansion and climate change. The idea of kitchen gardening is examined in this chapter along with its benefits, planning, methods, difficulties, and potential future applications in sustainable vegetable production. Sustainable vegetable production has emerged as a top issue in light of the world's increasing urbanization, climate change, and food poverty. Kitchen gardening, an ancient tradition that is regaining popularity in contemporary urban settings, is one viable and approachable way to solve this dilemma. Kitchen gardening, commonly known as home gardening, is the practice of growing vegetables, herbs, and even tiny fruits on one's property, such as a backyard, balcony, rooftop, or even a window ledge. This approach promotes community well-being and environmental sustainability while empowering people and families to grow fresh, nutritious, and pesticide-free food. A lifestyle that emphasizes self-reliance in food production, resource efficiency, and a closer relationship with nature, kitchen gardening is more than simply a way to produce food. Urban dwellers are increasingly looking to kitchen gardens as a dependable option due to the rising expense of vegetables, the increased use of hazardous pesticides in conventional farming, and the growing public awareness of nutrition and health. These little, self-tended gardens give individuals control over the quality of the food they eat, lessen reliance on outside food systems, and offer a consistent supply of in-season veggies. From a sustainability standpoint, kitchen gardening fits in nicely with the ideas of responsible living and environmental preservation. It considerably lowers the supply chain's carbon footprint by reducing the requirement for food transportation. Additionally, the practice promotes the composting and reuse of kitchen waste, which lowers family trash and organically enriches the soil. Organic waste, including leftovers and peels, may be composted to create nutrient-rich manure, and water used to wash rice or vegetables can be recycled for irrigation. Kitchen gardening is a low-input, zero-waste hobby that promotes eco-friendly living and the circular economy thanks to these straightforward yet efficient methods. Kitchen gardening has significant social and psychological benefits in addition to environmental ones. By guaranteeing consistent access to fresh, unadulterated veggies, it improves food and nutritional security. When family members—including young children and the elderly—garden together, it also acts as a constructive recreational activity that lowers stress, enhances mental health, and promotes intergenerational learning. Kitchen gardens enhance air quality and lessen the heat island effect in crowded urban areas by adding to the urban green cover. Kitchen gardening provides a viable and scalable way to produce food sustainably at the home level as cities becoming more crowded and arable land becomes more limited. Even the tiniest areas may be turned into fruitful gardens with careful design, the right crop selection, and the application of contemporary methods like hydroponics, vertical farming, and organic pest management. Furthermore, the influence of kitchen gardening may be increased by incorporating it into government programs, school curriculum, and urban development strategies.

1. Concept of Kitchen Gardening

Kitchen gardening refers to the cultivation of edible plants in small plots of land, containers, balconies, terraces, or rooftops, usually adjacent to or near the kitchen. In contrast to commercial farming, the main goal of kitchen gardening is to meet the household's nutritional requirements rather than produce for the market. The activity of growing vegetables, herbs, and occasionally fruits in and around the home, usually for domestic use, is known as kitchen gardening. It is an inexpensive, sustainable, and small-scale way to grow fresh food, frequently on windowsills, balconies, terraces, or backyards. In contrast to commercial agriculture, kitchen gardening prioritizes environmental health, nourishment, and self-sufficiency over financial gain. It promotes families to cultivate their own produce, take charge of their food supply, and lessen their need on veggies from the market. The idea encourages the economical use of resources including sunshine, water, organic kitchen waste, and space. Even those with little area may have fruitful gardens by using easy methods like composting, vertical stacking, and container planting. By combining various crops, herbs, and beneficial insects in a compact space, kitchen gardening also promotes biodiversity. By doing away with the packaging and shipping that come with store-bought vegetables, it contributes to a smaller carbon impact. Additionally, kitchen gardening is essential for enhancing food security in the home, fostering health, and providing recreational and educational advantages. It acts as a useful example of responsible living and urban sustainability. Kitchen gardening is becoming more and more popular as a dependable and fulfilling hobby in contemporary households as awareness of food quality and ecological effect increases.

1.1 Objectives of Kitchen Gardening:

- To provide fresh and pesticide-free vegetables.
- To ensure nutritional security at the household level.
- To recycle household biodegradable waste as compost.
- To utilize limited space and water resources effectively.
- To promote physical and mental well-being.

1.2 Scope and Importance

The need for organic food and growing health consciousness have made kitchen gardening much more important. In addition to its economic and health advantages, it also helps the environment by lowering the carbon footprint of packing and shipping of vegetables purchased from the market. Kitchen gardening is becoming more and more popular, particularly in metropolitan and peri-urban settings where people are becoming more concerned about sustainability, food safety, and health. With little room and money, it offers families and individuals an efficient way to grow fresh, pesticide-free veggies. Kitchen gardening may be adapted to many environmental circumstances and lifestyles, making it appropriate for both urban and rural apartment inhabitants, whether it is done on rooftops, balconies, terraces, or tiny backyard plots. Kitchen gardening is significant since it has several advantages for the environment, economics, and health. By guaranteeing access to fresh, nutrient-dense, and in-season vegetables, it improves food and nutritional security. It lowers home food expenses, lessens reliance on market produce, and promotes composting of biodegradable trash. Because veggies don't need to be packaged or transported across great distances, it lessens their environmental impact. Additionally, kitchen gardening raises knowledge of biodiversity, ecological methods, and the sources of food. It may also be used as a therapeutic exercise for people of all ages and as an educational tool for kids. Kitchen gardening offers a viable and significant way to alleviate urban food issues and promote healthier and more environmentally friendly lives as society shifts toward more sustainable living patterns.

2. Role of Kitchen Gardening in Sustainable Vegetable Production

Kitchen gardening plays a vital role in promoting sustainable vegetable production by encouraging environmentally friendly, low-input, and resource-efficient practices. By enabling homes to produce vegetables organically without the use of artificial chemicals, it preserves biodiversity, improves soil health, and lowers pollution. Kitchen gardening lessens the strain on farms and the ecological footprint associated with the transportation and packing of food by making use of tiny urban areas like backyards, balconies, and roofs. By composting kitchen trash, using basic irrigation techniques to conserve water, and cultivating a variety of crops, it promotes sustainable living. It improves food security and nutritious consumption while economically lowering household spending on veggies. Socially, it promotes health awareness, knowledge exchange, and community involvement. Additionally, kitchen gardening encourages climate resilience at the local level and gives people the power to take charge of their food systems. It combines the production of food with ecological management and responsible consumption, making it a useful example of sustainability. By encouraging biodiversity, lowering reliance on outside inputs, and avoiding environmental damage, kitchen gardening is consistent with the tenets of sustainable agriculture.

2.1 Environmental Sustainability

Kitchen gardening significantly contributes to environmental sustainability by reducing food miles and lowering greenhouse gas emissions associated with the transportation, packaging, and storage of commercially produced vegetables. Kitchen gardens reduce the damaging effects of long supply chains on the environment by growing food near where it is eaten. This method also encourages the composting of organic household trash, which turns leftover food, fruit scraps, and vegetable peels into nutrient-rich manure. In addition to lowering the amount of garbage dumped in landfills, this organically improves the soil and lessens the need for artificial fertilizers. Furthermore, kitchen gardens add extra green space to cities, particularly in places with high population densities. The addition of plants to homes, balconies, and rooftops improves air quality, lowers the urban heat island effect, and promotes biodiversity by drawing beneficial insects and pollinators. In this way, kitchen gardening becomes a practical tool for promoting ecological balance and environmental health in urban settings.

2.2 Economic Sustainability

Kitchen gardening plays a significant role in promoting economic sustainability at the household level. Since a portion of their nutrition comes from their own garden, families may significantly reduce their daily food expenditures by producing vegetables at home. This independence lessens reliance on goods bought from the market, which frequently has price swings. Because fewer excursions to supermarkets or vegetable markets are needed, it also indirectly lowers gasoline and transportation expenses. Kitchen gardening also creates small-scale business options for a lot of urban and peri-urban residents. The demand for organically farmed vegetables and herbs is rising, and excess produce may be sold in nearby villages. Additionally, some families and individuals make extra money by selling garden kits, compost, or plant seeds. Thus, kitchen gardening not only supports a sustainable food system but also encourages economic empowerment and income diversification through home-based agricultural activities.

2.3 Social and Nutritional Sustainability

Kitchen gardening contributes meaningfully to both social and nutritional sustainability. A healthy and balanced diet depends on frequent access to fresh, in-season, and nutrient-rich produce, which is ensured by empowering homes to cultivate their own veggies. By doing this, the consumption of highly processed or chemically treated vegetables which are frequently seen in commercial markets is decreased. In addition to enhancing nutrition, kitchen gardening helps family members including kids develop their food literacy by teaching them about the origins and cultivation methods of food. It raises awareness of sustainable living methods, the value of food diversity, and good eating habits. Through communal gardens, knowledge-sharing clubs, or shared growing areas, kitchen gardening may foster social cohesion, particularly in metropolitan areas. These exchanges foster a culture of environmental stewardship, foster collaboration, and build ties within the community. As a result, kitchen gardening not only nurtures the body but also cultivates a sense of community and shared purpose.

3. Planning a Kitchen Garden

Planning a kitchen garden involves selecting a sunny location, organizing space efficiently with containers or beds, choosing seasonal crops, and ensuring access to water and compost. Proper planning enhances productivity, conserves resources, and supports continuous harvests. It transforms even small urban spaces into sustainable sources of fresh, healthy vegetables. Successful kitchen gardening requires careful planning considering available space, climate, crop selection, and resource availability.

3.1 Site Selection

Choosing a location is essential to starting a successful kitchen garden. Since most vegetable crops need enough light to develop healthily and produce at their best, the chosen spot should ideally get 4 to 6 hours of direct sunshine every day. Additionally, choosing a location near the kitchen is crucial for frequent maintenance and harvesting convenience. Simple access promotes regular participation and garden upkeep. In order to avoid waterlogging, which can damage plant roots, the location also has to have a trustworthy water source close by and enough drainage. A successful kitchen garden starts with a well-chosen location.

3.2 Garden Layout

For kitchen gardening to maximize space and production, an effective garden layout is crucial. To cultivate a variety of vegetables, one can use hanging pots, vertical stacking, raised beds, or containers, depending on the available space. Creating zones in the garden facilitates better crop management; for example, allocating certain spaces for leafy vegetables, fruiting plants, and herbs improves maintenance and harvesting effectiveness. Furthermore, using companion planting strategies, like matching marigold with vegetables or basil with tomatoes, can naturally ward off pests and increase production. Better use of resources, stronger plants, and year-round vegetable output are all guaranteed by a well-planned layout.

3.3 Tools and Inputs

Effective kitchen gardening requires having the appropriate equipment and supplies. For chores like soil preparation, planting, watering, and trimming, basic hand tools like a trowel, hoe, watering can, and pruners are needed. For plants to develop healthily, high-quality inputs are just as important as equipment. These consist of vermicompost to increase soil fertility, coco peat to improve moisture retention in containers, neem oil for natural insect management, organic compost to enhance the soil, and seeds of appropriate vegetable kinds. A successful, environmentally responsible, and manageable kitchen gardening experience is ensured by using the right equipment and organic supplies.

4. Suitable Vegetables and Herbs for Kitchen Gardening

Some vegetables and herbs are particularly well-suited for kitchen gardening due to their short growing cycles and adaptability to containers.

4.1 Leafy Vegetables

Leafy vegetables are ideal for kitchen gardening due to their quick growth, high nutritional value, and suitability for small spaces. Common leafy greens such as spinach, fenugreek, lettuce, amaranth, and coriander can be easily grown in containers, raised beds, or even small trays. These crops require minimal maintenance and can be harvested multiple times, offering a continuous supply of fresh, pesticide-free greens for household consumption. They thrive well in partial sunlight and are perfect for balcony or terrace gardens. Including leafy vegetables in a kitchen garden ensures regular access to essential vitamins, minerals, and dietary fibre.

4.2 Fruiting Vegetables

Since fruiting vegetables are frequently used in everyday cooking and offer large yields, they are attractive candidates for kitchen gardening. Tomato, brinjal (eggplant), chilli, okra, cucumber, and other crops do well in containers, grow bags, or raised beds that receive enough sunlight and attention. Stakes or trellises are typically needed for these plants in order to promote healthy development and improved fruiting, particularly for tomatoes and cucumbers. They flourish in nutrient-rich, well-drained soil and gain from frequent watering and organic fertilization. A consistent supply of fresh, chemical-free product is guaranteed when growing fruity veggies at home.

4.3 Root and Tuber Crops

When planted in raised beds with loose, well-drained soil, grow bags, or deep containers, root and tuber crops thrive in the kitchen. Radish, carrot, beetroot, onion, and garlic are among the often planted varieties. For healthy development, these crops need a lot of subterranean area, and they thrive in sandy-loam soil that has been supplemented with compost. They require little care and may be produced from bulbs and cloves (onion and garlic) or seeds (carrot and radish). Vegetables with roots and tubers are a nutritious supplement to everyday meals and are high in vital nutrients. They are perfect for urban kitchen gardens since they can be grown successfully in tiny areas.

4.4 Herbs

Herbs are an essential component of kitchen gardening due to their culinary, medicinal, and aromatic value. Herbs like mint, basil, curry leaves, lemongrass, and oregano are easy to grow in window boxes, little pots, or containers and require little room and care. These plants like sunny spots with frequent watering and do best in soil that drains properly. Basil and oregano are perfect for flavoring and garnishing, while mint and lemongrass are resilient and spread easily. Curry leaves may be grown in bigger pots and are used extensively in Indian cooking, despite their slower growth rate. A kitchen garden that includes herbs guarantees a year-round supply that is tasty, fresh, and healthful.

5. Sustainable Practices in Kitchen Gardening

In addition to increasing output, using sustainable kitchen gardening techniques guarantees resource efficiency and environmental preservation. Over time, the garden will become healthier and more robust thanks to these techniques, which emphasize organic inputs, natural insect control, water conservation, and intelligent crop management. Using organic fertilizers and manure is one of the most significant sustainable strategies. Gardeners may make compost from home kitchen waste, such as vegetable peels, fruit scraps, and leftover food, as an alternative to artificial fertilizers. In addition to lowering household trash, this organically improves the soil. Applying vermicompost, cow dung manure, and bio-fertilizers improves soil fertility even more, encourages microbial activity, and gives plants vital nutrients. Long-term soil sustainability and plant health are enhanced by these organic inputs. Another important aspect of sustainable kitchen gardening is managing pests and diseases. Natural alternatives to conventional pesticides, such soap solutions, garlic-chilli extracts, and neem oil sprays, can be used to keep pests away. When planted alongside crops, some plants, such as marigold, can act as organic insect repellents. For small-scale gardens, manual removal of pests and diseases leaves works well as well. These environmentally friendly techniques support the preservation of ecological equilibrium without endangering the ecosystem or beneficial insects. Particularly in metropolitan areas where water supplies are scarce, effective water conservation measures are essential. For container plants, drip irrigation systems may be utilized to assure focused watering and reduce water waste. Mulching with straw, grass clippings, or dried leaves helps control temperature, inhibit weed development, and hold onto soil moisture. Another useful strategy to save water and cut down on home waste is to reuse kitchen wastewater for plant watering after it has been filtered and checked for dangerous substances. By improving soil health and lowering the accumulation of pests and diseases, crop rotation and intercropping are also beneficial for sustainability. To avoid nutrient depletion and disturb insect life cycles, crops including leafy greens, root vegetables, and fruiting plants should be rotated in different cycles. Growing two or more suitable crops together, known as intercropping, makes the most of available space, boosts production, and builds a more resilient and varied garden ecology. Legumes, for example, may naturally raise soil nitrogen levels when planted with heavy feeders like tomatoes. Together, these sustainable practices create a kitchen garden that is not only productive but also environmentally responsible. They promote a closed-loop system where waste is minimized, resources are optimized, and food is grown in harmony with nature making kitchen gardening a true model of urban agricultural sustainability.

6. Challenges in Urban Kitchen Gardening

Urban kitchen gardening presents a number of practical difficulties despite its many advantages. Space limitations are one of the biggest problems because most urban residences have a small balcony or patio. This limits the kind and quantity of crops that may be cultivated; therefore creative solutions like wall-mounted planters, hanging pots, and vertical gardening are needed to make the most of the space. The ignorance and incompetence of urban dwellers is another significant issue. Essential elements of soil management, pest and disease control, organic agriculture methods, and plant care are often unknown to the general public. This disparity emphasizes the necessity of focused training initiatives, public awareness campaigns, and professional advice. Another major issue is water shortage, as regular irrigation is impacted by cities' erratic water supplies. Promoting effective watering techniques like drip or micro-irrigation is necessary to get around this. Additionally, pests and diseases are common in urban gardens, particularly in tiny, varied plots where plant protection becomes increasingly difficult. Last but not least, kitchen gardens are frequently neglected and poorly maintained due to time restrictions brought on by hectic metropolitan lifestyles and work commitments. To make urban kitchen gardening more sustainable and accessible, these issues must be addressed by community support, clever solutions, and education.

7. Future Prospects and Recommendations

In the upcoming decades, kitchen gardening has enormous promise as a sustainable way to address food and nutritional security, particularly in light of the rising public concern about food quality, increased urbanization, and climate change. Kitchen gardening has the potential to grow from a small-scale pastime into a major movement that supports resilient food systems and healthier communities with the right encouragement, creativity, and incorporation into urban design. Integration with smart cities is one possible approach. Edible landscaping the design of public and private settings with food-producing plants—can encourage kitchen gardening as urban development increasingly embraces green and sustainable practices. By incorporating kitchen gardens into the very fabric of city planning, policies and incentives that promote green rooftops, balcony gardening, and vertical farming systems may transform underutilized areas into environmentally friendly and productive areas. Innovations in technology will also be essential to the advancement of kitchen gardening. Gardeners may get up-to-date advice on planting, disease detection, pest control, and harvest management by using mobile applications. Furthermore, automated technology like fertigation systems, drip irrigation controllers, and moisture sensors may minimize human labor and maximize resource utilization, making gardening simpler and more effective for time-pressed city dwellers. Research and development expenditures are essential to the future of kitchen gardening. The development of small, fast-growing, high-yielding vegetable types that are suitable for container or terrace gardening is necessary. Particularly in urban areas with low soil quality, advancements in soilless growth medium such as coco peat, hydroponic solutions, and organic fertilizer formulations can increase productivity and lessen reliance on conventional soil resources. Finally, the key to mainstreaming kitchen gardening is awareness and education. It may foster an early understanding of sustainable food systems and environmental responsibility by being incorporated into curricula at schools and universities. Workshops at the community level, practical demonstrations, and online training sessions can equip more individuals with the skills and self-assurance they need to begin their own gardens. Partnerships with housing societies, local governments, and non-governmental organizations can also increase outreach and offer resource or infrastructural support.

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URBAN ORCHARD DEVELOPMENT: PLANNING AND MANAGEMENT IN COMPACT SPACES

Satyendra Kumar*[1], Chandra Jeet Yadav[2] and Krishan Pal[3]

[1]Department of Vegetable Science,

Chandra Shekhar Azad University of Agriculture & Technology, Kanpur, Uttar Praesh

[2]Sam Hingginbottom University of Agriculture Technology and Sciences, Prayagraj

[3]College of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab

*Corresponding author E-mail: drskraja9@gmail.com

1. Introduction:

Urbanization is rapidly transforming landscapes across the globe, often leading to the loss of green spaces and agricultural land. Agriculture and horticulture are being forced farther away from urban areas due to the tremendous strain that growing cities and populations are putting on the land. Cities are thus confronted with issues including decreased domestic food production, heightened reliance on food imports, biodiversity loss, and deteriorated environmental quality. The idea of urban orchards has drawn a lot of interest in response to these worries as well as growing awareness of food security, environmental sustainability, and the health advantages of green spaces. Intentional plantings of fruit-bearing trees and shrubs inside city limits, known as urban orchards, have become a creative and useful way to regenerate urban areas, re-establish a connection between communities and environment, and encourage local food production. There are several social, economic, and ecological advantages to urban orchards. As natural carbon sinks, these green projects contribute to a reduction in air pollution on an ecological level. Urban air quality is improved by trees because they emit oxygen and collect carbon dioxide. Additionally, by lowering surface temperatures and offering shade, they help to moderate urban heat islands. By stabilizing the soil and lowering runoff, their roots lessen the likelihood of urban flooding. Because orchards provide microhabitats for beneficial insects, pollinators, and birds, biodiversity is also improved and the urban environment becomes more robust and balanced. In terms of nutrition, urban orchards offer a supply of locally grown, seasonal, and fresh fruits that can enhance urban dwellers' diets. These orchards may be extremely important in guaranteeing food availability and nutrition security in many metropolitan locations, particularly in underprivileged populations or food deserts where access to fresh fruit is restricted. Communities may lessen their reliance on processed foods and long-distance supply chains, which frequently contribute to greenhouse gas emissions and food spoilage, by picking fruits straight from nearby trees. Through the sale of fruits, jams, juices, and other value-added goods, urban orchards can economically lower family food prices and create possibilities for small-scale urban businesses. From a sociological point of view, urban orchards promote pride and a sense of communal engagement. They frequently develop into centers for leisure, social interaction, and education. By taking part in planting, caring for, and harvesting activities, community members especially kids, students, and older citizens can improve civic participation and intergenerational linkages. These orchards may serve as living labs for educational institutions, providing hands-on learning opportunities in disciplines like nutrition, biology, and environmental science. Access to fresh fruit and open areas improves mental and physical health, lowers stress levels, and encourages active lives, all of which promote public health.

However, careful planning and creative approaches are needed to create and maintain urban orchards in constrained areas. Given the constrained and frequently dispersed land resources found in cities, finding appropriate sites for fruit tree planting necessitates an innovative strategy. There is potential for orchard development in underutilized areas including rooftops, balconies, terraces, school grounds, roadside verges, abandoned lots, and even vertical walls. Particularly popular in many urban locations are rooftop orchards, which turn concrete surfaces into fruitful landscapes. Similar to this, fruit may be grown over walls and fences using vertical gardening systems and espalier techniques, which maximize productivity per square meter. Choosing suitable plant species that are tolerant of the local climate, low care, and able to flourish in limited root zones is essential when designing an urban orchard in a space-constrained environment. Fruit trees of the dwarf and semi-dwarf species are especially well suited since they reach manageable heights and are simpler to maintain, harvest, and keep pests away from. Examples include berry-producing shrubs like mulberries, gooseberries, and blueberries, as well as citrus, pomegranate, fig, apple, and miniature guava kinds. To improve the space's visual and sensory appeal, species selection should take into account not just edibility but also aesthetics, aroma, and shade-providing qualities. The use of suitable growing techniques designed for small spaces is also essential to the development of urban orchards. In situations where soil is inadequate or unavailable, fruit plants are increasingly being grown using container gardening raised beds, soil-less medium like coco-peat, and hydroponic systems. Maintaining orchards with low water use requires effective irrigation methods, especially drip irrigation and rainwater collection. Urban sustainability may be completed by composting and reusing organic waste produced in homes and communities as a source of nutrients. To protect inhabitants' health and safety, an emphasis on integrated pest management (IPM) techniques such as companion planting, biological control, and natural repellents should take precedence over the use of chemicals. The development and use of inclusive policy frameworks is another crucial component of urban orchard planning. Urban planning organizations, municipal authorities, and local governments must acknowledge the value of green infrastructure and integrate orchard development into zoning laws, city master plans, and climate action plans. Tax breaks, subsidies, and technical support are a few examples of incentives that might motivate private developers, residents' welfare organizations, schools, and people to start orchard initiatives. Community-driven strategies and public-private partnerships work particularly well for long-term sustainability of such programs.

Urban orchard upkeep calls for on-going community participation and responsibility. Collaborative gardening activities, volunteer initiatives, and training seminars may all support knowledge transfer and capacity building. Mobile applications for pest identification, care reminders, and orchard mapping are examples of digital solutions that can further simplify maintenance tasks and include tech-savvy urban youth. Numerous effective urban orchard initiatives across the world offer motivation and useful advice. For example, the Incredible Edible movement in the UK has used community-led fruit and vegetable plantings to turn towns into edible landscapes. In the United States, fruit parks and edible walking routes are open to the public in places like Los Angeles and Seattle. In Indian cities like Delhi and Mumbai, groups like "Edible Routes" and "Urban Leaves" are advocating for permaculture gardens and rooftop orchards. These case studies show that, with the correct combination of foresight, dedication, and cooperation, urban orchards may thrive and are not just abstract ideas. The creation of urban orchards offers a creative, sustainable, and neighbourhood focused strategy for improving the greenness, health, and independence of cities. Fruit-bearing trees, no matter how little or unusual, may be carefully incorporated into urban landscapes to help cities tackle some of the most important issues of the twenty-first century, such as social isolation, food poverty, and climate change. Multipurpose green areas are becoming more and more necessary as urban populations continue to rise. At the nexus of ecology, economy, and equity, urban orchards provide a viable way forward for creating resilient and regenerative urban futures. This chapter explores the architectural frameworks, plant choices, best practices, guiding concepts, and real-world examples that influence how urban orchards in small city areas develop over time.

2. Concept and Scope of Urban Orchards

An urban orchard is a planned green space within city environments where fruit trees, shrubs, and other edible plants are grown for community benefit rather than commercial production. These orchards are typically integrated into public parks, schools, rooftops, vacant lots, and residential areas, promoting sustainable urban living. The construction of multifunctional landscapes that promote local food availability, biodiversity, environmental quality, and community participation is the main objective rather than maximizing production. In addition to providing city residents, especially those in underprivileged areas, with fresh, in-season fruits, urban orchards also act as educational centers for teaching ecology, gardening, and nutrition. They also improve mental health, lower urban heat, and serve as carbon sinks. Beyond only producing food, urban orchards may also promote social cohesiveness, cultural enrichment, and ecological restoration. These orchards greatly enhance urban resilience, sustainability, and the greening of quickly growing cities by making use of underutilized urban sites.

2.1 Benefits of Urban Orchards

- **Environmental Benefits**: Improve urban air quality, reduce the urban heat island effect, enhance soil structure, and support biodiversity.
- **Economic Benefits**: Reduce food expenses, support local markets, and create green job opportunities.
- **Social and Cultural Benefits**: Promote food security, community bonding, intergenerational learning, and cultural heritage.
- **Health Benefits**: Encourage physical activity, reduce stress, and provide access to nutritious fruits.

3. Site Selection and Planning in Compact Urban Spaces

3.1 Site Assessment Criteria

Selecting the right site is critical for the success of an urban orchard in space-constrained areas. Key factors include:

- **Available Space**: Evaluate rooftop space, balconies, community plots, or street-side strips.
- **Sunlight**: Most fruit trees require at least 6 to 8 hours of direct sunlight.
- **Soil Condition**: Assess for contamination, pH, drainage, and nutrient levels.
- **Water Availability**: Proximity to water sources or rainwater harvesting systems.
- **Accessibility and Safety**: Safe access for maintenance and harvesting.
- **Zoning and Permissions**: Compliance with municipal rules and building codes.

3.2 Urban Orchard Spaces

Urban orchards can be developed in a variety of innovative and space-efficient ways to suit the constraints of modern cities. Rooftop orchards transform otherwise underutilized areas into useful green spaces by using the flat rooftops of residential, commercial, or institutional buildings. In addition to offering fresh fruits, these systems improve insulation and lessen heat absorption in the structure. Orchards in the backyard or on a balcony are perfect for single-family homes with little outside space. Dwarf fruit trees in pots may be supported on even the smallest balconies with proper design, providing individual access to products cultivated in the home. Community orchards are created by converting common public or private areas, including parks, schoolyards, or empty plots, into communal fruit-growing areas that are cared for by neighbourhood groups or residents. These areas promote fair food distribution, education, and a sense of community. Vertical and wall-mounted orchard systems use trellises, vertical planters, and modular growing units attached to walls or fences, making it possible to cultivate fruit-bearing plants in the tightest urban niches.

3.3 Planning Considerations

Urban orchard development and sustainability depend heavily on careful planning. Whether the orchard's primary goal is food production, environmental education, aesthetic enhancement, community enjoyment, or a combination of these, the first step is to clearly describe it. Decisions on plant structure, management techniques, and selection are guided by a clear objective. Involving local communities, schools, NGOs, and municipal authorities early on guarantees shared ownership, a variety of contributions, and a deeper commitment to the project. Stakeholder participation is equally important. Since initial installation expenses, on-going maintenance, instructional programs, and infrastructure like irrigation or composting systems demand financial resources, securing a budget and financing is also crucial. Public grants, private sponsorships, neighbourhood fundraisers, and corporate social responsibility programs are some ways to obtain funding. To guarantee that the orchard survives for many years to come, a thorough sustainability plan should be created those details long-term care measures like as maintenance schedules, volunteer recruiting, skill development, and monitoring.

4. Design and Layout Principles

4.1 Space Optimization Techniques

In urban environments where space is often limited, maximizing the use of available areas is essential for successful orchard development. Fruit trees may be trained to grow flat against walls or fences by pruning them, a method known as espalier training. In addition to saving room, this adds a useful and attractive element to confined spaces. Another creative option is the use of columnar trees, which are upright, thin trees that are developed especially for urban environments and can flourish in small areas without spreading far laterally. Fruit trees may be grown in pots or raised beds, providing mobility and controlled growth conditions, making container planting an excellent option for areas with paved surfaces or poor soil conditions. Furthermore, a very effective technique is vertical layering, which involves growing many plant species in layers inside a single unit, including miniature trees, fruiting shrubs, and ground coverings. This is perfect for small urban orchards since it maximizes yield per square foot and replicates the architecture of natural forests.

4.2 Orchard Layout Models

The layout model of urban orchards is crucial for optimizing space, enhancing productivity, and ensuring ease of maintenance. The linear row layout is ideal for narrow spaces, offering easy access for pruning, harvesting, and irrigation. The grid pattern is suitable for rectangular or square plots, allowing uniform tree spacing for balanced sunlight exposure and efficient resource distribution. The mandala or spiral design is ideal for circular spaces or gardens with unconventional shapes, offering a central access point and concentric planting zones. Mixed intercropping, which integrates herbs, vegetables, and flowering plants, enhances biodiversity, supports natural pest control, and improves soil health, making it an excellent choice for community orchards.

4.3 Integration with Urban Infrastructure

Urban orchards can be integrated into city infrastructure to improve sustainability and resource efficiency. Green roofs and rain gardens can support orchard growth, rainwater harvesting, and building insulation. Smart irrigation systems, like drip irrigation and moisture sensors, ensure optimal water usage with minimal waste. On-site composting units can recycle organic waste from households, gardens, or markets, enriching soil and reducing dependency on chemical fertilizers. These integrations make urban orchards more self-reliant, efficient, and environmentally friendly, making them more self-reliant, efficient, and environmentally friendly. These technologies are particularly valuable in urban settings where water conservation is crucial.

5. Plant Selection and Propagation

5.1 Criteria for Selection

Urban orchards require careful selection of plant species and varieties, especially in diverse environmental conditions. Climate suitability is crucial for healthy growth and fruiting, while growth habits like dwarf, semi-dwarf, or naturally bushy are preferred due to their compact size and ease of maintenance. Rootstock compatibility is crucial for grafted fruit trees, as it influences tree vigour, disease resistance, and adaptability to limited soil volume. Pollination needs are also important, as some varieties require cross-pollination partners to bear fruit. Finally, yield and maturity period should be assessed, with a preference for early-bearing, high-yielding, and multi-season cultivars to ensure consistent production and maximize harvest within limited space and time.

5.2 Suitable Fruit Trees for Urban Orchards

When selecting fruit trees for urban orchards, especially in compact or container-based setups, it is essential to choose species and varieties that are well-adapted to limited space and urban conditions. Dwarf citrus trees are excellent choices due to their compact, evergreen nature and the ability to bear fruit throughout the year, making them ideal for container gardening. Guava is another hardy option that requires moderate space and performs well in containers; its self-pollinating nature adds to its convenience. Figs are known for their wide adaptability and quick bearing capacity, although they benefit greatly from regular pruning to maintain size and productivity. Pomegranate trees are valued for their drought resistance and the availability of compact varieties, requiring minimal maintenance once established. Dwarf papaya trees offer vertical growth and quick fruiting, although they are sensitive to frost and require protection in colder climates. Dwarf banana varieties are shade-tolerant and produce fruit within 9–12 months; they prefer consistently moist soil and shelter from strong winds. Lastly, tropical apple varieties, or low-chill apples, can be grown in warmer climates but require careful selection to match local chilling requirements, and most will need compatible pollinators planted nearby for successful fruiting

5.3 Propagation Techniques

Grafting and budding are frequently used to produce urban orchard trees in order to guarantee uniformity, disease resistance, and true-to-type seedlings. For plants like citrus, fig, and guava, air layering works well and speeds up roots. Pomegranate, mulberry, and fig cuttings are frequently utilized because of their simplicity of usage and high success rate. Due to delayed fruiting and genetic diversity, seed propagation is often avoided.

6. Management Practices

6.1 Soil and Nutrition Management

Fertile, well-drained soil is necessary for urban orchards growing on raised beds or containers. Frequent mulching improves soil health and preserves moisture. Compost, vermicompost, and bio-fertilizers preserve the nutrient supply, encouraging sustainable development. In small areas, these organic methods lessen the need for artificial fertilizers, enhance soil structure, and encourage microorganisms.

6.2 Water Management

Urban orchards require effective water management. While mulching lowers evaporation, drip irrigation guarantees accurate watering with little waste. Particularly on roofs, rainwater collection devices can provide sustainable irrigation supplies. Moisture sensors also aid in precise irrigation scheduling, avoiding overwatering or under watering and encouraging robust plant development with less water use.

6.3 Pruning and Training

For urban orchards to manage tree growth, form, and production, pruning and training are essential. Frequent trimming eliminates unhealthy or dead branches and enhances air flow and sunshine penetration. By directing growth in constrained areas, training methods like espalier or trellising assist trees become easier to handle and improve fruit production and accessibility.

6.4 Pest and Disease Control

To guarantee safe and nutritious food, urban orchards must practice sustainable pest and disease control. Neem-based products and biological control agents provide environmentally benign alternatives for synthetic pesticides. Pests are naturally repelled by companion planting with plants like basil and marigold. Diseases can be stopped from spreading by early removal of contaminated plant parts and routine monitoring.

6.5 Harvesting and Post-Harvest Handling

In urban orchards, fruit quality and shelf life are guaranteed by appropriate harvesting and post-harvest procedures. To minimize heat stress and spoiling, fruits should be picked in the cooler hours of the day. Utilize sanitized containers or baskets to avoid infection. Fruits must be swiftly cleaned, sorted, and kept under ideal circumstances if they are not to be eaten right away.

7. Community Engagement and Educational Role

For urban orchards to be successful and sustainable, community involvement is essential. Long-term care and common ownership are promoted via community-led orchard models that involve housing societies, schools, institutions of worship, and non-governmental organizations. Roles, duties, and benefit-sharing are all better defined with clear agreements. Urban orchards function as living classrooms in educational institutions, combining practical tasks like planting, harvesting, and monitoring with environmental teaching. Students' understanding of food systems and sustainability is improved by this hands-on experience. By engaging women, young people, and older individuals in a variety of activities, urban orchards also foster social inclusion and empowerment. By taking part in planning, upkeep, and harvesting, these organizations may support the growth of the community. Programs for awareness and training help people develop their skills in areas including tree care, insect control, and composting. All things considered, urban orchards serve as centers of education, involvement, and empowerment in addition to offering food and greenery. This fosters communal ties and encourages environmental stewardship in people of all ages.

8. Policy Support and Institutional Framework

Urban orchard initiatives require strong policy support and institutional backing. Smart city plans should prioritize orchard inclusion, offering incentives for rooftop-greening and land lease schemes for community gardening. Financial assistance can be provided through subsidies for containers, compost units, and water-efficient systems. Technical assistance from horticulture departments, agricultural universities, and CSR-backed partnerships can enhance planning and management skills. However, regulatory challenges like zoning restrictions, ambiguous land-use rights, and safety codes need to be addressed. Clear guidelines on liability and maintenance are crucial to avoid disputes. A collaborative framework involving government, communities, and private stakeholders is essential for promoting inclusive, sustainable, and productive urban orchards.

9. Challenges and Solutions

There are a number of environmental and logistical issues facing urban orchard growth that call for creative, neighbourhood based solutions. In heavily populated locations, space and sunshine are key constraints. Trellises, vertical gardening methods, and the planting of fruit species that can withstand shade and are suited for small spaces can all help with this. The lack of understanding and technical expertise among city dwellers is a second issue. People can acquire necessary skills by setting up training sessions, offering online materials, and starting community mentorship initiatives. Another issue is the poisoning of soil by pollutants and heavy metals. Containers, raised beds, and soil-cleaning phytoremediation plants can all help to lessen this. Urban regions frequently experience water scarcity, but this may be avoided using drip irrigation systems, rainwater collection, and grey water reuse. Finally, encouraging community ownership, erecting protective fence, and holding local engagement activities to develop shared responsibility may all help reduce vandalism and neglect in public orchards.

10. Future Prospects

The future of urban orchard development is bright and holds transformative potential for urban sustainability, food resilience, and community well-being. Urban orchards provide a natural remedy that may be easily incorporated into city design and infrastructure in light of growing urban population pressure, climate change, and the loss of green places. Compact, dwarf, and fast-bearing fruit cultivars that have been specially selected for urban environments will make orchard farming possible even in limited areas like community lots, terraces, and balconies. Urban orchard expansion will be greatly aided by technological advancements. Even non-experts will be able to efficiently maintain orchards with the help of IoT-based sensors for real-time monitoring of soil moisture, temperature, and plant health, as well as AI-driven irrigation scheduling and smartphone applications for disease detection and advisory services. Automated drip systems, grey water recycling, and rooftop rainfall collection will all aid in addressing the problem of urban water shortages. The importance of green infrastructure, such as orchards, edible landscapes, and vertical gardens, is becoming more widely acknowledged by urban planning authorities. Smart city planning and development strategies that include urban orchards will promote biodiversity, lessen the impact of the urban heat island, and provide livable microclimates. Community-based orchard models will keep growing, providing therapeutic, recreational, and educational advantages in addition to food. Urban orchards in public parks, educational institutions, and schools may serve as living classrooms that encourage young people to take care of the environment. It will be crucial in the future for local communities, academic institutions, the commercial sector, and government agencies to work together more closely. This change will be accelerated by policies that encourage urban horticulture research, training, financing, and land access. With the potential to completely change how cities produce, consume, and cohabit with nature, urban orchards once thought of as experimental are increasingly becoming an essential part of resilient, inclusive, and sustainable urban ecosystems.

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CROP REGULATION IN FRUIT CROPS

Santosh Mavinalli*[1], S. N. Patil[1], Iranna Biradar[2], Deepak S. Kore[1], S. S. Lohakare[3], S. S. Pardeshi[3], M. B. Shinde[3] and M. N. Magar[3]

[1]Department of Fruit Science,
University of Horticultural Sciences, Bagalkot, Karnataka, India, 587 104
[2]Department of Food Science and Nutrition,
College of Community Science, University of Agricultural Sciences, Dharwad
[3]Department of Horticulture, Fruit Science, College of Agriculture, Latur
Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani
*Corresponding author E-mail: santoshm7977@gmail.com

Abstract:

Crop regulation, commonly referred to as *bahar treatment*, is a vital practice in tropical and subtropical fruit production systems. It involves manipulation of flowering and fruiting cycles through cultural and chemical methods to achieve synchronized, uniform, and high-quality harvests in a single season. This dissertation discusses the physiological principles of crop regulation, traditional and modern methods, bahar treatment, crop-specific strategies and their socio-economic impact. Emphasis is placed on advantages such as yield stabilization, quality improvement, alternate bearing reduction, resource optimization and enhanced farmer income. Limitations and challenges—including irrigation dependency, labor intensity and climate change—are also examined. Finally, the future prospects of crop regulation in the context of precision horticulture, biotechnology and climate-smart strategies are explored. Overall, crop regulation emerges as both a biological and economic necessity for sustainable horticultural development.

Keywords: Crop Regulation, Bahar Treatment, Flowering and Fruiting Cycles, Yield Stabilization, Precision Horticulture

1. Introduction:

1.1 Concept of Crop Regulation

Crop regulation, also known as *bahar treatment* or crop growth manipulation, is an important horticultural practice designed to synchronize the flowering and fruiting cycles of perennial fruit crops. In tropical and subtropical conditions, fruit crops such as guava (*Psidium guajava*), pomegranate (*Punica granatum*) and citrus (*Citrus* spp.) tend to flower and fruit irregularly or multiple times during the year, which negatively impacts fruit quality, market supply and uniformity of production (Mishra *et al.,* 2021).

Crop regulation acts as a management intervention that ensures fruit production is concentrated in one favorable season by inducing a temporary stress period followed by synchronized flowering. The main objectives are to maximize fruit quality, improve uniformity, stabilize yields and enhance profitability for growers (Chauhan, Ladon, & Bhakti, 2022).

1.2 Historical Development

Traditional farmers in India practiced irrigation withholding and root exposure in pomegranate and citrus centuries ago, long before scientific explanations were available. Over time, the practice evolved into what is formally known as *bahar treatment*—selectively regulating fruiting seasons, such as Ambe Bahar (spring flowering), Mrig Bahar (monsoon flowering) and Hasth Bahar (autumn flowering)—depending on market and climatic suitability (Vigyan Varta, 2020). Later, the discovery and application of plant growth regulators further advanced the precision of crop regulation (Pooja, 2020).

1.3 Significance in Horticulture

Crop regulation is significant because it ensures:

- Uniform production and synchronized harvest cycles.
- Improved fruit quality (color, size, taste and shelf life).
- Reduction in alternate bearing, especially in mango and citrus.
- Efficient use of inputs, such as irrigation, fertilizers and labor.
- Higher profitability, since produce can be timed with periods of high consumer demand (Bhakti, 2025; *Jat et al.,* 2020).

In essence, crop regulation improves not only the biological management of orchards but also their economic sustainability.

2. Physiological Basis of Crop Regulation

2.1 Flowering Physiology in Fruit Crops

Flowering in fruit crops is controlled by an intricate balance of carbohydrates, hormones and environmental triggers. In tropical fruit crops like guava and pomegranate, continuous cycles of growth often result in irregular flowering. Adequate carbohydrate reserves, reduced nitrogen supply and environmental stress such as water deficit encourage reproductive growth (*Mishra et al.,* 2021).

2.2 Carbohydrate–Nitrogen (C:N) Ratio

The C:N ratio of a plant is a key determinant of flowering. A higher carbohydrate supply relative to nitrogen favors flower bud initiation and development, while elevated nitrogen prolongs vegetative growth. Practices like irrigation withholding, root pruning and defoliation manipulate this ratio to create conditions suitable for synchronized flowering (Agri Articles, 2023).

2.3 Hormonal Regulation of Flowering

Plant hormones are central to flower initiation and crop regulation:

- Auxins (IAA, NAA): Used for thinning and regulating fruit set (Pooja, 2020).

- Gibberellins (GA): Known to inhibit flowering in mango and citrus, favoring vegetative flushing.
- Cytokinins: Encourage cell division and help in flower bud differentiation.
- Abscisic Acid (ABA): Enhances dormancy and defoliation.
- Ethylene: Promotes flowering in specific crops such as pineapple and helps regulate flowering in guava and citrus (Kaur, Singh, & Mishra, 2024).

2.4 Alternate Bearing and Crop Load Management

Many fruit trees such as mango and citrus suffer from alternate bearing, where heavy cropping in one year exhausts carbohydrate reserves and impairs flowering in the subsequent year. Crop regulation practices—like flower thinning, controlled irrigation and chemical spraying—stabilize yields and ensure consistent quality production year after year (*Chauhan et al.,* 2022).

2.5 Stress Physiology as a Trigger

Environmental stress such as withholding water or root exposure forces trees into a rest period. This reduces vegetative metabolism and accumulates carbohydrates in buds, which are later mobilized when irrigation and nutrients are restored, resulting in abundant synchronized flowering (Vigyan Varta, 2020).

3. Types of Crop Regulation Practices

Crop regulation can be broadly categorized into cultural methods and chemical methods. Both approaches aim to manipulate the physiological state of the tree, either by inducing temporary stress or by altering hormonal balances, to synchronize flowering and fruiting during the desired season.

3.1 Cultural Methods of Crop Regulation

Cultural practices are the earliest and most widely used techniques, relying on manual interventions or environmental manipulations without the use of chemical inputs. These practices are eco-friendly, low-cost, and suitable for resource-poor farmers (*Jat et al.,* 2020).

3.1.1 Withholding Irrigation

Withholding irrigation is the most common technique used for inducing stress before the flowering season. For example, in guava and pomegranate, irrigation is withheld for about 45–60 days prior to the natural flowering season. This stress halts vegetative growth and increases carbohydrate accumulation. Once irrigation resumes, the plants produce a synchronized flush of flowers (*Mishra et al.,* 2021).

3.1.2 Root Pruning and Root Exposure

By cutting or partially exposing roots, water and nutrient uptake is restricted, thereby placing the tree under stress. This favors flower bud initiation. This method is commonly practiced in citrus and guava orchards where 15–20 cm of roots around the tree basin are exposed for 40–50 days (Chauhan, Ladon, & Bhakti, 2022).

3.1.3 Shoot Pruning and Bending

Pruning helps regulate the canopy, remove excessive vegetative growth and expose fruiting shoots to sunlight. In guava, severe pruning after harvest encourages new shoot growth which later differentiates into strong floral buds. Shoot bending reduces apical dominance and favors flowering (Agri Articles, 2023).

3.1.4 Defoliation

Inducing artificial leaf fall (either through manual removal or spray of defoliating chemicals) helps synchronize bud break and improve flowering intensity. In pomegranate and guava, hand defoliation or spraying urea (15–20%) is often employed (Bhakti, 2025).

3.1.5 Flower Thinning

Excessive flowers reduce fruit size and quality and exhaust tree reserves. Thinning is done manually by removing small or crowded flowers, or chemically using growth regulators like NAA, to ensure proper leaf-to-fruit ratio (Pooja, 2020).

3.1.6 Smudging and Smoking

Smudging (smoke generation by burning organic matter under the tree canopy) is a traditional practice to induce flowering in mango orchards. The smoke increases ethylene concentration around the canopy, which plays a role in flowering induction (Vigyan Varta, 2020).

3.2 Chemical Methods of Crop Regulation

The use of plant growth regulators (PGRs) and other chemicals forms an important component of crop regulation in commercial horticulture. These chemicals help regulate flowering intensity, adjust crop load, and induce defoliation or dormancy.

3.2.1 Auxins (NAA, 2,4-D)

- Naphthalene acetic acid (NAA): Applied for thinning excessive flowers and young fruits in guava and citrus. Helps balance crop load and ensures better quality fruits (Kaur, Singh, & Mishra, 2024).
- 2,4-D: Used at low concentrations to prevent premature fruit drop in citrus and mango.

3.2.2 Ethylene Releasing Compounds (Ethephon)

Ethephon is used to induce flowering in pineapple and also for synchronized flowering in citrus and guava orchards (Pooja, 2020). As an ethylene-releasing compound, it helps manipulate reproductive growth.

3.2.3 Defoliants (Urea, Potassium Nitrate)

High concentration of urea sprays (15–20%) serve as a chemical defoliant to trigger synchronized flowering. Similarly, potassium nitrate (KNO_3, 1–2%) is used to induce flowering, commonly in mango and citrus (Agri Articles, 2023).

3.2.4 Growth Retardants (Paclobutrazol, Cycocel)

- Paclobutrazol: A widely used inhibitor of gibberellin biosynthesis. By suppressing vegetative growth, it enhances flowering in mango and citrus. Soil drenching at 5–10 g a.i. per tree is widely recommended (*Mishra et al.,* 2021).
- Cycocel (CCC): Used in guava and grapes to regulate vegetative vigor and promote fruit set.

3.2.5 Gibberellin Inhibitors

Since gibberellins generally inhibit flowering in many fruit crops, growth retardants that restrict GA synthesis are increasingly being adopted to maintain a balance between vegetative and reproductive growth (Kaur *et al.,* 2024).

3.3 Integrated Use of Methods

For effective crop regulation, cultural and chemical methods are often **combined**. For example, in pomegranate, irrigation withholding followed by defoliation with urea and paclobutrazol drenching ensures a well-synchronized bahar crop with uniform flowering and increased yield.

4. Bahar Treatment in Fruit Crops

4.1 Concept of Bahar Treatment

Bahar treatment is a traditional and scientifically validated crop regulation practice widely used in India for fruit crops such as guava (*Psidium guajava*), pomegranate (*Punica granatum*), and citrus (*Citrus* spp.). The word *"Bahar"* means "season" in Hindi, and the system involves forcing rest in fruit trees by withholding irrigation and other cultural operations, followed by restoration of irrigation and nutrients to induce synchronized flowering in the desired season (Vigyan Varta, 2020).

Unlike temperate fruits, which flower once a year, tropical and subtropical fruit crops flower more than once if environmental conditions are favorable. This natural tendency leads to scattered harvests, poor fruit size, uneven quality and marketing difficulties. Bahar treatment overcomes these problems by concentrating fruiting in one chosen flush, aligned with the best season for climate and market demand (Chauhan, Ladon, & Bhakti, 2022).

4.2 Types of Bahar Seasons in India

In central and western parts of India, three major bahar seasons are recognized:

4.2.1 Ambe Bahar (Spring Flowering – January–February)

- Known as the "Mango-flush" season.

- Flowering occurs in Jan–Feb, leading to fruit harvests in June–July.
- Preferred in areas with assured irrigation facilities.
- Advantage: Fruits are available in summer when market demand and prices are high.
- Example: Widely practiced in guava and pomegranate in canal-irrigated regions of Maharashtra and Madhya Pradesh (*Mishra et al.,* 2021).

4.2.2 Mrig Bahar (Monsoon Flowering – June–July)

- Induced by withholding irrigation during hot summer months (April–May) and restoring water supply with the onset of monsoon.
- Flowering happens in June–July, with harvest extending from November to January.
- Advantage: Natural rainfall supports crop growth; fruits mature in the winter season with better color, sweetness and shelf life.
- Example: Preferred for citrus and pomegranate in Maharashtra and parts of Karnataka where monsoon is reliable (Vigyan Varta, 2020).

4.2.3 Hasth Bahar (Autumn Flowering – September–October)

- Flowering obtained in Sept–Oct leads to fruits in March–April.
- Less preferred in many regions due to high pest–disease incidence during flowering and fruiting stages.
- However, in southern parts of India, Hasth Bahar is advantageous as irrigation availability supports the crop and the harvest coincides with summer markets (Bhakti, 2025).

4.3 Steps in Bahar Treatment

Bahar treatment involves the following sequence of practices (Agri Articles, 2023):

1. Withholding irrigation for 45–60 days during the pre-flowering stage to induce rest and mild stress.
2. Soil cultivation/root exposure around the tree basin to further limit water absorption.
3. Application of defoliants (e.g., urea 15–20%) to remove old leaves and synchronize bud break.
4. Resumption of irrigation and fertilizer application after the desired rest period, usually aligned with the onset of the season (spring, monsoon, or autumn).
5. Pruning to regulate shoot growth and channel energy into productive buds.
6. Plant growth regulator sprays (paclobutrazol, NAA, ethephon) where required for enhanced flowering synchronization.

4.4 Bahar Treatment in Key Fruit Crops

4.4.1 Guava (*Psidium guajava*)

- Naturally flowers thrice a year (spring, monsoon and late autumn), which leads to poor fruit quality in the rainy season crop.

- Bahar treatment is applied to suppress rainy season fruiting (which is watery and pest-prone) and promote winter fruiting, which is superior in taste, sweetness and shelf life (*Mishra et al.,* 2021).

4.4.2 Pomegranate (*Punica granatum*)

- Bears multiple flushes in a year.
- Bahar treatment is essential to synchronize harvest and target profitable seasons.
- Mrig Bahar is often preferred in Maharashtra as fruits harvested in winter fetch higher market prices and have better skin color (*Chauhan et al.,* 2022).

4.4.3 Citrus (*Citrus reticulata*, *C. aurantifolia*)

- Citrus trees naturally flower irregularly in multiple flushes.
- Withholding irrigation combined with paclobutrazol application is common to induce synchronized flowering.
- Ambe Bahar is generally more profitable with heavy fruit set and summer market advantage (Kaur, Singh, & Mishra, 2024).

4.5 Advantages of Bahar Treatment

Bahar treatment provides several agronomic and economic benefits:

- Ensures synchronized flowering and uniform harvest.
- Results in improved fruit quality (better size, color, sweetness and firmness).
- Reduces incidence of poor-quality rainy season fruits (especially in guava).
- Improves resource efficiency (irrigation, fertilizers, labor).
- Enhances profitability by timing harvest with premium market prices.

4.6 Limitations of Bahar Treatment

Despite its advantages, some limitations exist:

- Requires strict control of irrigation and orchard management.
- Not feasible in areas of continuous rainfall (e.g., coastal zones).
- Increased pest–disease pressure in Hasth Bahar crops.
- Requires adequate knowledge of seasonal climate patterns to choose the best bahar season (*Jat et al.,* 2020).

5. Crop Regulation in Major Fruit Crops

Crop regulation practices differ depending on the biological behavior and fruiting pattern of each crop. Below are the commonly adopted strategies in some commercially important fruit crops.

5.1 Mango (*Mangifera indica*)

Mango is one of the most important fruit crops in India but is highly susceptible to alternate bearing. A heavy crop in one year exhausts carbohydrates, leading to poor flowering the following year (*Mishra et al.,* 2021).

Common crop regulation methods in mango include:

- Flower Thinning: During heavy flowering years, excess flowers are manually or chemically thinned using NAA to balance crop load.
- Pruning and Canopy Management: After harvest, pruning of old branches is done to encourage new shoots that provide better flowering sites.
- Paclobutrazol Application: Soil drenching with paclobutrazol (4–10 g a.i. per tree) suppresses gibberellin activity, reducing vegetative flush and promoting flowering uniformity (Kaur, Singh, & Mishra, 2024).
- Foliar Nutrient Supplements: Application of KNO_3 (1–2%) helps correct nutrient deficiencies, promotes bud differentiation, and improves flowering.

By combining these practices, farmers can minimize alternate bearing and achieve relatively stable mango yields (Chauhan, Ladon, & Bhakti, 2022).

5.2 Guava (*Psidium guajava*)

Guava bears three natural flowering seasons—spring, monsoon and autumn—which leads to poor quality rainy season fruits (watery, pest-prone) and reduced market value (Bhakti, 2025).

Regulation strategies:

- Suppressing Rainy Season Crop (Dashehari treatment): Irrigation is withheld in May–June, trees are defoliated (15–20% urea spray) and pruned to prevent flowering during monsoon.
- Encouraging Winter Crop: Winter crop fruiting (Nov–Dec harvest) is preferred, as these fruits are sweeter, firmer and fetch premium prices.
- Pruning: Cutting back shoots after rainy-season harvest results in new growth that flowers in winter.
- Chemical Regulation: NAA sprays are used to thin excess flowers and CCC (cycocel) is sometimes applied to check vegetative growth (Agri Articles, 2023).

Thus, regulation ensures guava fruits are harvested mainly in winter, aligning with quality and market benefits (*Mishra et al.,* 2021).

5.3 Pomegranate (*Punica granatum*)

Pomegranate has the capacity to flower in multiple flushes throughout the year, but unregulated fruiting leads to poor fruit set and low quality. In Maharashtra and Karnataka, crop regulation through Bahar treatment is a common practice (Vigyan Varta, 2020).

Regulation Practices Include:

- Mrig Bahar Preferred: Chosen in most regions as fruits mature in winter, resulting in bright red color, sweetness and long shelf life.
- Withholding Irrigation: For about 45–60 days before the onset of monsoon.
- Defoliation: Manual leaf removal or urea spray (15–20%) to induce simultaneous bud break.
- Paclobutrazol Application: Soil application to promote flowering and suppress continuous vegetative growth.

By regulating to one preferred bahar, farmers avoid low-quality fruits of off-season crops and increase export potential (*Chauhan et al.,* 2022).

5.4 Citrus (*Citrus reticulata*, *C. sinensis*, *C. aurantifolia*)

Citrus trees flower in multiple flushes but produce variable crop qualities. Crop regulation is crucial for ensuring synchronized harvest and reducing alternate bearing (*Mishra et al.,* 2021).

Key methods:

- Withholding Irrigation: Particularly before Ambe Bahar, to induce profuse flowering in Jan–Feb.
- Fruit/Fruitlet Thinning: To reduce excessive crop load and improve fruit size.
- Paclobutrazol and Cycocel: Used to suppress vegetative growth and enhance reproductive flush.
- Application of KNO_3: Corrects nutrient balance and supports flowering induction.

Ambe Bahar is usually chosen in citrus as it ensures good quality fruits ready in summer, which fetch high market prices (Bhakti, 2025).

5.5 Banana (*Musa* spp.)

Banana is an ever-bearing crop, but fruit maturity and harvesting can be regulated for market advantages.

Common practices:

- Desuckering and Removal of Excess Shoots: Helps concentrate nutrients in the main mother plant.
- Bunch Covering and Thinning: Regulates bunch shape and fruit size uniformity.
- Ethephon Spray: Sometimes used to regulate synchronized flowering and uniform bunch emergence (Kaur *et al.,* 2024).

5.6 Sapota (*Manilkara zapota*)

Sapota flowers and fruits almost continuously in subtropical climates, leading to irregular harvesting and poor fruit quality.

Regulation methods include:

- Withholding Irrigation in summer months to suppress unwanted flowering.
- Pruning to reduce continuous flowering and promote synchronized flushes.
- Chemical applications like NAA and cycocel to regulate flowering intensity (Agri Articles, 2023).

5.7 Grapes (*Vitis vinifera*)

Crop regulation in grapes is achieved primarily through pruning practices:

- Summer Pruning (Back pruning): Stimulates new vegetative shoots.
- Winter Pruning (Forward pruning): Induces buds that bear fruit.
- Use of Hydrogen Cyanamide (Dormex): Breaks bud dormancy and synchronizes bud sprouting.

  This ensures uniform berry development and harvest scheduling for domestic and export markets (*Mishra et al.,* 2021)

6. Advantages of Crop Regulation

Crop regulation is not only a biological intervention in fruit crops but also an agronomic and economic necessity. By synchronizing flowering and fruiting into one desired season, it offers both scientific benefits (improved physiological performance of the plant) and commercial advantages (quality produce, better prices, and market control).

6.1 Improved Fruit Quality

Fruit quality is directly affected by unregulated and excessive fruiting. When plants continuously bear fruits over multiple seasons, nutrient reserves are divided, leading to small, watery, or poor-colored fruits. Crop regulation ensures:

- Better size and weight due to optimum leaf-to-fruit ratio.
- Improved sweetness and flavor as carbohydrate reserves are utilized efficiently for fewer fruits (Bhakti, 2025).
- Enhanced external appearance (uniform color, shape, and firmness), making fruits more marketable (Chauhan, Ladon, & Bhakti, 2022).

For instance, in guava, suppression of the rainy-season crop leads to winter harvests with superior sweetness, firmness, and shelf life, improving consumer acceptance (*Mishra et al.,* 2021).

6.2 Higher and Uniform Yields

Synchronizing flowering and fruiting ensures that plants bear a single heavy flush which is easier to manage and harvest. Benefits include:

- Higher cumulative yields compared to scattered irregular crops.
- Uniform maturity period, making harvesting operations more cost-effective.

- Reduced premature fruit drop due to controlled crop load.

In citrus and pomegranate orchards of Maharashtra, practice of Mrig Bahar treatment has been shown to improve yield stability while reducing input costs (Vigyan Varta, 2020).

6.3 Reduction in Alternate/Biennial Bearing

Alternate bearing (heavy crop in one year followed by light or no crop in the next) is a common problem in fruit crops such as mango and citrus. Crop regulation mitigates this by:

- Thinning excessive flowers and fruits during heavy bearing years to maintain balance.
- Inducing a regular flowering pattern each season.
- Helping trees conserve adequate reserves for the following year (Agri Articles, 2023).

Paclobutrazol treatments in mango, for example, help minimize alternate bearing by regulating vegetative flush and encouraging stable flowering cycles (Kaur, Singh, & Mishra, 2024).

6.4 Efficient Use of Inputs

Crop regulation reduces unnecessary use of resources such as fertilizers, pesticides and labor. When fruiting is concentrated:

- Fertilizers and water can be applied at specific times for maximum efficiency.
- Pest and disease control becomes easier since fruits develop in one synchronized season.
- Labor costs decline due to single harvest periods instead of multiple scattered harvests (*Jat et al.,* 2020).

This efficiency is particularly important for small and medium farmers in India, ensuring better returns on limited resources.

6.5 Market and Economic Benefits

Unregulated harvests flood the market with irregular supplies, lowering prices. Crop regulation enables farmers to:

- Time production with peak demand periods, such as summer for mango and citrus, or winter for guava and pomegranate.
- Supply uniform batches of export-quality produce, crucial for international trade competitiveness.
- Achieve higher farmgate prices due to improved fruit quality and market coordination (*Mishra et al.,* 2021).

For instance, Mrig Bahar pomegranates from Maharashtra are in high demand in domestic and export markets because of their uniform red color, sweetness and extended shelf life, achieved through crop regulation.

6.6 Stability and Farmer Income Security

Perhaps the most important impact is economic stability for farmers. Crop regulation helps in:

- Avoiding gluts in the market that lead to steep price crashes.
- Providing predictable and assured incomes due to quality harvests.
- Enhancing export opportunities, improving India's presence in international fruit markets (Bhakti, 2025).

6.7 Environmental and Sustainable Advantages

From a sustainability perspective, crop regulation supports:

- Efficient water use by scheduling irrigation strategically.
- Reduced chemical usage since one synchronized crop means fewer pesticide rounds.
- Better energy and labor management, fitting into resource-smart and climate-smart horticulture practices (*Chauhan et al.,* 2022).

7. Limitations and Challenges of Crop Regulation

Although crop regulation offers tremendous advantages for fruit production, it is not without limitations and challenges. Many small and marginal farmers in India and other tropical nations face constraints in adopting these practices effectively. Moreover, environmental, socio-economic, and agronomic limitations need to be considered to ensure successful implementation.

7.1 Dependence on Irrigation Control

Most crop regulation methods rely on withholding irrigation during pre-flowering stages to induce stress (e.g., in guava and pomegranate). However:

- In rain-fed areas with unpredictable monsoons, irrigation control is difficult.
- Farmers with poor irrigation infrastructure cannot precisely adopt bahar treatment (*Mishra et al.,* 2021).
- Excess rainfall during the rest period can nullify the effect of irrigation withholding, leading to irregular flowering (Vigyan Varta, 2020).

7.2 High Labor and Management Requirements

Many crop regulation practices such as pruning, defoliation, flower thinning and smudging are labor-intensive. For smallholders with limited labor availability, these operations can be costly and difficult (Chauhan, Ladon, & Bhakti, 2022).

Furthermore, timely operations require technical knowledge and precision, which many farmers may lack without adequate training (Bhakti, 2025).

7.3 Risks Associated with Chemical Use

Chemical methods such as application of paclobutrazol, cycocel, NAA and ethephon have shown significant success. However, challenges exist:

- Overuse or misuse can cause phytotoxicity, reduced vigor and long-term soil residue issues (Kaur, Singh, & Mishra, 2024).
- Some chemicals (e.g., paclobutrazol) remain in the soil for years, raising environmental sustainability concerns.
- Continuous reliance on chemicals may also increase production costs for economically weaker farmers (Agri Articles, 2023).

7.4 Climate Change and Uncertainty

Crop regulation is highly dependent on seasonal synchronization. Changing climatic patterns are posing new constraints:

- Unpredictable rainfall disrupts rest periods required for bahar treatment.
- Unseasonal temperature rise induces untimely flowering, disrupting planned harvest schedules.
- Shifts in onset and withdrawal of monsoons reduce reliability of traditional Ambe/Mrig/Hasth bahars (*Jat et al.,* 2020).

7.5 Pest and Disease Pressure

While crop regulation improves fruit quality, concentrating fruiting in one season may sometimes increase pest and disease load during that peak period (*Mishra et al.,* 2021). For example:

- Mrig Bahar crops of pomegranate and citrus coincide with high humidity, enhancing fungal and bacterial infection risks.
- Suppressed rainy-season guava reduces poor-quality fruits but requires intensive management of fruit borer and wilt attack in winter crop.

7.6 Socio-Economic Constraints

Adoption of crop regulation is often lower among small and marginal farmers due to:

- Knowledge gaps and lack of training on precise timing and techniques.
- Limited access to inputs such as defoliants or paclobutrazol.
- Risk aversion, since a failed bahar season means no income for that year (Bhakti, 2025).
- Further, large orchards can manage risks with assured irrigation and trained labor, whereas smallholders are more vulnerable.

7.7 Region-Specific Limitations

- In coastal and humid areas, prolonged rainfall prevents effective irrigation withholding.
- In dry arid zones with scarce water, excessive stress can permanently damage trees.
- Bahar treatment is highly location-specific; what works in Maharashtra (Mrig Bahar) may not work in Tamil Nadu, where Hasth Bahar may be more profitable (Vigyan Varta, 2020).

8. Modern and Advanced Approaches in Crop Regulation

Crop regulation in fruit crops has traditionally relied on cultural (pruning, irrigation control, defoliation) and chemical (PGRs, paclobutrazol, ethephon) methods. However, with advances in precision agriculture, biotechnology and digital tools, modern approaches are now being explored to make crop regulation more scientific, climate-resilient and farmer-friendly (Kaur, Singh, & Mishra, 2024).

8.1 Precision Irrigation and Fertigation

Traditional bahar treatment involves manually withholding and restoring irrigation. Modern practices now integrate:

- Drip irrigation systems that allow precise control of water stress during pre-flowering phases.
- Sensors and automated fertigation units that deliver nutrients and water based on real-time soil moisture and plant growth data (Agri Articles, 2023).
- Reduced water wastage and more uniform stress induction, ensuring reliable flowering across the orchard.

For example, pomegranate growers in Maharashtra increasingly use drip fertigation systems to synchronize bahar treatment more effectively (Bhakti, 2025).

8.2 Remote Sensing and Digital Monitoring

Digital agriculture technologies such as drones, satellite imaging and sensors are increasingly applied in orchard management:

- Canopy imaging and NDVI (Normalized Difference Vegetation Index): Used to assess canopy vigor and predict flowering response.
- Drone spraying: Ensures uniform application of foliar PGRs and defoliants across large orchards.
- IoT (Internet of Things) devices and apps: Provide farmers with alerts on irrigation scheduling and bahar timing (Chauhan, Ladon, & Bhakti, 2022).

8.3 Biotechnology and Molecular Approaches

Understanding the molecular physiology behind flowering has opened doors for genetic and biotechnological interventions

- Flowering gene manipulation (FT, LFY, AP1 genes): CRISPR-based editing can potentially regulate flower initiation in perennial crops (*Mishra et al.,* 2021).
- Transcriptomics and proteomics: Used to identify key pathways of flowering under stress and hormonal signals.
- Biostimulants and bio-PGRs: Microbial and natural extracts are being tested as eco-friendly alternatives to synthetic chemicals like paclobutrazol (Kaur *et al.,* 2024).

Biotechnology-based regulation remains at the research stage but holds promise for climate-smart horticulture.

8.4 Artificial Intelligence (AI) & Machine Learning

AI and machine learning models are being developed to predict:

- The best season to induce flowering based on climate data and soil conditions.
- Yield forecasting and crop load estimation using advanced image recognition from orchard photos.
- Pest and disease prediction models integrated with crop regulation schedules to optimize spraying (*Jat et al.,* 2020).

Such AI-supported decision tools allow farmers to minimize risks associated with uncertain weather and market demand.

8.5 Climate-Smart Crop Regulation

Climate change is disrupting traditional bahar systems. To build resilience, researchers are exploring:

- Drought-tolerant rootstocks that can maintain productivity under stress.
- Shifting bahar timings and developing region-specific models for regulated cropping.
- Sustainable, low-cost and eco-friendly alternatives to chemical regulation such as organic PGRs and green defoliants (Vigyan Varta, 2020).

8.6 Integration of Traditional & Modern Practices

Modern technology cannot completely replace traditional farmer wisdom. A hybrid approach combining:

- *Traditional bahar treatment* (cultural stress induction)
- *Modern digital tools* (sensors, drones, AI-based decision aids)
- *Eco-friendly chemical/biological regulators*

It offers the most practical pathway forward. It ensures sustainability, affordability and efficiency while meeting consumer demand for safe, high-quality fruits.

9: Impact on Farmers and Economy

Crop regulation is not only a horticultural practice but also a socio-economic tool that directly impacts farmer livelihoods, market dynamics and the rural economy. By ensuring quality yields, synchronized harvests and stable market supply, it has significantly contributed to income improvement, export competitiveness and employment generation in fruit-growing regions of India (*Mishra et al.,*2021).

9.1 Enhanced Farmer Income and Profitability

- Regulated crops fetch higher farm-gate prices due to better size, flavor and shelf life.

- Concentrating fruiting in one profitable season reduces unnecessary expenditure on fertilizers, pesticides and repeated harvesting operations.
- Case study: Mrig Bahar pomegranates from Maharashtra are in high demand in both domestic and international markets due to uniform red color and long shelf life. Farmers adopting Mrig Bahar treatment have reported a 30–40% increase in net returns compared to unregulated crops (Vigyan Varta, 2020).

9.2 Market Synchronization and Demand Fulfillment

Unregulated fruiting causes supply gluts, leading to price crashes. Crop regulation helps farmers:

- Harvest during lean seasons when competition is low (e.g., winter guava).
- Time fruit maturity with festival and export seasons, maximizing profit.
- Provide uniform bulk supply to organized markets, exporters and processors (*Jat et al.,* 2020).

This synchronization makes it possible to link smallholder farmers with larger value chains like supermarkets and export companies.

9.3 Employment Generation and Labor Management

- By concentrating orchard operations (pruning, spraying, harvesting) into defined windows, crop regulation generates seasonal employment for rural laborers.
- Reduced year-round workload also means farmers can diversify their time into other income-generating activities such as intercropping or allied enterprises (Bhakti, 2025).

Thus, crop regulation not only improves fruit returns but also contributes to rural livelihood diversification.

9.4 Reduction in Post-Harvest Losses

Scattered production across multiple seasons increases storage and handling **costs**, while perishable fruits may spoil before reaching markets. Crop regulation ensures:

- Bulk harvesting in one season, enabling farmers to plan cold storage, packaging, and transport more effectively.
- Improved shelf life of regulated crops (e.g., winter guava, Mrig Bahar pomegranate).
- Opportunities for processing industries (juices, concentrates, dried products) that rely on uniform raw material supplies (*Mishra et al.,*2021).

9.5 Export Competitiveness

Export markets demand uniform fruit batches, consistent supply timing and high quality standards. Crop regulation plays a crucial role:

- Indian pomegranates (Mrig Bahar) and citrus (Ambe Bahar) crops are strategically harvested to meet European and Middle Eastern demand windows (Chauhan, Ladon, & Bhakti, 2022).
- Fruits with better size, appearance and shelf life are more export-oriented.
- Case study: India's pomegranate exports surged due to adoption of regulated Mrig Bahar season, where fruits mature during cooler months, enhancing skin color and storage potential (Vigyan Varta, 2020).

9.6 Contribution to Doubling Farmers' Income

Government policies in India emphasize doubling farmers' income. Crop regulation contributes by:

- Stabilizing yields and reducing risks of alternate bearing.
- Enabling orchardists to become linked with export supply chains.
- Offering predictable and premium incomes from superior regulated harvests.
- Providing regional branding opportunities (e.g., Solapur Pomegranates, Allahabad Guava).

These benefits go beyond individual orchards, strengthening entire horticulture-based rural economies (Agri Articles, 2023).

9.7 Case Studies from India

9.7.1 Guava in Uttar Pradesh

- Farmers regulating guava crops to winter season reported 60–70% higher profits due to better fruit sweetness, firmness and consumer demand (*Mishra et al.,*2021).

9.7.2 Pomegranate in Maharashtra

- Mrig Bahar practice aligned with cooler winter resulted in improved red skin color and higher export readiness, raising farmer profitability significantly (*Chauhan et al.,* 2022).

9.7.3 Citrus in Madhya Pradesh and Nagpur Region

- Ambe Bahar treatment in citrus orchards yielded high-quality fruits with better juice content during summer demand, increasing market price realization (Bhakti, 2025).

10. Conclusion and Future Prospects

10.1 Conclusion

Crop regulation in fruit crops has emerged as a crucial horticultural practice that integrates plant physiology, agronomy, and economics. By controlling flowering and fruiting through cultural methods (withholding irrigation, pruning, defoliation, bahar treatment) and chemical methods (NAA, paclobutrazol, ethephon, urea), farmers can achieve synchronized, uniform and market-oriented production (*Mishra et al.,*2021).

The practice has proven particularly significant in fruit crops like mango, guava, pomegranate, and citrus, where irregular flowering and alternate bearing reduce productivity and profitability. Through crop regulation, these crops yield better fruit size, sweetness, appearance and marketability (Chauhan, Ladon, & Bhakti, 2022).

Economically, crop regulation improves farmer incomes, reduces post-harvest losses, enables export competitiveness, and contributes to rural livelihood generation. It also addresses sustainability concerns by optimizing input use (water, fertilizers, pesticides) and aligning production with market demand (Bhakti, 2025).

10.2 Future Prospects

Looking ahead, crop regulation will continue to play a vital role in climate-smart and precision horticulture. Emerging areas that hold promise include:

10.2.1 Integration with Precision Agriculture

- Wider adoption of drip fertigation, IoT-based irrigation scheduling and drone spraying will make crop regulation more efficient and less labor-intensive (Agri Articles, 2023).
- Digital tools will help farmers control stress more precisely and avoid guesswork.

10.2.2 Climate-Resilient Strategies

- Since climate change is disrupting bahar timings and rainfall reliability, there is need for region-specific crop regulation models.
- Use of drought- and stress-tolerant rootstocks can enhance effectiveness under adverse conditions (Vigyan Varta, 2020).

10.2.3 Eco-Friendly Alternatives to Chemicals

- Dependence on synthetic growth regulators like paclobutrazol raises concerns about residue and sustainability.
- Research on biostimulants, organic PGRs, microbial formulations and nano-nutrients will provide green alternatives for crop manipulation (Kaur, Singh, & Mishra, 2024).

10.2.4 Biotechnology and Genetic Approaches

- Advances in CRISPR-Cas gene editing may allow manipulation of flowering genes such as *FT* and *AP1*, making future crop regulation more precise and less dependent on external stress (*Mishra et al.,*2021).
- Development of climate-resilient varieties with controlled flowering responses is a long-term but promising direction.

10.2.5 Policy and Institutional Support

- Government and institutional support in the form of training programs, extension services, and subsidies for technology adoption is critical for large-scale implementation.
- Development of export clusters and farmer cooperatives (FPOs) can ensure that regulated crops reach premium markets efficiently.

Conclusion:

In summary, crop regulation stands at the intersection of traditional wisdom and modern science. It has the potential to transform tropical fruit production systems by ensuring:

- Quality fruits for consumers
- Stable incomes for farmers
- Sustainability for ecosystems

The future of horticulture in India and across tropical countries will depend on how effectively crop regulation is mainstreamed and modernized, making it a powerful tool to strengthen agricultural economies and contribute to food and nutritional security.

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DIVERSITY OF SMALL RUMINANT BREEDS IN INDIA: GOATS AND SHEEP

Mukund R. Kachave[1], Manoj Kumar Goud Pyatla[2],
Amit Kumar[3], Rajesh Kumar[4] and Komal[5]

[1]ICAR- National Dairy Research Institute, Karnal, Haryana-132001, India
[2]Department of Veterinary Biotechnology,
ICAR-Indian Veterinary Research Institute, Bareilly-243122, Uttar Pradesh
[3]Department of Veterinary Biochemistry,
[4]Department of Veterinary and Animal Husbandry Extension Education,
[5]Department of Animal Nutrition,
Mahatma Gandhi Veterinary College, Bharatpur, Rajasthan, India
*Corresponding author email: mukundrkachave@gmail.com

Abstract:

India possesses a rich diversity of indigenous small ruminant breeds (Goats and Sheep), which play a vital role in rural livelihoods, nutrition, and the national economy. These breeds are uniquely adapted to diverse agro-climatic conditions, thriving in arid, semi-arid, hilly, and desert regions where other livestock may not sustain. Indigenous goats contribute significantly to milk, meat, and skin production, while sheep are valued for their wool, meat, and carpet-quality fiber, including the world-renowned Pashmina. Despite their importance, the genetic resources of these breeds face threats from indiscriminate crossbreeding, shrinking grazing lands, and changing production systems. Conservation and scientific management of native goat and sheep breeds are essential to safeguard genetic diversity, enhance climate resilience, and ensure sustainable small ruminant farming in India.

Keywords: Goat Breeds, Sheep Breeds, Milk, Meat, Wool, Pashmina, Genetic Diversity.

Introduction:

The Small ruminants, primarily goats and sheep, are the most important domesticated livestock species in India. They are termed “small ruminants” because of their relatively smaller body size compared to large ruminants such as cattle and buffalo, and their ruminant digestive system that enables them to efficiently utilize roughages, shrubs, and low-quality forage. These animals are hardy, highly adaptable, and capable of thriving in diverse agro-climatic regions ranging from arid deserts and semi-arid plains to hilly and high-altitude zones.

Goats and sheep play a vital role in the livelihood security of small and marginal farmers, landless laborers, and pastoral communities. They provide multiple outputs such as milk, meat, wool, fiber (including the world-famous Pashmina from Changthangi sheep), skin, and manure, making them integral to rural economies. Goats are often called the “poor man’s cow” due to their contribution to household nutrition and income through milk and meat production, while sheep are traditionally valued for wool and carpet-quality fiber along with mutton.

India is endowed with a wide range of indigenous goat and sheep breeds that are genetically diverse and adapted to local environments. These breeds not only support food and livelihood security but also represent a valuable reservoir of traits such as disease resistance, tolerance to heat and water scarcity, and ability to survive under low-input management systems. With changing agricultural practices and threats of genetic erosion, it has become crucial to document, conserve, and sustainably utilize these indigenous small ruminant breeds for future livestock development and climate-resilient farming.

According to the 20th Livestock Census (2019), India's small ruminant population comprises about 150 million goats and 75 million sheep, reflecting their immense importance in the country's livestock sector. India is home to a remarkable diversity of indigenous small ruminant breeds, with 41 recognized goat breeds and 46 recognized sheep breeds, each uniquely adapted to specific agro-climatic zones and production systems. These breeds play a crucial role in supporting rural livelihoods, nutrition, and the economy through the production of milk, meat, wool, fiber, and skin. The important characteristics of these breeds are mentioned as fallows.

1. Sheep Breeds of India

In India the sheep breeds are classified into four regions on the basis of agro climatic condition viz; are Northan Temperate Region (Gaddi, Gurez, Kashmir Merino, Changthangi etc), North-Western, Central arid and semi-arid region (Chokla, Marwari, Patanwari, Muzzafanagri etc), Sourthern Peninsular region (Deccani, Nellore, Nilagiri, Madras Red etc), and Eastern region (Shahabadi, Ganjam, Tibetan etc)

Balangir: The Balangir sheep is native to the Balangir, Sambalpur, and Sundargarh districts of Odisha. This breed is medium-sized, with a variety of coat colors ranging from white to light brown and mixed hues. The Balangir sheep is characterized by small, stumpy ears and a medium-length, thin tail. The fleece is notably coarse, hairy, and open, with the legs and belly devoid of wool. The horns are present only in males.

Bellary: The Bellary sheep, found primarily in the Bellary, Davangere, and Haveri districts of Karnataka, is a medium-sized breed with a strong build. The body color varies from white to various combinations of black and white. The ears are medium-long, flat, and drooping, and the horns are found in only about 30% of the males. Bellary sheep are known for their robust constitution and high adaptability.

Bhakarwal: The Bhakarwal breed native from Jammu & Kashmir, with no distinct home tract as the sheep are entirely migratory. These medium-sized animals are recognizable by their typical Roman nose. Most animals have a white fleece, although some may have colored fleeces, ranging from fawn to grey. The ears are long and drooping, and the tail is small and thin.

Bonpala: The Bonpala sheep, found in the southern part of Sikkim, is known for its tall, leggy, and well-built frame. The fleece color can range from completely white to black, with numerous intermediary tones. The ears are small and tubular, while the tail is thin and short. The fleece is coarse, hairy, and open, with the legs and belly devoid of wool.

Changthangi: The Changthangi sheep from Changthang region of Ladakh, Jammu and Kashmir. It is known for its strong build, large frame, and excellent fleece cover, which includes extraordinarily long staples. This breed is highly valued for its wool, which is considered among the best in the world.

Chevaadu: The Chevaadu or Arichevaadu sheep is native to the Tirunelveli district of Tamil Nadu. These animals are light brown in colour. The horns are highly corrugated, curving outward, backward, and upward with blunt conical tips and thick ridges. The body is characterized by a light brown dorsal part and a lighter ventral part, from the jaw to the inguinal region.

Chokala: Distributed across Churu, Sikar, and Nagaur districts of Rajasthan, is a light to medium-sized breed. These animals have a straight head profile and small to medium-sized ears that are tubular and relatively fine. The tail is thin and medium-length, while the fleece is white, dense, and relatively fine, covering the entire body, including the belly and most of the legs. The fleece is characteristic of the breed and is considered of good quality. Males weigh around 41.3 ± 1.1 kg, and females weigh 29.9 ± 0.4 kg.

Chottanagpuri: Native to Jharkhand and West Bengal, is a small, lightweight breed. The coat color is typically light grey or brown, with small, horizontally-aligned ears that are parallel to the head. The tail is thin and short, and the fleece is coarse, hairy, and open.

Coimbatore: Present in Coimbatore and Madurai districts of Tamil Nadu, is a medium-sized breed with a white coat adorned with black or brown spots. The ears are medium-sized and directed outward and backward. The tail is small and thin, and the fleece is white, coarse, hairy, and open. Males weigh around 32.30 kg, while females weigh 23.19 kg.

Deccani: The Deccani sheep, found in Maharashtra, Andhra Pradesh, and Karnataka, is a medium-sized breed with a black coat marked with white spots. The ears are medium in length, flat, and drooping, and the tail is short and thin. The fleece is coarse, hairy, and open, which is typical for the breed. The Deccani sheep is known for its adaptability and resilience to harsh conditions. Males weigh around 49.3 ± 1.70 kg, and females weigh 35.4 ± 0.49 kg.

Gaddi: The Gaddi sheep, native to Jammu and Kashmir, Himachal Pradesh, and Uttarakhand, is a medium-sized breed. The fleece is typically white, though tan-brown and mixed colors are occasionally seen. The tail is small and thin, and the fleece is relatively fine and dense.

Ganjam: Breed from Odisha, it is a medium-sized breed with a coat ranging from brown to dark tan. Some animals have white spots on their faces and bodies. The ears are medium-sized and drooping, and the tail is medium-length and thin. The fleece is short and hairy.

Garole: The Garole sheep, native to the Sunderban region of South 24-Parganas district in West Bengal, is a small breed with relatively low body weight. The body is compact and square, with small heads, medium-sized ears, and short, thin tails. The fleece is open, coarse, and dense, and the breed is known for frequently producing twins.

Gurez: The Gurez sheep, found in the Gurej in the Baramulla district of Kashmir, is one of the largest sheep breeds in Jammu & Kashmir. The coat is generally white, though brown, black, or spotted individuals are also observed. The ears are long, thin, and pointed. Males typically weigh 35.3 ± 3.20 kg, and females weigh 40.6 ± 0.55 kg.

Hassan: The Hassan sheep, native to the Hassan district of Karnataka, is a small breed with a white body adorned with light brown or black spots. The fleece is white, extremely coarse, and open. The legs and belly are devoid of wool. Males weigh approximately 32.8 ± 0.85 kg, and females weigh 28.3 ± 0.34 kg.

Jaisalmeri: Named after its presence in Jaisalmer district of Rajasthan. These sheep are typically well-built, square, deep, and tall in appearance. The face is dark brown or black, extending to the neck, and they have a characteristic Roman nose. The ears are long, drooping, and often have a cartilaginous appendage. The fleece is white, of medium carpet quality, and not very dense.

Jalauni: The Jalauni sheep, found in Uttar Pradesh and Madhya Pradesh, is a medium-sized breed. These sheep have a straight nose line and large, flat, drooping ears. The tail is thin and medium in length, while the fleece is coarse, short-stapled, and open, usually white.

Kajali: Kajali sheep is a prominent breed native to the state of Punjab. Known for its large, well-built body, this breed exhibits two color variants based on coat coloration: White (Chitti) and Black (Kali). Both male and female Kajali sheep are typically polled, lacking horns. As one of the heaviest sheep breeds in India, Kajali sheep are highly regarded for their substantial body weight.

Karnah: The Karnah sheep is a medium-sized breed found primarily in the Kupwara district of Jammu & Kashmir. These sheep have a round and compact body with a prominent Roman nose. The rams of this breed are particularly noted for their large, curved horns with pointed tips. The coat is predominantly creamy white, and the ears are pendulous and of medium length. The tail is thin, straight, and medium-sized.

Katchaikatty Black: Originating from the Madurai district in Tamil Nadu, is a medium-sized sheep breed. Its most notable feature is the black coat color, although variations can sometimes occur. The breed is distinguished by large, widespread, and twisted horns. The animals have a compact body with a moderate-length, concave face with a depression, and a moderately broad forehead.

Kendrapada: The Kendrapada sheep is native to Odisha. The animals are primarily brown in color, with button-type horns present in only a few males. The head, face, belly, and legs of these sheep are bare, with the rest of the body covered in non-lustrous hair. Their ears are horizontal, and they possess a short, straight, and drooping tail.

Kenguri: Found in the Raichur and Koppala districts of Karnataka, is a medium-sized breed. The coat color of these animals is primarily dark brown or coconut-colored, although variations ranging from white to black with spots are also observed. The ears are medium-long and drooping, while the tail is short and thin.

Kilakarsal: Kilakarsal sheep are medium-sized animals found in the Tamil Nadu. The breed is characterized by a dark tan coat with black spots on the head, belly, and legs. Males typically have thick, twisted horns. A distinctive feature of the breed is the presence of wattle in most animals.

Kheri Sheep: The Kheri sheep is found in the Tonk, Ajmer, Jaipur, Nagaur, Pali, and Jodhpur districts of Rajasthan. Known for their tall stature and majestic appearance, these sheep are favored by farmers for their ability to walk long distances, making them ideal for migration. They are well-adapted to harsh climates and can survive during feed and fodder scarcity.

Madras Red: The Madras Red breed, originating from the Chengalpattu and Madras districts of Tamil Nadu, is a medium-sized breed with a predominant brown coat. The intensity of the color varies from light tan to dark brown, and some animals may have white markings on the forehead, inside the thigh, and on the lower abdomen. The ears are medium in size, long, and drooping. Rams of this breed have strong, corrugated horns.

Magra: The Magra sheep, found primarily in the Rajasthan districts of Bikaner, Nagaur, Jaisalmer, and Churu, is a medium to large-sized breed. These sheep are characterized by a white face with light brown patches around the eyes, which is a distinctive feature of the breed. The skin color is pink, and the ears are small to medium-sized and tubular. The fleece is of medium carpet quality, extremely white, lustrous, and not very dense.

Malpura: The Malpura sheep, native to Rajasthan districts like Tonk, Sawaimadhopur, Jaipur, and Dausa, is known for its well-built structure and long legs. The face of these sheep is typically light brown, extending to the neck, and their ears are short and tubular. The fleece is white, coarse, and hairy, with the belly and legs devoid of wool.

Mandya: Mandya sheep are relatively small animals found in the Mandya district and surrounding areas of Mysore and Bengaluru in Karnataka. The body color is predominantly white, although the face may occasionally be light brown, with this coloration extending up to the neck. Both sexes are polled, and the fleece is extremely coarse and hairy.

Marwari: The Marwari sheep, native to Rajasthan and Gujarat, is a medium-sized breed. The face of the breed is black, extending to the lower part of the neck. Ears are extremely small and tubular, and both sexes are polled. The tail is short to medium and thin. The fleece is white and not very dense. Males weigh around 40.69 ± 1.13 kg, and females weigh approximately 30.11 ± 0.28 kg.

Macherla: The Macherla sheep is a meat breed from Guntur, Krishna, and Prakasam districts of Andhra Pradesh and nearby regions of Telangana. It is medium to large in size, with a white coat marked by large black or brown patches on the body, face, and legs.

Mecheri: Native to the Tamil Nadu, Mecheri sheep are medium-sized animals with a light brown coat color. The ears are medium-sized, and the tail is short and thin. The body is covered with very small hair. Males typically weigh 33.13 kg, and females weigh 28.29 kg.

Muzaffarnagri: The Muzaffarnagri sheep is a medium to large breed found in Uttar Pradesh, Uttarakhand, Delhi, and Haryana. These sheep have a slightly convex face with white bodies, sometimes marked with brown or black patches. Their ears can be black, and both sexes are polled. The tail is long, reaching the fetlock. Their fleece is white, coarse, and open, with woolless bellies and legs. Males typically weigh 50.21 ± 1.46 kg, and females weigh 39.61 ± 0.38 kg.

Nali: The Nali sheep, found in Rajasthan, and the southern parts of Rohtak and Hissar districts of Haryana, is a medium-sized breed. The face is light brown, with pink skin. Both sexes are polled, and the ears are large and leafy. The fleece is white, coarse, dense, and long-stalped, with wool covering the forehead, belly, and legs.

Nellore: The Nellore sheep, native to the Nellore, Prakasham, and Ongole districts of Andhra Pradesh, are relatively tall animals with minimal hair except at the brisket, wither, and breech. The ears are long and drooping, and the tail is short and thin. Males typically weigh 36.69 ± 2.56 kg, and females weigh 30.0 ± 0.27 kg.

Nilgiri: Native to the Nilgiri hills in Tamil Nadu, are medium-sized animals with a predominantly white body color. These sheep have a convex face line, which gives them a typical Roman nose. Their ears are broad, flat, and drooping. Males have horn buds and scars, while females are polled. The tail is medium in length and thin, and the fleece is fine and dense.

Panchali: Panchali sheep, found in the Surendranagar, Rajkot, Botad, Bhavnagar, and Kutchchh districts of Gujarat, are characterized by their white color. However, the head and facial parts may be light brown, blackish brown, brown, or black, and this color may extend to the ventral part of the neck and to the forelegs below the knee joint and hind legs below the hock joint. These animals have a convex head, long, pendulous ears, and a long tail.

Patanwadi: The Patanwadi sheep is native to Gujarat. These animals are medium to large in size, characterized by their relatively long legs and a typical Roman nose. Their face is predominantly brown, with distinct tan spots, and their ears are medium to large in size, tubular, and adorned with a tuft of hair. The tail is thin and short, and both sexes of the Patanwadi breed are polled. The fleece is predominantly white and of medium carpet quality, though not very dense.

Poonchi: The Poonchi breed hails from Jammu & Kashmir. Poonchi sheep are primarily white in color, though some individuals may exhibit spots ranging from brown to light black. Their ears are medium in length, and they have a low-set conformation due to short legs.

Pugal: The Pugal breed is primarily found in the Bikaner and Jaisalmer districts of Rajasthan. These sheep are fairly well-built, with a characteristic black face. They often feature small light-brown stripes above their eyes, with the lower jaw being typically light brown. The black color may extend up to the neck. Pugal sheep have short, tubular ears, and both sexes are polled.

Ramnad White: The Ramnad White breed is native to the Ramnathapuram district in Tamil Nadu. These sheep are medium-sized and predominantly white, though some animals may have fawn or black markings on their bodies. This breed is known for its white fleece, which is coarse and not very dense.

Rampur Bushair: Sheep from Himachal and Uttarakhand. These medium-sized sheep have a slightly convex face with a characteristic Roman nose. The fleece color is mostly grey, sometimes with black spots. The tail is extremely long and thin, and the fleece is coarse, open, and hairy.

Shahabadi: Native to the Bihar state, These medium-sized animals have long legs and are known for their grey fleece, often interspersed with black spots. Their ears are medium-sized and drooping, and their tail is extremely long and thin. The fleece is coarse, open, and hairy, and the legs and belly are devoid of wool.

Sonadi: Sonadi sheep are found primarily in the Udaipur, Dungarpur, Chittorgarh, and Banswara districts of Rajasthan. These sheep are well-built and somewhat smaller than the Malpura breed, with long legs. Their ears are large, flat, and drooping, and the tail is thin and medium in length. Both sexes are polled, and the fleece is white, coarse, and hairy.

Tibetan: Tibetan sheep from Arunachal Pradesh region, particularly in the Sikkim and Kameng districts. These medium-sized animals are mostly white, though black or brown faces and brown and white spots on the body are also common. Their ears are small, broad, and drooping, and their fleece is relatively fine and dense. The body weight of male Tibetan sheep averages 46 kg, while females typically weigh 44 kg.

Tiruchi Black: Tiruchi Black sheep are small-sized animals found in the Tiruchy, Arcot, Salem, and Dharmapuri districts of Tamil Nadu. The breed is completely black, and the ears are short, directed downward and forward. Their tail is short and thin, and the fleece is extremely coarse, open, and hairy.

Vembur: The Vembur sheep breed native to Tamil Nadu. These tall animals are white with irregular red and fawn patches scattered across their bodies. Their ears are medium-sized and drooping, and the tail is thin and short. Their bodies are covered with short hair. The average body weight of male is 34.33 ± 1.71 kg, while females weigh around 27.93 ± 0.23 kg.

2. Goat Breeds of India

Indian goat breeds are classified into four regions on the basis of location they found viz; Northern Himalayan region (Gaddi, Chegu, Changthangi etc), North-Western, Central arid and semi-arid region (Jamnapari, Marwari, Surti, Sirohi etc), Sourthern Peninsular region (Sangamneri, Malabari, Osmanabadi etc), and Eastern region (Black Bengal, Ganjam etc)

Assam Hill Goat: The Assam Hill goat is found in the Assam and Meghalaya. These goats are short-legged and small-bodied, with cylindrical horns that taper towards the end and are pointed at the tip. The horns are typically straight, though in some animals, they may curve slightly backward. Both bucks and does are bearded, and their ears are medium in size, horizontally placed with pointed tips. The average body weight of male Assam Hill goats is 19.81 kg, while females weigh around 18.61 kg.

Andamani Goat: The Andamani goat is a medium-sized meat breed native in the Middle and North Andaman districts of the Andaman & Nicobar Islands, well-adapted to the region's hot and humid tropical climate.

Anjori: The Anjori goat is a medium-sized breed primarily raised for meat production. It is found in several districts of Chhattisgarh state**.** The majority of Anjori goats exhibit a brown coat color. This breed is notable for its hardiness and excellent adaptability to the local climate, making it a valuable resource for the region's farmers.

Attapady Black Goat: The Attapady Black goat, native to the Palakkad/Palghat district of Kerala, is known for its black coat color, although some variations may include white spots. The horns of this breed are small in size, curved, and oriented backward. The tail is a bunchy type, and these goats are medium-sized animals.

Barbari Goat: The Barbari goat is primarily found in the Bharatpur district of Rajasthan and parts of Uttar Pradesh, including Aligarh, Agra, and Etawah. These goats are small in size, characterized by their white coats with tan or dark red spots. Their horns are twisted and medium in size, directed upward and outward. The ears are small, tubular, and prick, while the tail is short. Both male and female Barbari goats are typically bearded.

Beetal Goat: The Beetal breed, found in Punjab, is known for its tall stature and black coat, though brown goats with white spots are also common. Beetal goats have medium-sized horns, which are carried horizontally with a slight twist, directed backward and upward.

Berari Goat: Native to the Maharashtra, the Berari goat is light to dark tan in color, with a reddish hue being common. These goats have small, flat horns that are oriented upward and backward. These goats are medium-sized, and the average body weight of males is 36 kg, while females weigh 30 kg.

Bhakarwali Goat: The Bhakarwali goat, also known as Kagani, is found in the Jammu & Kashmir. These large-sized goats are predominantly white, with some individuals having black faces or hindquarters. Their horns are curved and screw-like, directed upward and backward, measuring about 15 cm in size. The body is covered with long hair, and the udder is pendulous and medium in size.

Bidri Goat: The Bidri goat, found in the Bidar and Gulbarga districts of Karnataka, is characterized by its black coat, with some goats having white spots on their ears, forehead, neck, and knees. The horns are curved and directed backward, outward, and downward. Bidri goats have a straight forehead, and their muzzle, eyelids, and hooves are black. The average body weight for males is 36.78 kg, and females weigh 32.36 kg.

Black Bengal Goat: This goat is widely distributed across the northeastern states of India, including West Bengal, Odisha, Assam, Manipur, Meghalaya, Tripura, and Arunachal Pradesh. These goats are predominantly black, although brown, grey, and white variations are also found. Horns are small to medium in size, ranging from 5.8 to 11.5 cm, and are directed upward or sometimes backward. Males typically weigh 32.37 kg, while females weigh 20.38 kg.

Bundelkhandi goat: Medium-sized breed primarily raised for meat. Found in districts Jhansi, Banda, Chitrakoot (U.P.) and Sagar, Panna, Damoh (M.P.). Goats are black in color, well-adapted, and capable of covering long distances while grazing.

Changthangi Goat: Native to the Leh region in Ladakh, Jammu & Kashmir, is a sturdily built breed with about 50% of the animals having a white coat, while the rest have black, grey, or brown coats. The horns of the Changthangi goat are large and turned outward, upward, and inward to form a semi-circle. These medium-sized goats have a solid build and are well-suited to harsh climates.

Chaugarkha: The Chaugarkha, or Kumaoni goat, is distributed across Almora, Pithoragarh, Nainital, Champawat, and Bageshwar districts of Uttarakhand. It is primarily raised for meat production. The average adult body weight is 27 kg for males and 24 kg for females.

Chegu Goat: Present in the Himachal Pradesh and the Ladakh region of Jammu & Kashmir. The coat colors varied, including white, black, grey, brown, or mixtures of these colors. Their horns are long and cork-shaped, directed upward, backward, and inward/outward, with males having an average horn length of 59 cm and females 33 cm. These goats have reddish, tan, or black coloration around the head and neck and a second coat of pashmina wool beneath the long hair.

Gaddi Goat: Native to Himachal Pradesh and Jammu & Kashmir, is primarily white, though black individuals are also present. These goats have tough skin covered with coarse long hair, measuring between 17 to 25 cm. The ears are drooping and pointed. Males typically weigh 28 kg, while females weigh 23.4 kg.

Ganjam Goat: Native to the Ganjam and Koraput districts of Odisha, the Ganjam goat is typically black or brown-black, although white, brown, and spotted animals are also found. The horns of this breed are twisted and curved, long and parallel, and directed backward and upward. The ears are pendulous and medium in size (14.5 cm), and wattles are mostly absent.

Gohilwadi Goat: Local to Gujarat, goats are black in color, and their horns are slightly twisted, oriented backward. The horns are about 8 to 10 cm long in females and 12 to 15 cm in males. The nose line is slightly convex, and their ears are tubular and drooping. The body is covered with coarse long hairs.

Jakhrana: Primarily found in the Rajasthan, predominantly black in color, with distinctive white spots on their ears and muzzle. They are characterized by broad, flat horns that curve backward. known for their large udder size, with conical teats. The males typically weigh around 57.8 kg, while females weigh 44.5 kg.

Jamunapari: Jamunapari goats are found in the districts of Agra, Mathura, and Etawah in Uttar Pradesh, as well as in Bhind and Morena districts of Madhya Pradesh. These goats have a unique appearance with white coats that are adorned with patches of tan or black, mainly on the head and neck. Horns are short and sword-shaped, adding to their distinctive look. The face is large and convex, with a tuft of hair, and their ears are long, pendulous, and drooping, measuring about 30 cm in length. Males weigh 44.66 kg, while females weigh 38.03 kg.

Kahmi: The Kahmi breed, also known as Desi, is primarily distributed in Gujarat and Uttar Pradesh. The most striking feature of the Kahmi breed is its unique coat color cranial reddish-brown and caudal black. The horns are curved upward and backward, with males having larger, longer horns. The goats have long, tubular, and coiled ears, referred to as "veludi," and a convex forehead.

Kanni Adu: Found in the Tamil Nadu region, especially in the districts of Tirunelveli and Thoothukudi/Tuticorin, the Kanni Adu breed is notable for its black coat with white markings on the face and legs. The horns of the Kanni Adu are broad, small, and directed backward. A distinguishing feature of these goats is the white stripes that run on either side of the face, extending from the base of the horn to the corner of the muzzle. Males weigh approximately 34.05 kg, while females weigh 28.17 kg.

Kodi Adu: The Kodi Adu, also referred to as Porai Adu, is native to the Ramanathapuram and Thoothukudi districts of Tamil Nadu.This breed is recognized by its white coat, with splashes of black or reddish-brown color. The horns of the Kodi Adu are directed upward and backward, curved downward or sharp at the tip, with a size range of 15-25 cm.

Konkan Kanyal: The Konkan Kanyal breed is primarily found in the Sindhudurg district of Maharashtra. These goats are black in color, with white markings on the collar, lower jaw, and ventral surface. The horns are cylindrical, backward-curved, and medium-sized. A unique feature of these goats is the bilateral white strips that run from the nostrils to the ears. The tail is dorsally black and ventrally white.

Kutchi: The Kutchi breed of goats is found in Gujarat, particularly in the Ahmedabad and Kutchchh districts, as well as in the Barmer, Bikaner, Jaisalmer, Jalore, Jodhpur, Pali, and Nagaur districts of Rajasthan. These goats predominantly have black coats, although some may exhibit white, brown, or spotted animals. The horns are short (10.6 cm), thick, and pointed upwards. The goats are known for their long, coarse hair and slightly Roman nose.

Malabari: The Malabari breed is primarily located in Kerala. These goats come in a variety of colors, including black, brown, and white, or mixtures of these colors. The horns are slightly twisted, directed outward and upward, and are small in size. The ears are medium-sized and directed outward and downward.

Marwari: The Marwari breed is predominantly distributed across Barmer, Bikaner, Jaisalmer, Jalore, Jodhpur, Pali, and Nagaur districts of Rajasthan. These goats are mostly black, with some exhibiting white or brown patches. The horns are short (about 10 cm), pointed, and directed upward and backward. Marwari goats have a long, shaggy hair coat and medium-sized, flat, and drooping ears. Males typically weigh 39.51 kg, while females weigh 31.86 kg.

Mehsana: Breed from Gujarat. These goats are predominantly black, with white spots at the base of the ears. The horns are screw-shaped, slightly twisted, and curved upward and backward. The ears often have white spots, ranging from a few to completely white. Males weigh around 37 kg, while females weigh 32 kg.

Nandidurga: Present in Karnataka, these goats have white coats, with some displaying black or brown spots on their ears, forehead, neck, and knees. The horns are curved and directed backward, downward, and inward. The udder is hairy and pendulous, with funnel-shaped teats. Males weigh 38.92 kg, while females weigh 30.11 kg.

Osmanabadi: Osmanabadi goats are distributed in the Maharashtra. They are predominantly black, with some goats having white ears and spots on the neck and forehead, and a few are reddish. The horns are straight, curved, and small. Osmanabadi goats come in five different types, ranging from entirely black with horns to combinations of black, white, and brown patches. Males weigh approximately 33.66 kg, while females weigh 32.52 kg.

Pantja: The breed is found in the Udhamsingh Nagar and Nainital districts of Uttarakhand. These goats are fawn to brown in color, with the ventral portion being lighter in shade. Their horns are small, triangular, twisted, slightly upwards and backwards, with pointed tips. Pantja goats have a white streak on either side of the face, and the head is slightly convex. The ears are pendulous. Males weigh 22.91 kg, while females weigh 18.81 kg.

Rohilkhandi: Native to Uttar Pradesh, The breed is predominantly black, though some animals display brown, fawn, or mixed color variations. A distinct feature of this breed is the slightly convex forehead, with a tuft of hair (black or brown) present in the thigh region. The tail of the Rohilkhandi goat is bunchy, and the ears are mostly pendulous.

Salem Black: Salem Black goats, distributed in Tamil Nadu. The breed is characterized by a completely black coat with a glossy texture. Salem Black goats do not follow a typical horn pattern; however, their horns are usually directed upward and backward with sharp tips. The head is of medium length with small, bright eyes and black eyelashes. The ears are medium in length, leaf-like, and semi-pendulous.

Sangamneri: Sangamneri goats are found in the Ahmednagar and Pune districts of Maharashtra. The breed exhibits a coat color that can be white, black, or brown, and some animals may have spotted patterns. These goats have a coarse and short hair coat, which is a notable characteristic of the breed. The average body weight of males is about 39.1 kg, while females weigh around 32.62 kg.

Sirohi: The Sirohi breed is native to the Sirohi district in Rajasthan. These goats are primarily brown in color with varying patches of light or dark brown, though some individuals are entirely white. The horns of the Sirohi goats are small and curved, pointing upward and backward. A defining feature of the breed is their flat, leaf-like, drooping ears. Sirohi goats are known for their well-built physique, and the males generally weigh 42.83 kg, while females average around 35.27 kg.

Sumi-Ne: The Sumi-Ne goat, also known as Apu-Asu-Ne or Nagaland Long Haired, is found in the Zunheboto district of Nagaland. These goats are primarily white with characteristic black markings on their head, neck, and legs. A straight head and horizontal ears further distinguish this breed. The average body weight is 16.18 kg for males and 13.5 kg for females.

Surti: The Surti goat is native to the Vadodara and Surat districts in Gujarat, with a predominantly white coat color. The horns of Surti goats are directed backward, and they are small in size. The ears are of medium size, and the body weight of males is about 29.03 kg, while females weigh approximately 31.06 kg.

Teressa: The Teressa goat, also known as Pookore, is found in the Nicobar district of the Andaman and Nicobar Islands. These goats exhibit a variety of coat colors, including dark tan, brown, white, and brown mixed, as well as black and brown mixed. A distinctive feature of Teressa goats is a peculiar white patch or line starting from the inner canthus of both eyes and extending to the nostrils or mouth.

Zalawadi: Zalawadi goats are native in the Rajkot and Surendranagar districts of Gujarat. The body is primarily covered with black, lustrous, and shiny hair, although some animals may have white or brown hairs. The horns are of the cork-screw type, moving straight upwards, backward, and slightly outward with pointed tips. The ears of Zalawadi goats are long, wide, leaf-like, and drooping. The breed is also known for its well-developed udder with large conical teats. The males of this breed typically weigh 38.8 kg, and females weigh around 33 kg.

Sojat: The Sojat goat is native to the Pali, Jodhpur, Nagaur, and Jaisalmer districts in Rajasthan. These goats are primarily white, with brown spots on the head, neck, ears, and legs, although pure white animals are also found. The horns of Sojat goats are curved downward and twisted in females, while males are completely polled. Most females of this breed possess wattles, while males do not.

Karauli: The Karauli goat breed is found in the Rajasthan. The coat color pattern is predominantly black with brown strips on the face, ears, abdomen, legs, and near the pin bones. The horns are medium-sized and corkscrew-shaped, pointing upwards. Karauli goats are characterized by their long, pendulous ears with folded brown lines on the borders. Males typically weigh 52 kg, and females weigh around 45 kg.

Gujari: Goats are found in the Jaipur and Sikar districts of Rajasthan. The coat color of these goats is a mix of brown and white, with a white face, legs, and abdomen being typical features. The horns are small, twisted, and directed backward. Gujari goats have long, pendulous, and folded ears. The body weight of males averages 69 kg, and females weigh about 58 kg.

Photographs of registered Sheep breeds of India
(source: Animal Genetic Resources of India- Information System)

Photographs of registered Goat breeds of India

(Source: Animal Genetic Resources of India- Information System)

INDIGENOUS CATTLE AND BUFFALO BREEDS: PILLARS OF INDIA'S LIVESTOCK HERITAGE

Mukund R. Kachave*[1], Komal[2], Rajesh Kumar[3], Amit Kumar[4] and Rajesh Kumar Bochliya[1]

[1]ICAR- National Dairy Research Institute, Karnal, Haryana-132001, India.

[2]Department of Animal Nutrition,

[3]Department of Veterinary and Animal Husbandry Extension Education,

[4]Department of Veterinary Biochemistry,

Mahatma Gandhi Veterinary College, Bharatpur, Rajasthan, India.

*Corresponding author E-mail: mukundrkachave@gmail.com

Abstract:

India is home to a rich diversity of indigenous cattle and buffalo breeds, which play a pivotal role in agriculture, rural livelihoods, and food security. These breeds are uniquely adapted to diverse agro-climatic zones and contribute significantly to milk production, draught power, and socio-cultural practices. Despite their importance, the population of native breeds is under threat due to indiscriminate crossbreeding, mechanization, and changing livestock management practices. Conservation of these genetic resources is vital to maintain breed diversity, productivity under low-input systems, and resilience against emerging challenges such as climate change and disease outbreaks. This chapter highlights the major indigenous cattle and buffalo breeds of India, their distinguishing characteristics, and the need for systematic conservation and sustainable utilization to safeguard the future of livestock farming.

Keywords: Cattle, Buffalo, Milk, Draught power

Introduction:

India is home to a rich diversity of indigenous cattle and buffalo breeds that have evolved over centuries to thrive in its varied climatic, geographical, and cultural landscapes. These breeds form the backbone of India's agriculture and rural economy, providing essential products such as milk, draught power, and manure, while also holding significant socio-cultural importance in rural life. For millions of farming households, indigenous cattle and buffalo not only ensure economic stability and nutritional security, but also contribute to sustainable farming practices through their adaptability to low-input systems and resilience to local diseases.

Despite their importance, several native cattle and buffalo breeds are facing a decline in population due to indiscriminate crossbreeding, mechanization of agriculture, and changing farming systems. Yet, these indigenous breeds possess unique and invaluable genetic diversity, making them vital for meeting future challenges such as climate change, emerging diseases, and resource constraints. Conserving and promoting native breeds is therefore essential to safeguard their distinct traits and ensure the long-term sustainability of livestock farming in India.

This chapter highlights the major indigenous cattle and buffalo breeds of India, their distinguishing characteristics, and the critical need for conservation and sustainable utilization strategies to preserve these national genetic resources for future generations.

According to the 20^{th} Livestock Census (2019), India's livestock population includes about 192.49 million cattle, 112 million buffaloes, 150 million goats, and 75 million sheep, along with significant populations of pigs, poultry, and other species. There are currently 53 indigenous cattle breeds**,** 21 buffalo breeds**,** 41 goat breeds**,** 46 sheep breeds**,** 8 horse and pony breeds**,** 9 camel breeds**,** 15 pig breeds**,** 4 donkey breeds**,** 5 dog breeds**,** 2 yak breeds**,** 20 chicken breeds**,** 4 duck breeds, and 1 goose breed**.**

This chapter highlights the major indigenous cattle and buffalo breeds of India, their distinguishing characteristics, and the critical need for conservation and sustainable utilization strategies to preserve these national genetic resources for future generations.

1. Cattle breeds of India

The Indian cattle breeds are classified as milch, draught and dual-purpose breeds based on utility. The Sahiwal, Red Sindhi, Gir, Deoni and Tharparkar are milch purpose cattle breeds of india. Draught purpose cattle breeds include Amritmahal, Khillari, Malvi, Nagori, Kangayam, Siri etc. and dual-purpose cattle breeds of India are Hariana, Rathi, Dangi, Ongole Kankrej etc

Amritmahal: Originating from Karnataka, they are primarily found in Chikmagalur, Chitradurga, and Hassan. They have a grey coat that ranges from white to nearly black, often with white-grey markings on the face and dewlap. Their distinctive long, curved horns emerge close together, arch backward, and turn inward with sharp black tips that may touch. These cattle are known for their tapering head, strong build, and endurance, making them well-suited for draught work.

Bachaur: Native to Bihar, near the Nepal border, they have a grey coat and medium-sized, stumpy horns that curve outward and upward. They are compact, medium-sized animals with a straight back and a flat to slightly convex forehead.

Badri: Indigenous to Uttarakhand's hilly regions, Badri cattle come in black, brown, red, white, or gray. They have small horns, a prominent hump, long legs, and compact udders. Their hooves and muzzles are typically black or brown, adapting them well to rugged terrains.

Bargur: These are found in Bargur Hills, Erode district, of Tamil Nadu. they have a brown coat with white markings and medium-sized, sharply tipped light brown horns that curve backward, outward, and upward with a forward bend. They are valued for their distinct coloration and light brown horns.

Belahi: They distributed in hilly regions of Haryana and surrounding areas, including Chandigarh and Mohali. The animals are red with white faces, abdomens, and feet, and black muzzles. Their horns curve upward and inward, forming a sickle shape. These medium-sized, strong animals are adapted to migratory lifestyles and are dual-purpose in nature.

Binjharpuri: Originating from Odisha's Jajpur district, Binjharpuri cattle are predominantly white, with some grey, black, or brown variants. They have medium-sized horns that curve upward and inward, while males feature black markings on the hump, neck, face, and back.

Dagri: Breed from Gujarat, is small and compact, with a predominantly white coat, sometimes shaded grey. Their short, thin horns curve upward in a lyre shape or remain straight with pointed tips.

Dangi: Spreads across hilly and forested regions of Gujarat (Dang district) and Maharashtra (Thane, Nashik, and Ahmednagar districts), particularly in the Sahyadri ranges. They have a distinct white coat with red or black spots distributed unevenly. Their horns are short and thick with tips pointing laterally, and their slightly protruding foreheads add to their unique appearance.

Deoni: Native to Bidar (Karnataka) and parts of Maharashtra (Parbhani, Nanded, Osmanabad, Latur), Deoni cattle have a black-and-white spotted coat with three strains: Balankya (white), Wannera (white with a black face), and Waghyd/Shevera (spotted). They have small, blunt-tipped horns curving outward, upward, and slightly backward, along with drooping ears and a prominent, slightly bulging forehead.

Gangatiri: Found in Eastern Uttar Pradesh and Bihar. These animals are predominantly white or light grey, with bulls showing a darker shade on the back. Their horns are small to medium in size, and their coat coloration makes them easily identifiable.

Gaolao: Cattle from Madhya Pradesh and Maharashtra. They have a white or light grey coat, with males often having darker grey necks. Their short, stumpy horns curve slightly backward. Their almond-shaped eyes and long, narrow heads are distinguishing features.

Ghumusari: They are small, robust animals suited for draught work they are from Odisha. They typically have a white coat, with some grey variants. They feature small heads with broad, flat foreheads and a depression between the eyes.

Gir: Originate from Gujarat, specifically in the districts of Amreli, Bhavnagar, and Junagadh. They are known for their striking red coat, although some individuals have speckled red patterns. The horns of Gir cattle are uniquely curved, starting from the crown base and taking a downward and backward curve before spiralling upward and inward in a half-moon shape. This breed is also distinguished by its long, pendulous ears, which are folded like leaves and hang with their inner surfaces facing forward. Gir cattle have a bulging convex forehead. The average milk yield of this breed is approximately 2110 kg.

Frieswal: This is a synthetic dairy cattle breed developed by the ICAR-Central Institute for Research on Cattle, Meerut. It has a genetic composition of 37.5% Sahiwal and 62.5% Holstein Friesian. This breed is well-acclimatized to the diverse agro-climatic conditions of India.


Amritmahal (Cattle) : Male

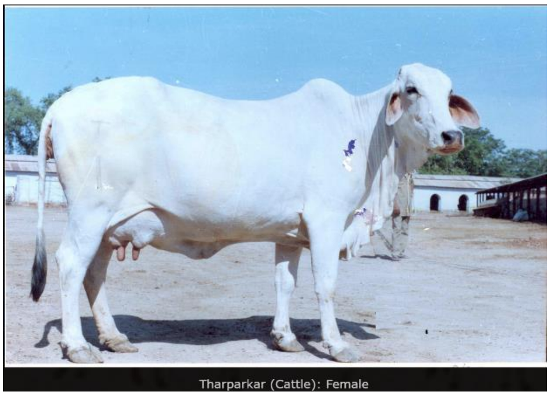

Hariana (Cattle) : Male


Kankrej (Cattle) : Male


Ongole (Cattle) : Male


Red Sindhi (Cattle): Female


Sahiwal (Cattle): Female


Tharparkar (Cattle): Female


Dangi (Cattle) : Male

Photographs of registered Cattle breeds of India

(Source: Animal Genetic Resources of India- Information System)

Hallikar: Indigenous to Karnataka (Chitradurga, Hassan, Kolar, Mandya, Mysore, Tumkur), Hallikar cattle have a grey to dark grey coat, often with shading on the forehead and hindquarters. Their horns emerge close at the poll, curving backward, then forward and slightly inward, ending in sharp black tips. They are known for their distinctive coloration and horn shape.

Hariana: Predominantly raised in Haryana, especially in the districts of Hisar, Rohtak, Jind, and Gurgaon, and are widely spread across the Indo-Gangetic plains. These animals are usually white or light grey, with bulls displaying darker coloration between the fore and hindquarters. The horns are relatively small in size. Hariana cattle have a long and narrow face with a well-defined bony prominence at the center of the poll.

Himachali Pahari: Found in the mountainous regions of Himachal Pradesh, have a black or blackish-brown coat. Small to medium-sized with a compact body, short legs, and a medium hump, they are well-adapted to cold climates and can thrive on limited fodder.

Kangayam: The breed is found in Coimbatore, Erode, Dindigul, Karur, and Namakkal districts of Tamil Nadu. Calves are born with a red coat that turns grey by six months. Bulls are grey with darker shading on the hump, forequarters, hindquarters, face, and legs, while cows are typically grey or white-grey, with some showing red, black, or fawn coats. The breed is known for its large hump, strong build, and long, curved horns.

Kathani: A dual-purpose breed, from Maharashtra, has coat colours ranging from white to reddish and blackish shades. Their straight, slightly curved horns and small to medium dewlap are distinguishing features.

Kankrej: Kankrej cattle are native to Gujarat (Ahmedabad, Banas Kantha, Kheda, Mehsana, Sabarkantha, and Kutch) and Rajasthan (Barmer and Jodhpur). The coat color ranges from silver-grey to iron-grey or steel-grey, with males showing darker shading on the forequarters, hindquarters, and hump. The horns are strong, curved outward and upward in a lyre shape, and extend longer due to their distinct curvature. This breed is one of the heaviest cattle breeds, characterized by its lyre-shaped horns, large pendulous ears, and robust body.

Kenkatha: Indigenous to Ken River region in Bundelkhand, are found in Tikamgarh (M.P.) and Lalitpur, Hamirpur, and Banda (U.P.) districts. They have a grey coat, darker on the neck and hindquarters, with forward-pointing horns ending in sharp tips. Small and sturdy, they are well-suited for draught work.

Khariar: These cattle are native to Odisha, have a brown coat, occasionally grey, with darker shading on the hump, neck, face, and back. Small and strong built, they are well-suited for draught work.

Kherigarh: Native to Uttar Pradesh's Kheri district, usually have a white coat, sometimes with grey shading on the face. Their medium-sized horns (15 cm) curve outward and upward, resembling the lyre-horned Malvi type. Small but agile, they are known for their activity and adaptability.

Khillar: Primarily found in Maharashtra and Karnataka, Variants include the Mhaswad and Atapadi Mahal types, which are greyish-white with males showing darker fore and hindquarters and mottled markings on the face. Their long, pointed horns follow a backward curve, turning upwards in a smooth bow shape. These animals are recognized for their distinctive nasal bridge and long, bow-shaped horns.

Konkan Kapila: Also called Konkan Gidda, are native to Maharashtra's coastal districts. Predominantly reddish-brown, they also show black, white/grey, mixed, brown, or fawn coats. Their straight horns curve outward and backward. Compact in build, they have horizontal ears and a straight forehead.

Kosali: Native to Chhattisgarh, have light red coats (60-65%), with whitish-grey (30-35%) and occasional black or red with white patches. Their stumpy horns curve outward, upward, and inward, they are distinguished by a black muzzle, eyelids, tail switch, and hooves, along with a broad, flat head and a small to medium hump.

Krishna Valley: Spread across Satara, Solapur, and Sangli districts of Maharashtra's, cattle are typically grey-white, with males showing darker fore and hindquarters, while females appear more whitish. Some individuals display brown-white, black-white, or mottled coats. Their small horns curve outward, upward, and inward. They have a massive body and a distinct forehead bulge.

Ladakhi: Found in Leh and Kargil districts, have a black coat, with some being brown. Their curved horns point upward and forward, Small in stature, they have short legs, a small hump, and a slightly long, hairy face.

Lakhimi: They are small cattle, native to Assam, with a brown or grey coat, straight horns, short legs, medium hump, and a slightly curved backline. Well-suited for draught work and milk production in tropical climates.

Malnad Gidda: Originates from Karnataka, Small, hardy cattle with a black coat, light fawn shades on thighs and shoulders, curved small horns, and a black tail switch. Well-adapted to the humid, rugged terrain of high-rainfall regions.

Malvi: The Malvi breed, found in Madhya Pradesh and Rajasthan, has a grey coat, with males being darker on the neck, shoulders, and hump, while cows and older animals are lighter. Their strong, lyre-shaped horns measure 20–25 cm. Known for their sturdy build, they are well-suited for draught work and semi-arid conditions.

Masilum: Cattle from Meghalaya, they are primarily black, brown, or a mixture of brown, grey, and black. They have short horns that are typically black in color. These cattle are well-suited to the hilly ecosystem of Meghalaya and are commonly reared by the Khasi and Jaintia communities for their participation in sports, manure production, and socio-cultural festivals.

Mewati: Spread across Haryana, Rajasthan, and Uttar Pradesh, are predominantly white with darker shades on the neck, shoulders, and quarters. Their horns curve backward from the outer angles of the poll.

Motu: The Motu breed, native to Odisha, is small yet strong, with a predominantly brown or reddish coat, though grey and white variations exist. Primarily used for draught work, they are well adapted to local terrain and farming practices.

Nagori: Originating from Nagaur and Bikaner districts of Rajasthan. They are usually white or light grey, sometimes with greyish shading on the head, face, and shoulders. Their medium-sized horns and narrow, horse-like face make them easily recognizable. Known for their agility and endurance, they are well-suited for draught work.

Nari: Spread across arid regions of Rajasthan (Sirohi, Pali) and Gujarat (Sabar Kantha, Banas Kantha). Their coat ranges from white to greyish white, with bulls sometimes appearing black or greyish white. They have long, spirally curved horns with a thick base and pointed tips. Well-adapted to hot climates, Nari cattle excel as draught animals in both plains and hilly forests.

Nimari: Breed of Madhya Pradesh and parts of Maharashtra, has a distinctive red coat with large white patches. Their horns curve upward, outward, and backward, similar to Gir cattle. With a massive build and a prominent bulging forehead, they are well-suited for draught work.

Ongole: Originate from Andhra Pradesh, where they are distributed across several districts, including Guntur and Nellore. These animals have a glossy white coat, with males displaying dark grey markings on the head, neck, and hump. The horns are short, stumpy, and firm, extending outward and backward. Ongole cattle are renowned for their majestic gait, prominent dewlap, and adaptability to tropical climates. Their stumpy horns and fleshy dewlap are key distinguishing features.

Poda Thurpu: Medium-sized cattle, from Nagarkurnool, Telangana, Their coat is white with brown patches or red/brown with white patches. They have straight horns pointing upward or forward and a convex forehead. Adapted for open grazing and long migrations, they excel in draught work and are suited for both dryland and wetland farming.

Ponwar: Small and hardy breed from Uttar Pradesh's Pilibhit district. They have a distinctive black-and-white coat with no fixed pattern. They are well-adapted to local agricultural practices.

Pullikulum: Originating from Tamil Nadu's Madurai and Sivagangai districts, they are small and compact with short legs. Males are dark grey, while females are white or light grey. They have wide, curved horns, broad foreheads with a central groove, and black muzzles, eyelids, and hooves.

Punganur: Native to Andhra Pradesh’s Chittoor district, are among the world's shortest breeds. Their coat varies in shades of white, grey, light brown, and dark brown, sometimes mixed with red or black. Males have small, crescent-shaped horns curving backward and forward, while females’ horns extend laterally and forward. Known for their adaptability, these cattle are highly valued.

Purnea: Local to Bihar, typically has a grey coat, with some red or black individuals. Their straight horns point upward or slightly lateral. Males have a bulging forehead, while females have a straight one. Small in size, they possess a medium hump and dewlap, with small to medium udders. Heat and drought-tolerant, they thrive on low-quality roughage and resist tropical diseases.

Rathi: The Rathi breed, found in Rajasthan's Bikaner and Jaisalmer districts, typically has a brown coat with white patches, though some are entirely brown or black with white markings. Their short to medium horns curve outward, upward, and inward. Known for their high milk yield, Rathi cattle are prized for their distinctive coat patterns and dairy potential.

Red Kandhari: Cattle with deep red coat, with shades ranging from dull red to brown from Maharashtra. Their medium-sized horns are evenly curved. Known for their uniform coloration and strong draught ability, these cattle are well-suited for agricultural work.

Red Sindhi: Red Sindhi cattle are found in organized farms across India, including Odisha and Tamil Nadu. They have a distinct red coat, with shades ranging from dark red to yellowish-red. Small white patches are sometimes observed on the dewlap or forehead. Their horns are thick at the base, curving upward. Red Sindhi cattle are known for their high milk yield, averaging 1840 kg, and their adaptability to tropical climates.

Sahiwal: The Sahiwal breed, native to Punjab and parts of Rajasthan, has a reddish-dun coat, occasionally mixed with white spots. The horns are short and stumpy, and the dewlap is large and loose. Known for their pale red coat, pendulous teats, and high milk yield (2325 kg on average), Sahiwal cattle are among India's most productive dairy breeds.

Sanchori: Breed from Jalore district of Rajasthan, with the majority of animals exhibiting a white coat Adapted to the hot and arid climate of Rajasthan, Sanchori cattle are an essential part of local dairy farming.

Siri: Present in West Bengal and Sikkim, have a Holstein-like coat with black or brown patches. Their horns curve outward, forward, and slightly upward. Adapted to hilly terrain, they are valued for resilience.

Sweta Kapila: Spread across Goa have a distinctive white coat, including the muzzle and tail switch, with a whitish-brown hue. Their horns are mostly straight, sometimes curving slightly upward and outward. These medium-sized cattle have a straight, triangular forehead with a slight furrow and are valued for milk production, often kept in Gaushalas.

Tharparkar: The Tharparkar breed, native to the states of Rajasthan and Gujarat, primarily inhabits regions like Kutchchh, Barmer, Jaisalmer, and Jodhpur. These cattle exhibit a distinct white or light grey coat, with darker shades on the face and extremities, particularly noticeable in bulls where the neck, hump, and forequarters are also darkened. The horns are typically spaced well apart, curving gently upward and outward in alignment with the poll, ending in blunt inward points. In males, the horns are shorter and thicker. Possess a convex forehead and large dewlap/neck skin. They are known for their impressive milk yield, averaging 1749 kg per lactation, making them a significant dairy breed in these arid regions.

Thutho: Localised breed from Nagaland adapted to the hilly terrain. Their coat ranges from black or brown, sometimes with white patches. The horns are short, stumpy, and curve outward and upward. Medium-sized and hardy, they have a straight forehead and an uneven backline, sloping behind a small hump. Known for their docility, they are well-suited for grazing on hill slopes, even in rainy conditions.

Umblachery: Cattle from Tamil Nadu, are born red or brown, turning grey by six months. Females have grey coats with white markings on the face, legs, and tail. Their small, outward-curving horns are thicker in bulls.

Vechur: Originating from Kottayam, Kerala, is one of India's smallest cattle breeds. They have light red, black, or fawn and white coats, with small, thin, forward-curving horns. Compact and resilient, they thrive in Kerala's dense vegetation and challenging conditions.

2. Buffalo Breeds of India

In India the buffalo breeds classified into four groups viz; are Murrah group (Murrah and Nili Ravi), Gujarat group (Jaffarabadi, Surti, Mehsana and Bunni), Uttar Pradesh group (Bhadawari) and Central India group (Nagpuri, Pandharpuri, Chilika, Manda etc).

Banni: The Banni buffalo, from state of Gujarat, primarily inhabits the districts of Kachchh, Sabarkantha, Surendranagar, Kheda, and Banaskantha. This breed is predominantly black, although copper-colored individuals are sometimes observed. The horns of Banni buffaloes are large, measuring between 24 to 30 cm in diameter, and exhibit a unique vertical and upward coiling pattern, either double or single.

Bargur: Also referred to as Malai Erumai or Malai Emmai, originates from the Tamil Nadu region. The breed features brownish-black to brown coat colors, with curved horns that grow backward and inward. The Bargur buffalo is characterized by a medium-sized body with a prominent black muzzle, eyelids, and tail switch, as well as grey hooves. This breed is known for its distinct appearance and adaptability to the region's climate.

Bhadawari: Found in the districts of Etawah, Chakranagar, Barhpura, and parts of Agra in Uttar Pradesh, as well as the Mahi region in Madhya Pradesh. Its coat ranges from blackish copper to light copper, with legs often exhibiting a wheat straw-like color. The horns are black and curl slightly outward, downward, and then backward, forming a parallel structure to the neck before curving upward. One distinctive feature of this breed is the two white lines on the lower neck, locally referred to as "Kanthy" or chevron. The average milk yield of the Bhadawari buffalo is approximately 1294 kg.

Chhattisgarhi: The breed is indigenous to Chhattisgarh and is located in districts such as Raipur**,** Bilaspur**,** Sarguja. The coat is typically black, though grey-colored individuals also exist. Chhattisgarhi buffaloes are medium-sized, with a straight head, large, heavy horns. The breed is well-known for producing ‘Peda,’ a traditional milk product.

Chilka: The Chilka buffalo, found primarily in Odisha's districts of Kurda, Puri, and Ganjam, is characterized by a brownish-black or black coat. The horns are curved upward and inward. This breed has a compact body, strong legs, and a small udder, making it well-suited for the region's agricultural practices.

Dharwadi: The Dharwadi buffalo is primarily found in the Dharwad district of Karnataka, has a black coat with semi-circular horns that almost touch the withers. Known for their straight head and erect ears, Dharwadi buffaloes are medium-sized and have cylindrical-shaped teats. Their milk is used for the preparation of Dharwad Peda, a popular sweet that has earned Geographical Indication (GI) recognition.

Gojri: Hailing from the hilly regions of Himachal Pradesh and Punjab. It typically has a brown or black coat. The horns of the Gojri buffalo are curved and form a significant loop. The breed is known for its straight head, heavy horns, and distinctive "Pattih wale seengh" loop, which makes it easily recognizable.

Jaffarabadi: The Jaffarabadi buffalo is primarily found in Gujarat's Saurashtra region, including the Gir forest, Junagarh, Bhavnagar, and Rajkot districts. These buffaloes are typically black, although some have grey or white markings on their forehead, feet, and tail. The horns of Jaffarabadi buffaloes are unique, curving downward and then inward to form a ring-like structure, which gives them a "study eye" appearance, particularly in males. This breed is known for its bulky head and high milk yield, averaging 2239 kg.

Kalahandi: Originating from Odisha's Kalahandi and Raygada districts, the Kalahandi buffalo typically has a blackish-grey coat. The horns are long curved to form a half-circle, moving horizontally backward, upward, and inward. Kalahandi buffaloes have a distinct black muzzle, eyelids, tail, and hooves, and their body is compact with a small hump. Their milk is highly valued in the region, especially for its rich quality.

Luit (Swamp): The Luit or Assamese Swamp buffalo, native to Assam (Tinsukia, Dibrugarh, Sibsagar, and Jorhat), is mostly black with semi-circular horns that curve backward and upward. Medium-sized and robust, they have a prominent forehead, wide muzzle, and distinct white stocking-like markings on their legs up to the knee.

Marathwadi: Native to Maharashtra, particularly in Aurangabad, Nanded, and Beed, the Marathwadi buffalo has a greyish-black to jet-black coat, with some individuals featuring white markings on the forehead and legs. The medium-sized horns typically extend to the shoulder but never beyond the shoulder blade. Marathwadi buffaloes are used for both milk production and draught purposes.

Manah: The Manah buffalo is a medium-sized breed, primarily used for both milk production and draught purposes. It is found in Assam. This breed typically produces about 1.75 kg of milk per day and serves a dual role in agriculture.

Manda: The Manda buffalo, native to Odisha's Koraput, Malkangiri, and Nawarangapur districts, has a grey coat with copper-colored hairs and lighter-colored lower legs. The horns are broad, emerging laterally, extending backward, and curving inward to form a half-circle. They are primarily used for dairy production.

Mehsana: The Mehsana buffalo, found in Gujarat's Mehsana, Sabarkantha, and Banaskantha districts, is mostly black, with some individuals having a brown or black-brown coat. The horns are sickle-shaped, bending downward and then curving upward, resembling the horns of a ram. Known for their prominent eyes and bulging black pupils, Mehsana buffaloes are a prominent dairy breed in Gujarat, with an average milk yield of 1988 kg.

Murrah: The Murrah buffalo, primarily found in Haryana's districts of Rohtak, Jind, Hisar, and Jhajhar, is renowned for its jet-black coat and tightly curled horns. These buffaloes have thin skin and a distinct spiral horn shape. Murrah buffaloes are highly valued for their milk production, with an average yield of 1752 kg, and are often used in crossbreeding programs to improve dairy production in other regions.

Nagpuri: The Nagpuri buffalo, originating from the Vidarbha region of Maharashtra, is usually black with white patches on the face, legs, and tail tips. The horns are flat, curved, and long. Nagpuri buffaloes are robust, with flat, curved horns carried back toward the shoulders. Their milk is highly valued for its richness and quality.

Nili-Ravi: Found in Punjab's districts of Gurdaspur, Amritsar, and Ferozpur, the Nili-Ravi buffalo has a black coat with distinct white markings on the forehead, face, muzzle, legs, and tail. The horns are tightly curled and small, forming a circular shape. Nili-Ravi buffaloes are highly regarded for their milk production, averaging 1850 kg per lactation, and are often preferred for their unique appearance and high-quality milk.

Pandharpuri: Native to the Solapur, Kolhapur, and Sangli districts of Maharashtra, is characterized by very long horns that extend beyond the shoulder blades, sometimes reaching the pin bones. The horns can be classified into three types: Bharkand, Toki, and Meti, each having distinct curvature patterns. The breed is known for its long horns, prominent nasal bone, and deep black coat.

Purnathadi: Buffalo from Vidarbha region of Maharashtra, is light brown to whitish in color, with white markings on the forehead and lower legs. The horns are long, tapering, and typically curve upward, resembling a hook. Purnathadi buffaloes are medium-sized animals, known for their adaptability to the local climate and their high-quality milk.

Surti: Spread across Gujarat's Kheda, Baroda, Bharuch, and Surat districts. Its coat varies from rusty brown to silver-grey, and the skin is typically black or brown. The horns are medium-sized, flat, and sickle-shaped, curving downward and backward before turning upward to form a hook at the tip. Surti buffaloes are medium-sized and are known for their high-quality milk, with an average yield of 1667 kg per lactation.

Toda: Originating from Nilgiri hills of Tamil Nadu, has a fawn-colored coat at birth, which changes to ash-grey as it matures. The horns are long and set wide apart, curving outward, slightly downward, and then upward, forming a crescent shape. Toda buffaloes are known for their unique appearance, with a distinct band of dense hair along the back and chevron markings on the neck. They are used for dairy production, and their milk is utilized in making traditional products.

Bhadawari (Buffalo): Female
Mehsana (Buffalo): Female
Jaffarabadi (Buffalo): Female
Murrah (Buffalo): Female
Nili Ravi (Buffalo): Female

Photographs of registered Buffalo breeds of India
(Source: Animal Genetic Resources of India- Information System)

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NEXT-GENERATION BIOTECHNOLOGICAL TOOLS FOR CROP IMPROVEMENT

Ravindra Kumar[1], Hitendra Kumar*[2] and Kamla Dhyani[3]
[1]Department of Biotechnology,
[2]Department of Entomology,
[3]Department of Horticulture,
School of Agricultural Sciences, Shri Guru Ram Rai University,
Dehradun-248001, Uttarakhand, India
*Corresponding author E-mail: hitendrakumar@sgrru.ac.in

Abstract:

A sustainable food supply is essential to meet the demands of a rapidly growing global population under the challenges of climate change, declining soil fertility, emerging pests, and nutritional requirements. Conventional breeding alone is often insufficient to address these issues, necessitating the integration of modern biotechnological tools. Advanced approaches such as genetic engineering, genome editing (CRISPR/Cas systems), molecular marker-assisted selection, tissue culture, doubled haploid technology, synthetic biology, and microbiome engineering have revolutionized crop improvement. These methods enable precise trait modification, development of stress-tolerant and high-yielding cultivars, and reduction in chemical input dependency, thereby supporting sustainable agriculture. Additionally, innovative gene delivery systems—including Agrobacterium-mediated transformation, biolistics, protoplast transfection, viral vectors, plastid transformation, nanocarriers, and liposome-mediated transfer—broaden the scope of genetic engineering across diverse crops. Complementary advances such as high-throughput phenotyping, RNA and protein-based crop protection, and the integration of artificial intelligence, data science, and automation further accelerate the Design–Build–Test–Learn cycle in plant breeding. Together, these tools represent a paradigm shift from traditional breeding to precision agriculture, ensuring improved crop resilience, productivity, and long-term food security.

Keywords: Genome Editing, Gene Transformation, Microbiome, Tissue Culture, Artificial Intelligence

Introduction:

Agriculture has long been the foundation of human civilization. Conventional breeding techniques, however, are frequently insufficient to solve contemporary agricultural issues like climate change, dwindling soil fertility, new pests and illnesses, and the demand for higher-quality nourishment. Within this framework, sophisticated biotechnology methods have become effective instruments to enhance and expedite agricultural development initiatives.

Modern biotechnology offers precise, efficient, and targeted approaches to modify plant traits, enabling the development of high-yielding, stress-tolerant, and resource-efficient crop varieties. Techniques such as genetic engineering, genome editing (CRISPR/Cas systems), molecular marker-assisted selection, tissue culture, doubled haploid production, synthetic biology, and microbiome engineering have revolutionized plant breeding. These methods not only enhance productivity and resilience but also reduce dependency on chemical inputs, thereby promoting sustainable agriculture.

The integration of biotechnology with data science, artificial intelligence, and high-throughput phenotyping further strengthens its potential to design climate-smart crops tailored for future food security. Thus, advanced biotechnological tools represent a transformative shift from traditional breeding towards precision agriculture, ensuring improved crop performance and long-term sustainability. In this chapter we will learn different biotechnological techniques for crop improvement.

1. Genome Editing and Gene regulation

Genome editing is a modern molecular technique used to make precise and targeted changes in the DNA of living organisms. It allows scientists to add, remove, or alter genetic material at specific locations in the genome. The most widely used tools for genome editing are CRISPR-Cas9**,** TALENs (Transcription Activator-Like Effector Nucleases), and ZFNs (Zinc Finger Nucleases). Among these, CRISPR-Cas9 is the most popular due to its efficiency, cost-effectiveness, and simplicity. Genome editing has wide applications in agriculture (developing stress-tolerant crops), medicine (gene therapy for genetic disorders), and research (understanding gene functions). Genome editing technologies such as CRISPR/Cas9, base editing, and prime editing enable precise modifications of plant genomes. Epigenome editing allows for reversible changes in gene expression without altering the DNA sequence. These tools are used for disease resistance, nutritional enhancement, and climate resilience.

Genome editing, also known as gene editing, refers to a set of modern technologies that allow scientists to add, remove, or modify DNA at specific locations within an organism's genome. The initial tools developed for this purpose included Zinc-Finger Nucleases (ZFNs), which use custom protein domains to bind DNA and induce cuts but are complex to design, and Transcription Activator-Like Effector Nucleases (TALENs), which are easier to engineer as they recognize single bases through repeat domains. Among these, the CRISPR-Cas9 system has emerged as the most widely used and efficient tool. Originating from a bacterial immune system that employs RNA-guided DNA targeting to defend against viruses, CRISPR-Cas9 works by using a guide RNA (gRNA or sg RNA) to direct the Cas9 nuclease to a precise DNA sequence.

Cas9 then creates a double-strand break (DSB), which the cell repairs either through non-homologous end joining (NHEJ), a fast but error-prone process that can result in insertions or deletions, or homology-directed repair (HDR), a more precise method that uses a repair template. Compared to earlier tools, CRISPR-Cas9 is faster, cheaper, more accurate, and highly efficient, making it a revolutionary approach in genome editing.

2. **Gene Transformation and Delivery methods**

Plant transformation methods include Agrobacterium-mediated delivery, biolistics (gene gun), protoplast transfection, and modern nanoparticle-mediated delivery systems. Viral vectors and de novo meristem induction are expanding the range of species that can be engineered.

a) Agrobacterium-mediated transformation

Agrobacterium-mediated gene transfer is one of the most widely used and efficient methods for introducing foreign genes into plants. *Agrobacterium tumefaciens*, a soil bacterium, naturally transfers a segment of its Ti (Tumor-inducing) plasmid, called T-DNA, into the genome of infected plant cells, causing crown gall disease. Scientists have modified this natural process by removing the tumor-causing genes and replacing them with desired genes of interest. In this method, the gene of interest is cloned into the T-DNA region of a disarmed Ti plasmid and introduced into *Agrobacterium*. When the bacterium infects plant cells (through methods like leaf disc, stem segment, or tissue culture transformation), the engineered T-DNA is transferred and stably integrated into the plant genome. Transformed cells are then regenerated into whole plants using tissue culture techniques.

This technique is advantageous because it usually results in stable integration, low copy number of inserted genes, and predictable expression**.** It is widely used in producing genetically modified (GM) crops with improved traits such as pest resistance (Bt crops), herbicide tolerance, improved nutrition, and stress tolerance.

Agrobacterium tumefaciens transfers a single-stranded T-DNA from a binary plasmid into plant cells; the T-DNA integrates and expresses the transgene. Modern protocols work across many dicots and, with optimization, cereals too.

Limitations:

Pros: Often single/low copy insertions, relatively clean integrations; inexpensive gear; robust across many labs.

Cons: Genotype dependence; tissue culture bottlenecks; some monocots remain finicky.

b) Particle bombardment / "gene gun" (biolistics)

The particle bombardment method, also called biolistics or the gene gun method, is a physical technique of introducing foreign DNA into plant cells. In this method, microscopic metal particles such as gold or tungsten are coated with the desired DNA and accelerated at high velocity using a device known as a gene gun. When these DNA-coated particles penetrate the plant cell wall and membrane, the DNA gets released and integrates into the plant genome.

This technique is especially useful for plants that are difficult to transform using Agrobacterium-mediated gene transfer. It can be applied to a wide range of plant species, including cereals (rice, maize, wheat), which are less susceptible to bacterial methods.

Advantages:

i. Applicable to both monocots and dicots.
ii. Bypasses the need for a biological vector.
iii. Can deliver DNA, RNA, or even proteins directly.

Limitations:

i. Requires expensive equipment and consumables.
ii. May cause cell damage due to particle penetration.
iii. Transformation efficiency can be lower compared to biological methods.

Overall, particle bombardment has played a significant role in developing **transgenic crops** with improved traits such as pest resistance, herbicide tolerance, and stress tolerance.

c) Protoplast transfection (PEG-Ca^{2+} or electroporation)

Protoplast transfection is a gene transfer method in which naked plant cells (protoplasts, i.e., plant cells without a cell wall) are directly introduced with foreign DNA, RNA, or other genetic material. Since the cell wall is removed enzymatically (using cellulase and pectinase), the uptake of nucleic acids becomes easier.

The common techniques used for protoplast transfection include:

- **Polyethylene glycol (PEG)-mediated transfection** – PEG induces fusion between protoplast membranes and DNA.
- **Electroporation** – brief electrical pulses create temporary pores in the protoplast membrane to allow DNA entry.

After transfection, the protoplasts are cultured under specific conditions to regenerate the cell wall and develop into whole plants, making it a useful tool for genetic engineering.

Applications:

- Functional analysis of genes and promoters
- Transient expression studies
- Stable transformation for plant improvement
- Production of transgenic plants

d) Viral vectors & Agro-infection

Viral vectors are modified plant viruses used as carriers to introduce foreign genes into plant cells. Since viruses naturally infect plants and multiply inside host cells, they can be engineered to carry desired DNA sequences without causing severe disease. They allow transient expression of genes, are efficient for large-scale protein production, and are widely used in functional genomics, vaccine development, and metabolic engineering in plants. Agroinfection (or agroinoculation) is a gene transfer method that combines the infection ability of plant viruses with *Agrobacterium tumefaciens*. In this technique, a viral genome engineered with the desired gene is cloned into a Ti plasmid and introduced into *Agrobacterium*. When the bacterium infects the plant, the viral genome is delivered into the plant cells, where it replicates and spreads systemically, expressing the foreign gene. This method is useful for plant virus-based gene transfer and studying plant–virus interactions.

DNA clones of plant RNA/DNA viruses are delivered (often by Agrobacterium), enabling high replication and expression or VIGS (silencing). Some systems ferry CRISPR guides or editors for **virus-induced genome editing**.

Limitations:

- **Pros:** Very fast systemic expression/silencing; great for functional genomics and rapid editing tests.
- **Cons:** Usually non-integrating; host range limited by virus; cargo size constraints.

e) Plastid (chloroplast) transformation

Plastid transformation is a genetic engineering technique in which foreign genes are introduced into the plastid genome (usually chloroplast DNA) of plants. Unlike nuclear transformation, plastid transformation allows stable integration of transgenes into plastid DNA through homologous recombination. Commonly achieved by particle bombardment (biolistics)**,** where DNA-coated microparticles are delivered into chloroplasts.

Advantages:

- High level of transgene expression due to multiple copies of plastid DNA.
- Maternal inheritance of plastids prevents gene flow through pollen, enhancing biosafety.
- Ability to express multiple genes in operon structures.

Applications:

- Production of recombinant proteins, vaccines, and industrial enzymes.
- Development of herbicide- and insect-resistant plants.
- Metabolic engineering for improved nutritional traits.

Thus, plastid transformation is a powerful tool in plant biotechnology, offering high expression levels and environmental biosafety compared to nuclear transformation.

f) Microinjection

Microinjection is a direct physical method of gene transfer in which foreign DNA is introduced into plant cells using a fine glass micropipette or needle under a microscope. The DNA solution is carefully injected into the nucleus or cytoplasm of an individual cell, usually a protoplast, zygote, or meristematic cell. This method ensures precise delivery of genetic material without the need for a vector.

For crop improvement, microinjection is particularly useful in transferring specific genes related to traits like disease resistance, stress tolerance, or enhanced nutritional quality. However, it is technically challenging, labor-intensive, and requires sophisticated equipment, making it less common than methods like Agrobacterium-mediated transformation or particle bombardment. Despite its limitations, microinjection provides a valuable tool for genetic engineering when precise and targeted gene transfer is required.

g) Silicon-carbide whiskers

The silicon carbide (SiC) method, also known as the silicon carbide whisker-mediated transformation, is a physical technique used for introducing foreign DNA into plant cells. In this method, plant cells or embryogenic calli are suspended in a solution containing microscopic silicon carbide fibers (whiskers) along with the target DNA. When the suspension is vortexed or agitated, the sharp whiskers create small wounds or pores in the cell wall and membrane, allowing the DNA molecules to enter the cells.

This method is relatively simple, inexpensive, and does not require sophisticated equipment. It has been successfully used in crops like rice, maize, and tobacco. However, it has some limitations, such as low transformation efficiency, potential cell damage due to the abrasive action of whiskers, and limited applicability to certain plant species.

Despite these drawbacks, the silicon carbide method remains a useful alternative for plant genetic transformation, particularly in monocots that are often recalcitrant to Agrobacterium-mediated transformation.

h) Liposome-Mediated Gene Transfer for Crop Improvement

Liposome-mediated gene transfer is a chemical method of delivering foreign DNA into plant cells using artificial lipid vesicles called *liposomes*. These liposomes are spherical structures composed of phospholipid bilayers, which can encapsulate nucleic acids (DNA or RNA) and protect them from degradation. When applied to plant protoplasts (cells without cell walls), the liposomes can fuse with the plasma membrane, releasing the genetic material into the cytoplasm.

This technique has several advantages: it is relatively simple, protects DNA from enzymatic degradation, and can carry large DNA fragments. Moreover, liposomes can be modified with specific ligands to improve targeted delivery. However, the efficiency of liposome-mediated transformation in plants is generally lower compared to methods like *Agrobacterium*-mediated transformation or particle bombardment, and it requires the preparation of viable protoplasts.

In crop improvement, liposome-mediated gene transfer holds potential for introducing desirable traits such as disease resistance, stress tolerance, or enhanced nutritional quality. Although not widely used in commercial plant biotechnology due to lower efficiency, ongoing research aims to optimize liposome formulations and delivery strategies to make this method more practical for crop genetic engineering.

i). Nano-carrier Mediated Gene Transfer in Plants

Nano-carrier mediated gene transfer is an advanced technique in plant biotechnology that uses engineered nanomaterials for delivering genetic material into plant cells. Nanocarriers such as carbon nanotubes, mesoporous silica nanoparticles, dendrimers, gold nanoparticles, and lipid-based nanostructures are employed to transport DNA, RNA, or proteins across rigid plant cell walls, which are often barriers in conventional transformation methods.

These nano-carriers protect nucleic acids from degradation, enhance penetration through cell walls and membranes, and allow targeted and controlled release of genetic material. Compared to traditional methods like *Agrobacterium*-mediated transfer or particle bombardment, nano-carriers are less damaging, more efficient, and can enable species-independent transformation.

Applications of this technology include crop improvement through the introduction of stress tolerance genes, enhanced nutrient use efficiency, improved yield, and resistance against pests and diseases. Nano-carrier systems also hold potential for precise genome editing using tools like CRISPR-Cas.

Thus, nano-carrier mediated gene transfer represents a promising, non-toxic, and versatile platform for next-generation plant genetic engineering.

3). Tissue culture and production of double haploid

Tissue culture is a collection of in vitro techniques where plant cells, tissues, or organs are grown under sterile and controlled conditions on a nutrient medium. It plays a vital role in crop improvement by enabling rapid and large-scale production of genetically uniform and disease-free plants. Techniques such as micropropagation help in mass multiplication of elite varieties, while somaclonal variation generates novel traits like disease resistance, stress tolerance, and improved yield. Additionally, tissue culture facilitates the production of haploids and doubled haploids, speeding up breeding programs by developing homozygous lines in a short time. It also supports genetic engineering and gene transfer by regenerating plants from transformed cells. Thus, tissue culture serves as a powerful tool in modern plant breeding and biotechnology for enhancing crop productivity and sustainability.

Tissue culture, somatic embryogenesis, and doubled haploid technology accelerate breeding programs by fixing traits in a single generation. These methods are complemented by cryopreservation and synthetic seed technologies for germplasm conservation.

4) Production of Doubled Haploid for Crop Improvement

Doubled haploid (DH) technology is an advanced plant breeding tool used to rapidly develop completely homozygous lines in a single generation. Normally, achieving homozygosity through conventional selfing requires several generations, but DH production shortens this process significantly.

In this method, haploid plants (n) are first produced through techniques like anther culture, microspore culture, wide hybridization, or chromosome elimination. Since haploids contain only one set of chromosomes, their fertility is low. To restore fertility, chromosome doubling is induced artificially using chemicals such as colchicine or spontaneously through mitotic irregularities, resulting in doubled haploids (2n).

These DH plants are pure homozygous, making them highly valuable for crop improvement. They are used for developing pure lines, improving hybrid breeding efficiency, speeding up marker-assisted selection, and enhancing genetic studies such as QTL mapping.

Thus, doubled haploid production provides a fast, efficient, and reliable method for producing uniform and stable crop varieties.

5) High-throughput phenotyping

High-throughput phenotyping (HTP) is an advanced technique used to measure and analyze plant traits rapidly and accurately using modern technologies. Unlike traditional phenotyping, which is labor-intensive and time-consuming, HTP employs tools like imaging systems, drones, sensors, robotics, and computer vision to collect large-scale data on plant growth, morphology, physiology, and stress responses.

HTP platforms can be field-based (using drones, satellites, and ground vehicles) or controlled-environment-based (greenhouses and growth chambers). These systems capture traits such as plant height, leaf area, canopy temperature, chlorophyll content, and biomass using non-destructive methods.

The data obtained are analyzed with bioinformatics, machine learning, and statistical tools to understand plant performance under different conditions. This accelerates crop breeding, stress tolerance studies, and precision agriculture.

Overall, HTP plays a vital role in improving crop improvement programs by linking genotypes to phenotypes, enhancing yield prediction, and supporting sustainable agricultural practices.

Applications

- Rapid screening of breeding populations for biomass, drought tolerance, disease resistance.
- Improving genomic selection models by adding HTP covariates (increases predictive accuracy).
- Time-series phenotyping for developmental studies and stress dynamics.
- Precision agriculture: monitoring crop status, targeted interventions (fertilizer, irrigation). Several published studies demonstrate successful links from HTP traits to yield prediction, stress detection and higher genetic gain when HTP traits are integrated into breeding pipelines.

6) Synthetic biology

Synthetic biology is an advanced interdisciplinary field that combines biology, engineering, and computational tools to design and construct new biological parts, devices, and systems. In crop improvement, synthetic biology provides innovative strategies to enhance yield, nutritional quality, and stress tolerance. By rewriting or assembling genetic circuits, researchers can introduce traits that are difficult to achieve through traditional breeding.

Applications include engineering plants with enhanced photosynthesis efficiency, nitrogen-use efficiency, and resistance to pests or diseases. Synthetic biology also enables the production of biofortified crops with improved vitamins, minerals, and metabolites to address malnutrition. Additionally, synthetic promoters and regulatory elements can precisely control gene expression, leading to optimized growth and stress adaptation under changing climates.

Thus, synthetic biology acts as a powerful tool in modern agriculture, offering sustainable solutions to global challenges such as food security, climate change, and environmental stress.

Applications

- Production of therapeutics, biofuels, chemicals (yeast/engineered microbes producing complex molecules).
- Biosensors that detect pollutants, disease biomarkers, or metabolites.
- Therapeutic microbes that deliver drugs or modulate host biology.
- Agricultural strains that fix nitrogen, produce growth-promoting compounds, or protect crops.
- Synthetic minimal cells and xenobiology (expanded genetic codes, non-standard nucleotides).

7) Microbiome Engineering

Microbiome engineering is an advanced approach in agricultural biotechnology that focuses on modifying or managing the community of beneficial microorganisms associated with plants to enhance crop growth, productivity, and resilience. Plants naturally harbor diverse microbes in the rhizosphere (soil-root interface), phyllosphere (leaf surface), and endosphere (inside plant tissues), which play crucial roles in nutrient uptake, stress tolerance, and disease resistance.

By engineering these plant-associated microbiomes, scientists can:

- **Enhance nutrient acquisition** (e.g., nitrogen fixation, phosphate solubilization).
- **Improve stress tolerance** against drought, salinity, and temperature fluctuations.
- **Provide biocontrol** by suppressing plant pathogens and reducing chemical pesticide use.
- **Boost plant growth** through production of growth-promoting hormones like auxins and gibberellins.

Techniques include selecting beneficial microbes, synthetic microbial community design, genetic modification of microbes, and microbiome transplantation. Overall, microbiome engineering is a sustainable and eco-friendly strategy for crop improvement, aligning with future needs of climate-smart and resilient agriculture.

8). RNA and Protein based Crop protection

RNA and protein-based crop protection are modern biotechnological strategies that provide environmentally friendly and highly specific alternatives to chemical pesticides.

I. **RNA-based crop protection**: This approach uses *RNA interference (RNAi)*, where double-stranded RNA (dsRNA) molecules are designed to silence essential genes in pests, pathogens, or weeds. When these organisms ingest the dsRNA, their target gene expression is suppressed, leading to reduced growth, reproduction, or survival. RNAi-based sprays and transgenic crops are being developed to control insects (e.g., corn rootworm) and viral diseases. It is highly specific, safe for non-target organisms, and biodegradable.

II. **Protein-based crop protection**: This strategy involves using naturally occurring or engineered proteins that provide resistance against pests and diseases. For example, *Bt toxins* (from *Bacillus thuringiensis*) are widely used in transgenic crops to kill insect larvae. Similarly, antifungal proteins, antimicrobial peptides, and plant defense-related proteins (like chitinases, glucanases, and defensins) are used to enhance resistance against fungal and bacterial infections. These proteins act by disrupting pathogen cell walls, membranes, or vital processes.

Together, RNA and protein-based crop protection methods offer sustainable, targeted, and eco-friendly solutions for crop improvement, reducing reliance on synthetic pesticides and supporting global food security.

Advantages:

- High specificity, lowering risk to non-target organisms.
- Low chemical residues, favorable environmental breakdown.
- New mode of action useful against pesticide-resistant pests.

- Flexible product types (GM plants or sprayable products).

9) Data, AI and Automation

Modern agriculture is undergoing a revolution thanks to the combination of data, automation, and artificial intelligence (AI), which makes farming more accurate, efficient, and sustainable. Soil health, crop development, weather, and insect trends are all revealed by the vast amounts of data collected by sensors, satellites, drones, and agricultural equipment. Artificial intelligence (AI) tools evaluate this data to forecast yields, identify illnesses, improve irrigation, and inform choices. Drones, robotic harvesters, and self-driving tractors are examples of automation that lowers labour costs and guarantees timely agricultural operations. When combined, these technologies reduce their negative effects on the environment while enabling precision farming, resource conservation, and increased output. Global food security and sustainable agriculture are ultimately supported by data-driven, AI-powered automation. Federated analytics, machine learning, and FAIR data principles are essential for handling big biological datasets. Crop improvement is being accelerated by robots and artificial intelligence (AI)-supported automated Design–Build–Test–Learn (DBTL) pipelines.

Examples:

1. Disease-resistant rice developed via multiplex CRISPR editing.
2. Enhanced nutritional quality in maize using base editing.
3. AI-driven genomic selection models in wheat breeding.
4. Microbial consortia developed for sustainable soil management.

Conclusion:

Modern biotechnology provides precise and sustainable solutions for crop improvement, enabling the development of high-yielding, stress-tolerant, and resource-efficient varieties. By integrating tools such as genome editing, tissue culture, synthetic biology, microbiome engineering, and AI-driven automation, agriculture can address challenges of climate change, pests, and food security. These advancements ensure long-term sustainability while reducing dependence on chemical inputs.

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UNDERSTANDING POLICY–INSTITUTIONAL SYNERGIES FOR AGRICULTURAL INCLUSIVITY

Debasmita Baruah and Pompi Dutta*
Department of Agricultural Economics,
Assam Agricultural University, Jorhat-13
*Corresponding author E-mail: pompi.dutta@aau.ac.in

Introduction:

Agriculture continues to be the cornerstone of Northeast India's (NEI) economy, sustaining direct or indirect livelihoods for nearly 70 percent of its population (NITI Aayog, 2021). The region's diverse agro-ecological zones from the fertile Brahmaputra Valley floodplains to the terraced hill slopes support the production of cereals, oilseeds, spices, and a wide array of horticultural crops (Panda, 2025). Yet, agricultural practices remain predominantly traditional, constrained by small and fragmented landholdings, limited mechanization, and low adoption of modern technologies all of which hinder productivity improvements (ICAR, 2022).

Shifting cultivation (jhum), deeply embedded in the region's cultural fabric, has, over time, exacerbated soil erosion, land degradation, and declining crop yields in several hill districts (Ray *et al.,* 2021). Studies across different elevation zones show that when the traditional jhum cycle is shortened, the land simply doesn't get enough time to heal. Without adequate vegetation recovery, the soil loses its strength, crop yields begin to fall, and the hills start showing scars of deforestation and erosion. In other words, what was once a sustainable practice balanced with nature has, under pressure, turned into one that is slowly wearing the land down (Das *et al.* 2022). Structural vulnerabilities are further exacerbated by recurrent challenges such as Assam's annual floods, frequent landslides in Meghalaya and Mizoram, insufficient rural infrastructure, and restricted access to quality inputs and credit—which together limit agricultural resilience and growth (Lotha *et al.,* 2024).

Inter-state disparities further compound these challenges: a recent assessment revealed wide variations in agricultural development across the eight NE states, with Assam ranking highest and Arunachal Pradesh at the bottom. Key constraints identified include low cropping intensity, limited irrigation, underutilization of high-yielding variety (HYV) seeds, and minimal consumption of NPK fertilizers (Sharma *et al.,* 2025)

Despite these challenges, Northeast India (NEI) holds remarkable potential for transformative and inclusive agricultural development. Its rich biodiversity and inherent suitability for organic farming offer unique opportunities, particularly considering the rising demand for high-value crops such as spices, fruits, and plantation goods (FAO, 2022). To harness this potential, the Government of India launched the Mission Organic Value Chain Development for Northeastern Region (MOVCD-NER) in 2015, aiming to strengthen farmer-producer organizations (FPOs), facilitate organic certification, and develop value chain infrastructure including collection centres, cold storage facilities, and refrigerated transport systems (Ministry of Agriculture & Farmers' Welfare, 2018).

Institutional interventions at the state level further underscore this momentum. In Nagaland, the Fostering Climate Resilient Upland Farming System (FOCUS) project, implemented with support from the International Fund for Agricultural Development (IFAD), has benefited over 118,000 households by improving rural infrastructure, enhancing market linkages, and bolstering climate resilience among upland farmers (IFAD, 2025).

The pursuit of inclusive agricultural growth in NEI transcends conventional productivity objectives, aligning closely with broader goals of rural prosperity, food security, and poverty reduction (World Bank, 2022). Back in 2018–19, farmers in the Northeastern Region got just a sliver of the country's agricultural credit—barely 0.9% of the total pie. To put that in perspective, farmers in the South cornered a massive 43% share. The contrast is stark: while one region was flush with financial support, the Northeast was left running on crumbs (Haque and Goyal, 2021). The agrarian landscape of NEI is dominated by small and marginal farmers, tribal households' groups that often face systemic disadvantages in accessing credit, markets, infrastructure, and institutional support (Bora & Mahanta, 2024). Achieving inclusivity requires bridging structural disparities through equitable access to productive assets, market linkages, and technological innovations (Chari, 2024). It is no longer a matter of theoretical discussion alone. Evidence from across the world shows that when value-chain approaches are effectively integrated with innovation, small farmers transition from being subsistence producers to becoming active participants in markets—enhancing their sales, improving incomes, and securing more resilient livelihoods (Devaux *et al.* 2018).

Given NEI's heightened vulnerability to climatic shocks including floods, landslides, and the fragile ecology of hill districts, strategies aimed at inclusion must embed resilience-building measures alongside economic interventions. Initiatives such as the Fostering Climate Resilient Upland Farming Systems (FOCUS) in Nagaland, implemented collaboratively with IFAD, were launched in 2018 and concluded in 2025. Covering 645 villages across nine districts, the project benefited approximately 118,000 households through infrastructure development, community seed banks, and improved market linkages (IFAD, 2021; Times of India, 2025). Similarly, the Mission Organic Value Chain Development for Northeastern Region (MOVCD-NER), operational since 2015–16, has supported the formation of nearly 100 FPOs/FPCs across 50,000 hectares, mobilizing 50,000 farmers, and establishing value-chain infrastructure including processing units and pack houses (PIB, 2023). In Assam, MOVCD-NER has led to the formation of six FPOs with an average cluster size of 88 hectares and 92 farmers per FIG, reflecting a robust organizational base for organic value-chain integration (Reddy, 2018).

Policy Imperatives and Institutional Mechanisms for Transforming Agriculture in Northeast India

The agricultural transformation of Northeast India (NEI) hinges on the formulation of context-specific public policies and the establishment of robust institutional frameworks. The region's complex geography, ecologically fragile landscapes, and socio-cultural diversity render traditional, uniform policy models inadequate. Instead, NEI demands nuanced and regionally adapted strategies capable of addressing its persistent constraints in infrastructure, technology adoption, and market accessibility.

Several flagship programs have been pivotal in driving this transformation. For example, the Mission Organic Value Chain Development for the Northeastern Region (MOVCD-NER) has facilitated the integration of organic farmers into structured value chains by offering training, infrastructure, and branding support, thereby enabling smallholder farmers to access both domestic and export markets. Complementary initiatives, such as the Pradhan Mantri Krishi Sinchai Yojana (PMKSY), have focused on expanding irrigation coverage, while the Digital Agriculture Mission has accelerated the adoption of precision farming technologies to enhance productivity (Kumar *et al.* 2023).

However, the successful implementation of such policies depends on the ability of farmers to adopt and operationalize them. Institutions like Krishi Vigyan Kendras (KVKs) and Agricultural Technology Management Agencies (ATMAs) have become critical intermediaries, facilitating the transfer of research innovations to farmers through demonstrations, training, and technical assistance (Mukherjee et al, 2024). Similarly, the national initiative to establish 10,000 Farmer Producer Organizations (FPOs) by 2027–28 represents a significant step toward farmer collectivization. These FPOs enable smallholders to pool resources, reduce transaction costs, access credit facilities, and secure better market prices (PIB, 2025).

Public Policies as Drivers of Agricultural Modernization in Northeast India

Public policies in Northeast India (NEI) extend far beyond the conventional roles of regulatory oversight or fiscal allocation; they serve as the driving force behind rural transformation, shaping the livelihoods, aspirations, and resilience of millions of farming households. In a region where agriculture is not only the dominant source of income but also deeply interwoven with cultural identity and social cohesion, well-crafted public policies form the very foundation of rural economic futures.

Rather than functioning solely as instruments for subsidy distribution or scheme implementation, these policies unlock the latent potential of the agricultural sector by facilitating access to modern technologies, credit systems, irrigation networks, and risk-mitigation mechanisms. They provide a buffer against vulnerabilities such as erratic monsoon patterns, recurring floods, and volatile market prices through crop insurance, price support measures, and the promotion of climate-resilient agricultural practices. Equally significant, they integrate smallholder and marginal farmers into broader socio-economic networks, linking them with cooperatives, Farmer Producer Organizations (FPOs), digital trading platforms, and value chains that transcend local markets to connect with national and even global economies.

Institutional Mechanisms in Agricultural Subsidies and Rural Credit Access

Central to the agricultural transformation of NEI is the strategic deployment of subsidies and credit access, both of which serve as catalysts for rural opportunity, technological adoption, and income diversification. These instruments not only enhance agricultural productivity but also strengthen the economic resilience of farming communities.

One of the most impactful interventions since 2015–16 has been the centrally administered Mission Organic Value Chain Development for the Northeastern Region (MOVCD-NER). This initiative has played a pivotal role across all eight states by developing essential infrastructure—collection centers, processing units, refrigerated transport, and pack houses—while also ensuring access to organic inputs and certification services. By strengthening FPOs, the program has helped integrate smallholder farmers into structured organic value chains, enabling them to access both domestic and export markets (Government of India, Ministry of Agriculture & Farmers' Welfare, 2018).

Impact evaluations further highlight that MOVCD-NER has surpassed its initial outreach targets, with most participating farmer groups reporting tangible benefits in terms of farmer clustering, certification, value addition, and enhanced market linkages. Nonetheless, the studies also reveal untapped potential for improvements in capacity building, FPO/FPC formation, infrastructure expansion, and brand development to ensure long-term sustainability and competitiveness (Reddy, 2018).

In Arunachal Pradesh, the Atma Nirbhar Krishi Yojana (ANKY) , a credit-linked subsidy framework, has offered tailored support to farmers, FPOs, and self-help groups. It covers 45% of equipment costs as subsidy, 45% via bank loans, and expects only a 10% contribution from applicants. This structure significantly lowers financial barriers, promoting mechanization and diversification within tribal agricultural communities (Govt Schemes India, 2024).

Assam has also implemented several meaningful schemes to bolster rural livelihoods and agricultural productivity: In 2018–19, the Assam Farmer's Credit Subsidy Scheme (AFCSS) launched as a credit-linked subsidy initiative, where the state government waived 25% of short-term crop loan amounts (up to ₹25,000 per farmer), benefiting approximately 400,000 farmers across 27,000 villages with a Rs 500 crore allocation (IndiaFilings, 2025). More recently, Assam extended a 50% subsidy on farm equipment, such as tractors and harvesters, under mission-led schemes like the National Food Security Mission and National Mission on Edible Oils. This initiative supports FPOs, agri-entrepreneurs, and individual farmers in embracing mechanized practices to enhance crop yield and reduce post-harvest losses. The state's 2025 budget allocated ₹10 lakh each to 500 FPOs, empowering them to adopt advanced farming techniques and equipment and direct investment in farmer collectives. Together, these instruments reflect a layered approach to rural financing ranging from institutional-level subsidies for collective enterprises to direct support for individual farmers and value-chain stakeholders.

Price Support and Risk Mitigation in Northeast India

Assuring stable prices and reducing risks are central to sustaining rural livelihoods in Northeast India (NEI), where agriculture remains the backbone of the regional economy. Yet, despite the presence of national price support mechanisms, their impact in NEI has historically been limited due to infrastructural constraints, limited procurement centers, and fragmented institutional outreach (Government of India, Ministry of Agriculture & Farmers Welfare, 2022).

The Minimum Support Price (MSP) system designed to guarantee remunerative returns for farmers has struggled to achieve full coverage in NEI. National-level data indicate that only 20–25% of paddy production in the region is procured at MSP rates, largely due to transportation bottlenecks, inadequate storage, and lack of awareness among smallholder farmers (Aditya *et al.* 201; Kapil, 2021). However, Assam provides a promising example: during the 2024–25 Kharif Marketing Season, the state successfully procured 600,000 metric tonnes of paddy, meeting 100% of its official procurement target through 169 collection centers. For many farmers, this represented not just income security but also a tangible acknowledgment of their labor and contribution to the state's food economy (Asom Barta, 2025).

Complementing price support, risk mitigation has emerged as another critical policy priority. The Pradhan Mantri Fasal Bima Yojana (PMFBY), operational since 2016, offers subsidized crop insurance to protect farmers from climate shocks, pest attacks, and market volatility. Recognizing the region's vulnerability to floods, droughts, and landslides, the government revised the cost-sharing ratio for NEI to 90:10 (Centre: State) beginning with the Kharif 2020 season, dramatically reducing the financial burden on small and marginal farmers (Press Information Bureau [PIB], 2021).

Together, MSP procurement and PMFBY crop insurance illustrate how price assurance and risk mitigation policies, when effectively implemented, can move beyond being mere schemes on paper to becoming lifelines for farming households navigating both economic and ecological uncertainty.

Institutional Interventions for Inclusive Agricultural Growth in North-East India

Institutional interventions play a pivotal role in the agricultural transformation of North-East India (NEI), bridging structural, informational, and technological gaps that hinder productivity and inclusivity. Given the region's complex agro-ecological and socio-economic diversity, multi-scalar interventions—ranging from extension networks and farmer collectives to research institutions and shared-resource infrastructures—are essential for fostering sustainable and equitable agricultural growth (Indian Council of Agricultural Research [ICAR], 2022).

Role of Krishi Vigyan Kendras, ATMA, and State Agricultural Departments

Krishi Vigyan Kendras (KVKs), operating under the aegis of ICAR and state agricultural universities, serve as the cornerstone for technology assessment, refinement, and dissemination at the grassroots level. KVKs, are like vital bridges that connect the work of our research institutions with the everyday lives of farmers. Spread across the country and closely linked to agricultural universities, they play a hands-on role in bringing new technologies, practical solutions, and knowledge directly to the fields. In the Northeast, especially, these centres have become lifelines—helping farmers build skills, improve productivity, and strengthen their resilience. (Singh *et al.* 2013)

In Assam, for example, 23 KVKs affiliated with Assam Agricultural University, along with additional centers under ICAR-ATARI, provide location-specific technologies and farmer training across diverse agro-ecological zones Complementing this network, Agricultural Technology Management Agencies (ATMAs) and state agricultural departments function as platforms for decentralized planning and coordination of extension activities. Initiatives such as the Viksit Krishi Sankalp Abhiyan (VKSA) have demonstrated the effectiveness of collaborative models involving KVKs, ATMAs, ICAR institutes, and state departments in strengthening farmer–scientist interactions across NEI (Deka *et al.* 2017; Press Information Bureau [PIB], 2022).

Farmer Producer Organizations and Cooperative Institutions

Farmer Producer Organizations (FPOs) have emerged as transformative institutional arrangements that promote collective action among small and marginal farmers (Bikkina *et al.* 2018). Evidence from NEI suggests that FPO membership enhances access to agricultural inputs, strengthens bargaining power in markets, and supports integration into value chains, thereby fostering income diversification and resilience (Kumar *et al.* 2025).

National-level studies corroborate these findings, highlighting that participation in FPOs is associated with greater crop diversity, increased household income, and the empowerment of women farmers (Jaacks *et al.* 2025). Such outcomes underline the importance of institutional mechanisms in advancing both economic and social dimensions of agricultural development.

Research and Extension Linkages through Universities and ICAR Institutes

Agricultural universities and ICAR research institutes form the backbone of research–extension linkages in NEI. Recent initiatives—including proposals to establish a Central Kiwi Research Institute in Arunachal Pradesh and the upgrading of ICAR research stations in mid-hill regions—signal a growing emphasis on location-specific agricultural research and innovation. Moreover, collaborative campaigns under the VKSA initiative have engaged more than 8,000 agricultural scientists from ICAR, KVKs, and state universities to promote integrated knowledge systems. These efforts have significantly accelerated technology adoption, capacity building, and farmer engagement across the region (PIB, 2022).

Conclusion:

Agriculture in Northeast India (NEI) constitutes both the backbone of rural livelihoods and a critical driver for inclusive, climate-resilient economic growth. With its diverse agro-ecological landscapes and rich cultural heritage, the region holds significant potential for high-value and sustainable agricultural development. Yet, this potential remains constrained by persistent structural challenges, including small and fragmented landholdings, inadequate infrastructure, and limited market integration.

Public policies and institutional interventions have sought to address these constraints through initiatives such as the Mission Organic Value Chain Development for the Northeastern Region (MOVCD-NER), the Pradhan Mantri Fasal Bima Yojana (PMFBY), and the promotion of Farmer Producer Organizations (FPOs). By connecting smallholders to credit, technology, and markets, these programs have improved productivity while also laying the foundation for risk mitigation, price stability, and value-chain development.

Moreover, institutional mechanisms—including Krishi Vigyan Kendras (KVKs), Agricultural Technology Management Agencies (ATMAs), and research–extension linkages through agricultural universities—have played a vital role in disseminating innovations and building farmer capacities. These platforms have ensured that technological advancements reach rural communities effectively, strengthening both knowledge transfer and adoption.

Moving forward, inclusive agricultural growth in NEI will require the deepening of these interventions through context-specific policy design, investments in climate-resilient infrastructure, and stronger farmer collectives. Ensuring equitable access to resources, promoting gender inclusivity, and prioritizing ecological sustainability will be essential to enable small and marginal farmers to transition from subsistence-oriented production toward market-oriented and climate-adaptive farming systems. Ultimately, the convergence of robust public policy, institutional capacity, and farmer-centric innovations presents the most promising pathway for transforming NEI into a hub of sustainable and inclusive agricultural development.

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INTEGRATED FARMING: A HOLISTIC APPROACH TO SUSTAINABLE AGRICULTURE

Santosh*[1], Suhal Sardar[2] and Ratnakiran D. Wankhade[3]

[1]Department of Genetics and Plant Breeding,

Faculty of Agriculture, Shri Ram College- Muzaffarnagar (Uttar Pradesh) 251001 India

[2]Department of Soil Science and Agricultural Chemistry,

School of Agriculture Sciences, IIMT University- Meerut, Uttar Pradesh 250001 India

[3]Department of Farm Machinery and Power Engineering,

Faculty of Agriculture, Shri Ram College- Muzaffarnagar (Uttar Pradesh) 251001 India

*Corresponding author E-mail: santosh.8956@gmail.com

Abstract:

Integrated Farming Systems (IFS) represent a revolutionary approach to sustainable agriculture by harmonizing diverse agricultural enterprises—crop cultivation, livestock, aquaculture, agroforestry, beekeeping, and more—on a single farm unit. Designed to increase productivity, improve livelihood security, conserve natural resources, and reduce environmental impacts, IFS align closely with agroecological principles and sustainable development goals. This chapter presents an in-depth exploration of the theoretical foundations, models, components, practices, economic viability, policy frameworks, and successful implementation of integrated farming systems, with a special focus on India. Supported by real-world case studies and scientific evidence, the chapter highlights IFS as a transformative pathway toward climate-resilient and circular agriculture.

Keywords: Integrated Farming System (IFS), Mixed Farming, Sustainable Agriculture, Livelihood Security, Agroecology, Resource Recycling, Circular Agriculture, Resilience, Diversification, Rural Economy.

Introduction:

The global food system is under mounting pressure due to climate change, land degradation, declining water resources, biodiversity loss, and increasing demand for food from a growing population. Traditional farming systems, heavily reliant on monoculture and external inputs, have failed to deliver long-term sustainability or equitable income distribution. In this context, Integrated Farming Systems (IFS) offer a viable alternative that emphasizes diversification, integration, and ecological harmony. IFS is not a new concept—it has deep roots in traditional knowledge and indigenous farming practices across Asia, Africa, and Latin America. What distinguishes the modern IFS paradigm is its scientific optimization and integration of enterprises to ensure resource-use efficiency, reduced risk, and enhanced income

(Gill *et al.,* 2009). The strategy provides multiple outputs from the same unit of land and time, thus offering food, nutritional, environmental, and livelihood security. The Food and Agriculture Organization (FAO) strongly endorses farming systems that promote ecological balance, sustainable intensification, and inclusive development (FAO, 2018). IFS is also essential to meeting the United Nations Sustainable Development Goals (SDGs), particularly SDG-1 (No Poverty), SDG-2 (Zero Hunger), and SDG-13 (Climate Action). India, home to 86% small and marginal farmers (Ag Census, 2015-16), urgently needs holistic farm-level solutions. IFS addresses issues of fragmented holdings, resource scarcity, rural unemployment, and ecological degradation by creating closed-loop systems that recycle energy, nutrients, and water.

Concept of Integrated Farming:

Integrated Farming refers to the synergistic integration of various farm enterprises—such as crop, livestock, fish, poultry, apiculture, horticulture, and agroforestry—within a farming unit to achieve maximum productivity in a sustainable and environmentally friendly manner. According to Singh *et al.* (2011), IFS is defined as "a judicious mix of two or more components for the efficient utilization of farm resources, recycling of residues, and stabilization of income and employment through year-round farm activity."

Characteristics of Integrated Farming:

1. Resource complementarity among components
2. Biological diversification
3. Risk reduction through enterprise diversity
4. Waste recycling within the system
5. Efficient land, labor, and capital use
6. Low reliance on external inputs

Principles of Integrated Farming Systems:

1. Diversification: IFS promotes **biological and enterprise diversification** to enhance productivity, reduce market risks, and use different agroecological niches.

2. Resource Optimization: It ensures efficient use of land, water, energy, and labor by combining enterprises that complement each other in resource demand and output.

3. Nutrient Recycling: Manure, crop residues, and waste biomass are recycled within the system to maintain soil fertility and reduce chemical inputs **(Ghosh *et al.,* 2015).**

4. Sustainability: By enhancing resilience and ecological balance, IFS sustains production even under stress conditions like drought or price collapse.

5. Socio-economic Integration: IFS models are customized to household needs, gender roles, and market accessibility, making them suitable for smallholder and tribal communities.

Components of Integrated Farming: Each IFS model integrates a set of components based on land availability, local resources, farmer skills, and market access. Major components include:

1. Crop Production: The core enterprise in most farming systems. Crops supply food, feed, biomass, and residues to other components. Intercropping, crop rotation, cover cropping, and system of crop intensification are practiced for yield enhancement.

2. Livestock: Animals such as cows, buffaloes, goats, pigs, and poultry provide Milk, meat, and eggs for consumption and sale, Manure for composting and biogas, Employment and insurance against crop failure. According to Pathak *et al.* (2012), the integration of livestock improves nutrient use efficiency by recycling up to 60% of farm waste.

3. Poultry: Backyard poultry, especially desi breeds (e.g., Kadaknath), are suitable for landless and smallholder farmers. Poultry manure is nutrient-rich and suitable for composting or vermicomposting.

4. Aquaculture: Integrated aquaculture (e.g., rice-fish farming) utilizes pond water for irrigation and supplies nutrient-rich silt for cropping. Fish ponds stocked with Indian major carps (e.g., Rohu, Catla) are common in eastern India.

5. Horticulture: Fruits (mango, banana), vegetables (tomato, spinach), and spices are integrated into the cropping pattern to provide year-round income and nutrition.

6. Apiculture: Honeybees enhance pollination efficiency, especially in fruit and oilseed crops. Beekeeping contributes to income and ecological services.

7. Agroforestry: Trees provide shade, biomass, fodder, fuel, timber, and nitrogen fixation. Species like *Leucaena leucocephala* and *Gliricidia sepium* are ideal for alley cropping.

8. Mushroom Cultivation: Mushrooms (oyster, button) utilize straw, compost, and animal dung to produce high-protein food and recycle nutrients.

9. Vermicomposting: Earthworms (e.g., Eisenia fetida) convert organic waste into nutrient-rich compost, improving soil health and reducing fertilizer costs.

10. Biogas: Biogas plants use cow dung and biomass to produce methane for cooking and lighting, while slurry acts as a potent fertilizer.

Examples of Integration:

Component 1	Component 2	Integration Benefit
Rice	Fish	Weed/pest control, nutrient cycling
Cow	Biogas	Clean energy, slurry fertilizer
Maize	Poultry	Residue-based litter, manure
Mango	Apiculture	Pollination, honey
Crop Field	Vermicompost	Soil health, reduced cost
Banana	Goat farming	Leaf fodder, manure recycling

Integrated Farming Models by Landholding: IFS must be tailored according to farm size, household needs, and resource availability. The Indian Council of Agricultural Research (ICAR) and State Agricultural Universities (SAUs) have proposed various models.

1. IFS for Marginal Farmers (<1 ha): Marginal farmers constitute over 68% of total farmers in India (Agricultural Census, 2015-16). Their IFS models emphasize vertical integration and space-efficient enterprises.

Components: 0.5 ha for multiple cropping, Backyard poultry and goats, Nutritional Garden, 100 m² fish tank, Vermicomposting unit.

Benefits: Annual income: ₹1.5–2.5 lakh, Family nutrition security, Year-round employment for 2–3 family members.

2. IFS for Small Farmers (1–2 ha): Model:1 ha cropping (cereals + pulses + oilseeds), 0.25 ha horticulture, 0.1 ha fish pond, 5–10 livestock (dairy/poultry), Mushroom or apiary unit. **B enefits:** Income: ₹2.5–4.5 lakh/year, High nutrient recycling (~65%), Balanced food basket.

3. IFS for Medium to Large Farmers (>2 ha): Model:1.5 ha field crops, 0.5 ha orchards, 0.2 ha fish ponds, Dairy unit (5–10 cattle), Biogas plant + agroforestry.

Outcome: Surplus market production, Export potential for honey, fruits, milk, Employment for 4–6 family labor + hired labor.

Region-Specific Integrated Farming Systems: IFS must be adapted to ecological, social, and cultural contexts.

1. Indo-Gangetic Plains (Uttar Pradesh, Bihar, West Bengal): Model: Rice–Wheat + Dairy + Fish + Mushroom. Fish culture in paddy-cum-fish fields, Mushroom from paddy straw, Dairy manure for compost and energy.

2. Arid and Semi-Arid Zones (Rajasthan, Gujarat): Model: Pearl millet + Goat + Horticulture + Vermicompost. Goats adapted to low water zones, Drought-tolerant crops and tree species (ber, khejri), Rainwater harvesting tanks integrated.

3. Hill Regions (North Eastern states, Himachal Pradesh): Model: Terrace farming + Dairy + Poultry + Beekeeping. Sloped land optimized using contour bunds, Local poultry breeds (Vanaraja), Apiculture for horticultural pollination

4. Coastal Regions (Odisha, Andhra Pradesh, Kerala): Model: Paddy + Fish + Duck + Coconut + Banana. Ducks control pests and fertilize fields, Intercrops between coconut plantations, Brackish water aquaculture (shrimp, crab).

5. Tribal and Rainfed Regions: Kitchen gardens + Small livestock + Minor millets, Indigenous knowledge-based mixed farming, Emphasis on nutrition and women's involvement (Thakur *et al.,* 2021; ICAR, 2019).

Role of IFS in Employment and Livelihood Security: IFS generates employment both on-farm and off-farm by integrating enterprises that function year-round.

1. Year-Round Labor Engagement: Unlike seasonal monocropping, IFS spreads labor demand: Cropping in kharif, rabi, and summer, Livestock and poultry care daily, Fish harvesting in cycles, Composting and mushroom throughout year.

2. Self-Employment and Youth Retention: Youth trained in IFS become rural entrepreneurs; IFS reduces distress migration by generating local employment. According to **AICRP-IFS data**, full adoption on 1 ha generates 400–600 man-days/year vs. 120–180 in monoculture.

3. Women Empowerment: Women manage poultry, dairy, kitchen gardens, In tribal Odisha, integrated backyard units led to increased decision-making by women (ICRISAT, 2019).

Integrated Farming and Climate Resilience: IFS is a climate-smart approach by virtue of

Diversity: Reduces vulnerability to climate shocks,

Recycling: Lowers dependence on external inputs,

Soil improvement: Increases water retention and resilience.

1. Mitigating Climate Risks: Integrated farms are less prone to total failure, Crop-livestock-fish systems buffer against irregular rainfall, Organic matter improves soil moisture holding (Pathak *et al.,* 2011).

2. Contribution to Low Emissions: Use of compost, biofertilizers, and biogas reduces greenhouse gas (GHG) emissions, Reduced synthetic nitrogen use cuts N_2O emissions (Choudhary *et al.,* 2021).

3. Adaptive Capacity Building: IFS increases farmers' adaptive capacity by enhancing livelihood assets and resilience. According to Pretty *et al.* (2006), diversified systems recover 40% faster from climate shocks than monoculture farms.

Nutritional Security Through IFS: IFS not only ensures food availability but also addresses hidden hunger (micronutrient deficiency).

1. Balanced Food Basket: An IFS model typically ensures access to Cereals (energy), Pulses (protein), Fruits and vegetables (vitamins, minerals), Milk, eggs, meat, fish (animal protein, iron, zinc), Honey and mushrooms (functional foods).

2. Bioavailability of Nutrients: Livestock and fish increase bioavailable iron and protein. Fruits and vegetables enhance dietary diversity. In ICAR-IFS models, protein consumption increased by 32–40% and vegetable intake doubled compared to monoculture households.

3. Women and Child Nutrition: Backyard IFS units managed by women lead to improved child feeding, especially in tribal and SC/ST communities (Ghosh *et al.,* 2015).

Waste Recycling and Circular Agriculture in IFS:

1. Concept of Circular Agriculture: Circular agriculture is a closed-loop system in which resources such as nutrients, energy, and water are efficiently reused. Integrated farming inherently aligns with circular agriculture by minimizing waste and maximizing resource use efficiency (FAO, 2020).

2. Resource Flow in IFS:

Waste Material	Reused in	Output/Benefit
Cow dung	Biogas unit, compost pit	Energy, fertilizer
Crop residues	Vermicompost, mushroom beds	Compost, mushrooms
Biogas slurry	Soil amendment	Nutrient-rich fertilizer
Poultry manure	Fish ponds, composting	Fish feed, compost
Pond silt	Crop fields	Soil fertility enhancement
Weeds	Mulch, compost	Moisture retention, organic matter

3. Environmental Impact: Reduction of greenhouse gas emissions by 20–30% (Pathak *et al.,* 2012). Enhanced carbon sequestration through biomass recycling. Reduced nutrient leaching and eutrophication

Organic and Natural Farming Integration:

1. Synergy Between IFS and Organic Farming: Organic farming avoids chemical inputs and relies on ecosystem services. When integrated with IFS: Internal resource use is maximized, Soil fertility is maintained through natural inputs, Ecosystem diversity enhances pest and disease control **(Sharma *et al.,* 2018).**

2. Natural Farming and Zero Budget Approaches: The Subhash Palekar Natural Farming (SPNF) model promotes IFS with: Jeevamrut (fermented cow dung + urine), Mulching and intercropping, Indigenous seeds and local breeds.

Natural farming is ideal for small and marginal farmers due to its low cost and ecological sustainability.

Certification and Market Linkages: IFS integrated with organic farming supports group certification (PGS-India) and direct marketing through Farmer Producer Organizations (FPOs), Organic retail outlets and online platforms, Farm tourism and niche markets (TNAU, 2020).

Economics and Cost-Benefit Analysis:

1. Economic Evaluation Parameters: Net Returns (Gross income – Cost), **Benefit-Cost Ratio (B:C), Employment Generation** (man-days/year), **Productivity per Unit Area.**

2. Empirical Evidence (Sources: Singh *et al.,* 2013; Ghosh *et al.,* 2015; ICAR reports, 2019)

IFS Model	Location	Net Return (₹/year)	B:C Ratio	Employment (man-days)
Crop + Goat + Vermicompost	Tamil Nadu (TNAU)	₹1.95 lakh	2.1	300
Rice + Fish + Poultry	Assam (AAU)	₹2.75 lakh	2.6	410
Crop + Dairy + Biogas + Fruits	Bihar (ICAR-RCER)	₹3.5 lakh	2.8	500
Pulses + Horticulture + Apiculture	Maharashtra	₹2.2 lakh	2.3	350

3. Risk-Adjusted Income: IFS smoothens income throughout the year. While cropping income may vary seasonally, livestock and horticulture provide consistent earnings.

Case Studies of Successful IFS Implementation:

1. Bihar: ICAR-RCER Model (0.7 ha): Components: Rice–Wheat, Dairy (2 cows), Fish (200 m^2), Fruits, Vermicompost, **Outcome**: Income rose from ₹65,000 to ₹2.2 lakh annually, **Impact**: Reduced input dependency, increased milk yield, better child nutrition.

2. Tamil Nadu: TNAU Tribal Model: Tribal Farmers in the Western Ghats implemented IFS with Millets, banana, goats, and pepper cultivation, Vermicomposting and bio-pesticides. **Result**: 150–200% income increase and significant improvement in soil organic matter

3. Odisha: Women-led Backyard IFS: ICRISAT and local NGOs supported tribal women with Kitchen gardens, Poultry coops, Micro fish ponds, **Impact**: Increased dietary diversity, improved child health, women's financial control **(ICRISAT, 2020).**

4. Punjab: Crop–Dairy–Biogas–Agroforestry Model: In Ludhiana, a 2 ha model integrated wheat-paddy with Guava trees, Dairy cows (4), Biogas and compost. **Results**: Clean energy for cooking, Reduction in fertilizer cost by 60%, Additional ₹1.4 lakh income from tree crops.

Digital Tools and Technological Innovations in IFS:

1. Digital Platforms for Farm Planning: Apps and tools support: Crop-livestock scheduling, Pest-disease diagnostics, Weather forecasting, Input-output tracking. **Examples**: **Krishi Jagran**, **mKisan**, and **Kisan Suvidha,** Decision support systems (DSS) for enterprise optimization.

2. Precision Agriculture in IFS: Drip irrigation and fertigation reduce water-nutrient loss, Drones for spraying, soil analysis, Sensors for livestock health monitoring.

3. IoT and Smart Farming: Internet of Things (IoT) devices can Monitor soil moisture and temperature, Automate feeding systems in poultry/dairy, Track water levels in fish ponds.

4. Role of Agri-Tech Startups: Startups like DeHaat, AgNext, and CropIn provide input advisories, weather alerts, and market access. e-Choupal and FPO networks connect IFS practitioners to better markets.

Gender Roles and Youth Involvement in Integrated Farming:

1. Gender Roles in IFS: Women play an indispensable role in integrated farming, particularly in Livestock care (milking, feeding, health care), Poultry and backyard management, Kitchen gardening, Composting and input preparation, Seed selection and post-harvest operations. According to FAO (2011), women contribute nearly 43% of the agricultural labor force in developing countries and over **60%** in Asia and Sub-Saharan Africa.

Benefits of IFS for Women: Low capital requirement enables independent entrepreneurship, promotes household nutrition, especially in maternal and child health, Encourages women's collective action in SHGs and FPOs.

Youth Engagement in IFS: The average age of Indian farmers is 50+. Engaging youth in integrated farming: Combats rural-urban migration, promotes agri-entrepreneurship, fosters innovation and digital integration.

Government Initiatives: **ARYA (Attracting and Retaining Youth in Agriculture)** by ICAR, Rural Youth Agri Clinics and business models based on IFS. Youth are key to upscaling climate-smart and tech-driven IFS models, including hydroponics, mobile-based advisories, and precision tools.

Biodiversity Conservation Through Integrated Farming:

1. On-Farm Biodiversity: IFS maintains a rich array of crops, animals, microbes, trees, and aquatic organisms. Crop-livestock-forestry integration sustains agro-biodiversity and genetic resources (Altieri, 2004). **Practices Supporting Biodiversity**: Intercropping and agroforestry, Indigenous livestock breeds (e.g., Gir, Malnad Gidda, Kadaknath), Seed-saving of heirloom crops, Pollinator-friendly habitats via horticulture and beekeeping.

2. Ecological Services of IFS: Natural pest control through diverse flora and fauna, Soil microbe enrichment via organic matter, Resilience against invasive species and diseases. IFS thus becomes a stronghold for in-situ conservation and ecosystem balance (Ghosh *et al.,* 2015).

Government Policies and Institutional Support:

1. Policy Support in India: Several policies promote integrated, sustainable farming:

Policy/Program	**Objectives Related to IFS**
National Mission on Sustainable Agriculture (NMSA)	Soil health, resource use efficiency, organic farming
Rashtriya Krishi Vikas Yojana (RKVY)	Fund state-level IFS projects and innovations
Paramparagat Krishi Vikas Yojana (PKVY)	Encourage organic, diversified farming systems
Mission for Integrated Development of Horticulture (MIDH)	Link horticulture to IFS and nutrition
Mahila Kisan Sashaktikaran Pariyojana (MKSP)	Empower women farmers through IFS-based models

2. ICAR-AICRP on IFS: The **All India Coordinated Research Project on IFS** has developed over 70 models for 26 agro-climatic zones, including: Rainfed IFS, Hill and tribal region IFS, Coastal zone models, Climate-resilient farm prototypes.

3. Global Support Systems: FAO's Climate-Smart Agriculture Program, World Bank and IFAD projects on integrated livelihood systems, CGIAR Initiatives via ICRISAT, IRRI, and CIFOR. These promote farmer-centric, region-specific IFS scaling strategies.

Global Perspectives on Integrated Farming:

1. Asia: China: Traditional rice–fish–duck systems still practiced. Government-supported circular agriculture clusters. **Vietnam**: VAC system (Vuon: Garden, Ao: Pond, Chuong:

Livestock) successfully sustains rural livelihoods. **Nepal**: Crop–goat–orchard–beekeeping models support hillside economies.

2. Africa: Integrated systems supported by **FAO** and **AGRA.** Emphasis on agroecology, small ruminants, and drought resilience. Example: Zambia's maize–legume–livestock mixed farms **(Sanginga *et al.,* 2009).**

3. Latin America: Cuba and Brazil lead in agroecological IFS. Emphasis on family farming, conservation agriculture, and community seed systems

4. Europe and North America: Agroecological hubs in France and Germany promote circular IFS. Urban IFS models in Canada and USA focus on hydroponics + poultry + composting.

5. Lessons for India: Farmer cooperatives and credit access crucial, Localized innovation and community training essential, Need for alignment with carbon credit and ecosystem payment schemes.

Challenges and Way Forward:

Key Challenges:

Category	**Challenges**
Economic	Initial capital costs, market linkage gaps
Technical	Lack of IFS-specific training and extension
Social	Gender bias, labor constraints
Environmental	Pest/disease management in dense systems
Institutional	Fragmented policies, poor inter-departmental coordination

Solutions and Recommendations:

1. **Integrated Policy Framework**: Combine IFS with soil, water, livestock, and horticulture schemes
2. **Capacity Building**: Establish regional training centers on IFS models
3. **Market Infrastructure**: Strengthen cold chains and value addition for perishable IFS products
4. **Research & Innovation**: Prioritize interdisciplinary, location-specific IFS research
5. **Youth and Women Engagement**: Targeted entrepreneurship programs and digital training

Conclusion:

Integrated Farming Systems (IFS) offer a strategic pathway toward sustainable, equitable, and climate-resilient agriculture. By synchronizing diverse farm enterprises—crops, livestock, fisheries, agroforestry, horticulture, and organic inputs—IFS maximizes the productive potential of limited resources while reducing environmental degradation and livelihood vulnerability. In the face of mounting global challenges such as climate change, biodiversity loss, soil degradation, and food insecurity, IFS has emerged as an adaptive and dynamic solution that promotes agroecological balance, year-round employment, and household nutritional security. Whether implemented on a marginal tribal farm in Odisha, a peri-urban organic setup in

Maharashtra, or a terraced hill farm in Himachal, IFS provides a locally adaptable and scalable model. The key to the successful adoption of IFS lies in holistic policy support, localized extension services, investment in capacity building, and market-driven integration. In a world striving to meet the Sustainable Development Goals (SDGs), integrated farming stands out as a blueprint for inclusive rural development, circular agriculture, and climate-smart food systems.

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PHENOMICS IN CROP IMPROVEMENT

Santosh*[1], Ratnakiran D. Wankhade[2] and Suhal Sardar[3]

[1]Department of Genetics and Plant Breeding,

Faculty of Agriculture, Shri Ram College- Muzaffarnagar (Uttar Pradesh) 251001 India

[2]Department of Farm Machinery and Power Engineering,

Faculty of Agriculture, Shri Ram College- Muzaffarnagar (Uttar Pradesh) 251001 India

[3]Department of Soil Science and Agricultural Chemistry,

School of Agriculture Sciences, IIMT University- Meerut, Uttar Pradesh 250001 India

*Corresponding author E-mail: santosh.8956@gmail.com

Abstract:

Phenomics, the large-scale study of phenotypes, plays a transformative role in modern crop improvement by enabling precise, rapid, and high-throughput analysis of plant traits. With increasing pressure to produce more food under the constraints of climate change, diminishing arable land, and water scarcity, traditional plant breeding approaches are inadequate. Phenomics bridges the gap between genomics and agronomic performance, allowing breeders to understand genotype-by-environment interactions in a more accurate and scalable way. Through automated imaging, robotics, sensor technology, and artificial intelligence, phenomics platforms can measure morphological, physiological, and biochemical traits non-destructively across developmental stages and environments. This chapter provides a comprehensive overview of the principles, platforms, and applications of phenomics in crop improvement. It emphasizes its integration with genomics, challenges in implementation, case studies across major crops, and its future in data-driven, precision agriculture.

Keywords: Phenomics, Crop Improvement, High-Throughput Phenotyping, Genotype-Environment Interaction, Image-Based Phenotyping, Precision Agriculture, Drones, Sensors, Machine Learning, Plant Breeding.

Introduction to Phenomics:

Phenomics is the study of phenotypes on a genome-wide scale, capturing and analyzing plant traits that are influenced by genetic and environmental factors. While genomics provides insights into the DNA sequence and potential functional genes, phenomics seeks to understand how those genes are expressed as observable characteristics under varying environmental conditions (Furbank & Tester, 2011). With global food demand expected to rise by over 50% by 2050 (FAO, 2020), crop improvement must become more efficient and accurate. Traditional breeding methods, although successful in the Green Revolution, are limited by their low throughput, subjectivity, and inability to handle complex traits like drought tolerance or nutrient use efficiency. Phenomics introduces a systematic, quantitative, and scalable approach to assess such traits using advanced imaging, sensors, and data analytics.

Historical Background and Evolution: The evolution of phenomics parallels advances in both molecular biology and information technology.

1. **1960s–1980s**: Phenotyping relied on manual measurement of morphological traits such as plant height, yield, or flowering time.
2. **1990s**: The genomic revolution, marked by the sequencing of *Arabidopsis thaliana*, brought the need for phenotypic validation of gene functions.
3. **2000s**: Emergence of high-throughput phenotyping (HTP) facilities and platforms using imaging, robotics, and environmental controls (Walter *et al.,* 2015).
4. **2010s–Present**: Integration of phenomics with genomics, transcriptomics, and artificial intelligence enables real-time phenotyping at multiple scales—from organ to canopy.

The term "Phenomics" was coined by Houle *et al.* (2010), emphasizing its importance as the next big frontier after genomics in biology.

Phenomics vs Genomics: Complementary Roles: Genomics and phenomics are complementary disciplines in plant breeding:

Genomics	Phenomics
Studies DNA sequence, SNPs, genes	Measures physical and physiological traits
Identifies genetic markers and QTLs	Links traits to performance under stress
Used in marker-assisted selection (MAS)	Used in trait-based selection
Static information	Dynamic, environment-influenced data

A genotype without accurate phenotypic data is of limited use. Conversely, phenotypic selection without knowledge of underlying genetics may lead to slow progress. Integrated approaches like genomic selection (GS) and genotype-phenotype association mapping rely on robust phenomics data (Araus & Cairns, 2014).

High-Throughput Phenotyping (HTP) Platforms: HTP platforms are automated systems designed to measure plant traits at high speed, scale, and precision. They enable screening of thousands of genotypes under controlled or field conditions.

1. Components of HTP Systems: Imaging units: RGB, infrared, hyperspectral, thermal, **Conveyor belts**: Move plants for scanning, **Environmental sensors**: Measure temperature, humidity, light intensity, Data acquisition and storage systems, Robotic arms or drones for mobile imaging.

2. Examples of HTP Facilities: (a) LemnaTec Scanalyzer (Germany): Greenhouse-based system for early growth traits. **(b) Phenomics Australia** (Australia): Multi-scale platform for crops and model plants. **(c) TERRA-REF** (USA): Field-based phenotyping using tractor-mounted sensors. **(d) ICRISAT Field Phenotyping Platform (IFPP)** (India): Drone and ground sensor-based system for dryland crops. Such systems enable real-time monitoring of traits like biomass, chlorophyll content, plant height, canopy temperature, and leaf area index (Fiorani & Schurr, 2013).

Field-Based vs Controlled-Environment Phenomics:

1. Controlled-Environment Phenomics: Occurs in growth chambers or greenhouses with precisely regulated: Temperature, Humidity, CO_2 concentration, Light intensity. **Advantages:** Reduced environmental variability, Accurate measurements of early vegetative traits, Ideal for studying gene functions and stress responses. **Limitations:** May not replicate real-world field conditions, Space and cost limitations.

2. Field-Based Phenomics: Uses drones, tractor-mounted systems, or fixed towers equipped with sensors and cameras. **Advantages:** Realistic assessment of genotype × environment (G×E) interactions, Large-scale phenotyping of breeding populations, Suited for traits like yield, drought tolerance, and lodging resistance. **Limitations:** Data complexity due to environmental noise, Weather-dependent operations.

3. Complementarity: Combining both systems gives a holistic view: Controlled environments for mechanistic insights, Field phenotyping for agronomic relevance.

Technologies in Phenomics: Phenomics relies heavily on advanced, multidisciplinary technologies that automate and enhance trait measurement. These include imaging systems, sensors, robotics, drones, and AI-based data analysis.

1. Imaging Technologies: a) RGB Imaging: Captures visible light in red, green, and blue bands. Used for measuring morphological traits like plant height, leaf area, and canopy cover. Low cost and high throughput. b) Thermal Imaging: Detects infrared radiation emitted by plants. Used to assess transpiration and stomatal conductance. Helps monitor water stress and drought response (Berger *et al.,* 2010). c) Hyperspectral Imaging: Captures data across hundreds of narrow spectral bands. Used to detect pigment composition, nutrient deficiency, and disease symptoms. d) Fluorescence Imaging: Detects chlorophyll fluorescence to assess photosynthetic efficiency. Early indicator of stress and senescence. e) 3D Imaging and LiDAR: Generates 3D models of plant architecture. Useful in quantifying plant biomass, lodging susceptibility, and canopy structure (Madec *et al.,* 2017).

2. Sensor Technologies: Soil sensors: Measure soil moisture, pH, temperature, and salinity. Canopy sensors: Track spectral reflectance and radiation interception. Sap flow sensors: Assess plant water use efficiency.

3. Robotics and Automation: Conveyor belts in greenhouses move plants to imaging stations. Automated arms handle watering, weighing, and rotating pots. Robotic phenotyping units like the Field Scanalyzer (UK) operate in open fields (Virlet *et al.,* 2017).

4. Drones (UAVs) and Satellites: Equipped with multispectral, thermal, or LiDAR sensors. Cover large fields in minimal time. Useful for mapping yield variability, stress zones, and crop health.

Phenotyping Traits in Crop Improvement: Phenomics captures a wide range of traits relevant to breeding programs:

1. Morphological Traits: Plant height, leaf angle, root depth, tiller number, Measured via RGB or 3D imaging

2. Physiological Traits: Photosynthetic rate, transpiration efficiency, chlorophyll content. Estimated using thermal and fluorescence imaging.

3. Biochemical Traits: Secondary metabolites, nutrient content, antioxidant levels. Assessed using hyperspectral imaging and metabolomic profiling.

4. Reproductive Traits: Flowering time, panicle architecture, fruit set, grain filling. Time-lapse imaging tracks transitions and developmental rates.

5. Root System Architecture (RSA): Difficult to measure traditionally but accessible through: Rhizotrons, Minirhizotrons, X-ray computed tomography (CT), Magnetic resonance imaging (MRI) . RSA is crucial for water and nutrient uptake under stress (Topp *et al.,* 2013).

Phenotyping for Abiotic Stress Tolerance: Abiotic stresses such as drought, heat, salinity, and nutrient deficiency drastically affect crop productivity. Phenomics enables the detection of stress responses early and precisely.

1. Drought Tolerance: Thermal imaging identifies genotypes with cooler canopies (indicative of stomatal conductance). NDVI and canopy spectral indices assess plant vigor. Example: In maize, cooler genotypes under drought stress showed higher yields (Cairns *et al.,* 2013).

2. Heat Tolerance: Monitored via leaf temperature, membrane stability, and chlorophyll fluorescence. Heat-resilient genotypes maintain stable photosynthetic activity.

3. Salinity Tolerance: Measured using fluorescence imaging to detect ion toxicity. Hyperspectral imaging detects changes in pigment composition.

4. Nutrient Deficiency: Spectral indices (e.g., red edge position) reveal nitrogen and phosphorus status. Imaging methods detect early chlorosis or purpling.

5. Cold and Frost Tolerance: Phenotyping platforms simulate frost conditions and evaluate Leaf necrosis, Recovery rate, Fluorescence decay.

Phenotyping for Biotic Stress Resistance: Phenomics allows the non-invasive and early detection of plant-pathogen and plant-pest interactions.

1. Disease Resistance: Hyperspectral and thermal imaging detect infections before visual symptoms. Example: In wheat, early yellow rust detection was achieved via UAV-based hyperspectral imagery (Mahlein *et al.,* 2013).

2. Insect and Pest Resistance: Imaging captures leaf damage, wilting, and feeding marks. Infrared sensing tracks metabolic heat due to pest-induced stress.
3. Machine Learning in Disease Identification: AI models trained on phenomics data can differentiate between: Fungal, viral, and bacterial diseases. Multiple stress symptoms (biotic vs abiotic).

These approaches reduce reliance on field pathologists and provide rapid feedback for breeders.

Integrating Phenomics with Genomics and Breeding: The integration of phenomics with genomics is transforming crop breeding by enabling genotype-to-phenotype (G2P) mapping. This synergy enhances the identification of quantitative trait loci (QTLs), supports genomic selection, and accelerates the development of superior cultivars.

1. Genotype-Phenotype Association Studies: Combines high-throughput phenotyping with genome-wide association studies (GWAS). Facilitates identification of marker-trait associations under diverse environments **(**Araus & Cairns, 2014). Example: In maize, phenomics-aided GWAS identified loci associated with stay-green traits under drought (Zhao *et al.,* 2019).

2. Genomic Selection (GS): Uses statistical models trained on both genomic and phenomic data to predict performance of untested genotypes. Improves selection accuracy and reduces breeding cycle time (Crossa *et al.,* 2017).

3. Phenomics-Assisted Backcross Breeding: Helps monitor trait introgression across generations. Tracks recovery of recurrent parent traits using real-time imaging and sensor data.

4. Multi-Omics Integration: Links genomics, transcriptomics, proteomics, metabolomics, and phenomics. Enables systems biology approaches to understand complex traits such as drought resilience, nutrient use efficiency, and disease resistance (Tardieu *et al.,* 2017).

Phenomics Data Management and Analysis: Phenomics generates large, multidimensional datasets—sometimes terabytes per experiment. Managing, storing, and analyzing such data is critical.

1. Data Acquisition: Images and sensor readings are collected at high frequencies across time and space. Includes metadata like growth conditions, genotype IDs, timestamps, etc.

2. Data Storage Systems: Cloud-based platforms like CyVerse, PhenomeNet, and PhenoFront offer scalable storage solutions. Need for structured databases with standardized file formats (e.g., MIAPPE, ISA-TAB) for interoperability (Papoutsoglou *et al.,* 2020).

3. Image and Signal Processing: Involves: Segmentation of plant parts, Feature extraction (leaf area, height, thermal index), Noise removal and normalization, Tools: ImageJ, PlantCV, LemnaGrid, and custom Python/R scripts.

4. Data Visualization: Use of dashboards, heat maps, and temporal charts for interpreting: Trait dynamics over time, Environmental effects, Genotype × environment interactions.

Machine Learning and AI in Phenomics: Artificial Intelligence (AI) plays a pivotal role in extracting meaningful patterns from complex phenomics data.

1. Supervised Learning: Uses labeled data to predict plant traits or classify stress responses. Algorithms: Random Forests, Support Vector Machines (SVM), Decision Trees. Example: CNN models have accurately identified leaf blight symptoms in maize from RGB images (Singh *et al.,* 2016).

2. Unsupervised Learning: Clusters genotypes or stress patterns without prior labels. Algorithms: K-means clustering, Principal Component Analysis (PCA).

3. Deep Learning: Convolutional Neural Networks (CNNs) process raw images directly. Applications: Root trait extraction, Flowering time prediction, Disease detection.

4. Reinforcement Learning: Dynamic decision-making systems that adapt to evolving plant environments. Can be used in real-time irrigation or fertilization recommendations based on phenotypic signals.

Challenges in Phenomics: Despite its transformative potential, phenomics faces several challenges:

1. Infrastructure and Cost: High capital investment for phenotyping platforms and sensors. Limited access in developing countries.

2. Data Volume and Complexity: Need for high-performance computing (HPC) infrastructure. Interdisciplinary expertise required in biology, engineering, and data science.

3. Standardization: Lack of universal protocols for trait measurement, calibration, and data sharing. Results are often **non-reproducible** across platforms or locations.

4. Scalability: Many systems are optimized for early growth stages or small plots. Difficult to scale for large breeding programs or real-world farms.

5. G×E×M Interactions: Capturing interactions between genotype (G), environment (E), and management (M) is complex and data-intensive.

6. Limited Integration with Traditional Breeding: Breeders often lack training or access to phenomic technologies. Requires cultural change and capacity building in national breeding programs.

Global Research Initiatives and Infrastructure: Worldwide, several institutions and consortiums have invested in developing phenomics infrastructure to drive crop innovation.

1. International Plant Phenomics Network (IPPN): A global network promoting phenotyping collaboration and standardization. Supports data interoperability, open-source tools, and technology transfer **(IPPN, 2023).**

2. European Infrastructure Initiatives: EMPHASIS: A pan-European plant phenotyping infrastructure under ESFRI. Aims to integrate field and controlled-environment phenotyping.

3. USA: TERRA-REF and ARPA-E: TERRA-REF: A field-based phenotyping platform integrating sensors, robotics, and data pipelines. **ARPA-E**: Funding projects like *ROOTS* to phenotype root traits non-invasively.

4. Australia: Phenomics Australia: Operates multiple sites using LemnaTec platforms and UAVs. Focus on cereals, pulses, and horticultural crops under climate variability.

5. India: NIPB and ICRISAT: ICAR's **National Institute of Plant Biotechnology (NIPB)** is developing indoor phenomics units. ICRISAT's Field Phenotyping Platform (IFPP) utilizes drone-based phenotyping for legumes and cereals in drylands.

Case Studies in Crop Improvement:

1. Rice: IRRI employs phenomics for salinity, submergence, and drought tolerance screening. Traits like canopy temperature, NDVI, and leaf rolling are linked to yield under stress.

2. Wheat: CIMMYT's field phenotyping aids in selecting genotypes for heat and drought resilience. Thermal and hyperspectral data inform stay-green and early vigor traits.

3. Maize: Phenomics helped identify root architecture traits associated with drought tolerance. Drones quantify cob growth and flowering synchrony (Rutkoski *et al.,* 2016).

4. Chickpea: ICRISAT used infrared imaging and canopy temperature depression for drought screening. Traits such as days to flowering and biomass accumulation are quantified across genotypes.

5. Tomato and Horticulture: High-resolution imaging is used to study fruit shape, size, color, and ripening. Helps in post-harvest quality and market trait selection.

Phenomics in Precision Agriculture: Phenomics plays a foundational role in digital, data-driven agriculture by improving crop monitoring and decision-making.

1. Crop Health Monitoring: UAVs equipped with multispectral sensors detect stress early. AI models predict diseases and nutrient deficiencies.

2. Variable Rate Application (VRA): Phenomics data inform real-time irrigation, nutrient, or pesticide application. Enhances **input-use efficiency** and reduces environmental load.

3. Decision Support Systems: Mobile apps integrate field phenomics with weather, soil, and satellite data. Offer **customized recommendations** on planting, irrigation, and harvesting.

4. Yield Forecasting: Machine learning models trained on phenomic data predict yield with high accuracy. Useful in logistics, market planning, and food security assessments.

Future Prospects and Innovations:

1. Miniaturized and Affordable Sensors: Future systems aim to bring phenomics to smallholder farms via: Smartphone sensors, Low-cost thermal and NDVI cameras.

2. Edge Computing and IoT Integration: On-field data processing to reduce bandwidth and latency. Supports **real-time feedback** and autonomous decision-making.

3. Phenotype Prediction from Genotypes: Advances in AI may enable direct prediction of phenotypes from genome sequences, accelerating breeding cycles.

4. Citizen Science and Crowdsourcing: Farmers contribute phenomics data via mobile platforms. Enhances participatory breeding and localized trait validation.

5. Phenomics in Climate-Resilient Agriculture: Essential for screening genotypes under multi-stress environments. Will support adaptation strategies under projected climate scenarios.

Conclusion:

Phenomics is revolutionizing crop improvement by bringing scale, speed, and precision to phenotyping. It complements genomics by allowing breeders to visualize and quantify how genes perform under real-world environments. High-throughput, image-based, and sensor-driven phenotyping platforms have empowered researchers to explore complex traits like drought tolerance, nutrient use efficiency, and disease resistance more effectively than ever before. However, challenges remain in terms of cost, data handling, standardization, and accessibility. Future innovations in artificial intelligence, miniaturized sensors, and participatory platforms will help democratize phenomics. As the world moves toward more sustainable and climate-smart agriculture, phenomics will be indispensable in designing resilient, productive, and resource-efficient crops for future generations.

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CURRENT DEVELOPMENTS IN ANIMAL HUSBANDRY AND SUSTAINABLE INNOVATIONS

S. M. Yeole
Department of Zoology,
MSP Mandal's Shri Shivaji College, Parbhani
Corresponding author E-mail: sachinyeolenotes@gmail.com

Introduction:

Animal husbandry is a vital branch of agriculture that deals with the management, breeding, feeding, and health care of domestic animals. Traditionally, the objective was to obtain milk, meat, fiber, draught power, and manure. However, with rising demand for animal products and concerns about food security, climate change, and animal welfare, animal husbandry has undergone a major transformation. Today, the focus is on sustainable production, genetic improvement, precision technologies, and environmental stewardship (FAO, 2020; Thornton, 2010).

1. Genetic Improvement and Breeding

Conventional selective breeding has significantly improved productivity in cattle, poultry, and sheep. Modern genomic selection tools such as SNP (single nucleotide polymorphism) chips now allow early identification of superior animals, leading to faster genetic gain (Meuwissen, Hayes & Goddard, 2016).

Artificial Insemination (AI) remains a cornerstone of dairy development. Sex-sorted semen increases the probability of female calves, ensuring faster herd expansion (Seidel, 2014). In vitro fertilization (IVF) and embryo transfer (ET) are increasingly used in India to propagate elite germplasm and conserve indigenous breeds such as Gir cattle and Murrah buffalo (NDDB, 2021; Singh *et al.,* 2020).

2. Precision Livestock Farming (PLF)

Wearable sensors, smart cameras, and automated feeding systems enable real-time monitoring of animal behavior and health. Rumination sensors and activity trackers detect early signs of mastitis, lameness, or metabolic disorders (Rutten *et al.,* 2013).

Artificial intelligence and machine learning interpret big data from farms to predict heat stress, optimize insemination timing, and identify disease outbreaks (Berckmans, 2017; Neethirajan, 2020).

3. Advances in Nutrition and Feeding

Balanced nutrition supported by probiotics, bypass proteins, and mineral mixtures increases milk yield and improves immunity (Kebreab *et al.,* 2019).

Climate-smart additives like 3-nitrooxypropanol (3-NOP) and red seaweed (*Asparagopsis taxiformis*) reduce methane emissions significantly (Roque *et al.,* 2021; Hristov *et al.,* 2015). Precision feeding systems provide individualized diets based on lactation stage, weight, and health status, thereby improving feed efficiency (Baudracco *et al.,* 2010).

4. Animal Health and Welfare

Advances in biosensors, PCR kits, and portable diagnostics allow early disease detection, reducing antibiotic use (Smith *et al.,* 2022). Large-scale vaccination and biosecurity programs against diseases such as FMD and Brucellosis are improving herd health globally (OIE, 2019; DAHD, 2020).

Animal welfare emphasizes housing, ventilation, humane handling, and enrichment, which not only improve ethical standards but also boost productivity (Fraser, 2008; Hemsworth & Coleman, 2011).

5. Sustainable and Climate-Smart Practices

Indigenous breeds with heat tolerance and disease resistance are key to future livestock sustainability (Singh *et al.,* 2020; Bhushan *et al.,* 2019). Manure-based biogas plants improve rural energy access and reduce emissions (Kinyua *et al.,* 2016).

Integrated crop–livestock systems help recycle nutrients, improve soil fertility, and enhance sustainability (Herrero *et al.,* 2010; Ryschawy *et al.,* 2017).

6. Digitalization and Extension Services

Mobile apps and online advisory services now provide farmers with timely information on AI, vaccination, and disease outbreaks. The e-Gopala app in India connects farmers to extension services and breeding programs (DAHD, 2020).

Conclusion:

Advances in animal husbandry are shaped by the integration of genomics, digital tools, climate-smart feeding, and welfare science. The future of livestock production will emphasize sustainability, disease resilience, and eco-friendly practices. Combining traditional knowledge with modern innovations ensures that animal husbandry continues to support both livelihoods and food security.

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Advances in Agriculture, Horticulture and Animal Husbandry Volume II

(ISBN: 978-81-992068-6-1)

About Editors

Dr. Mudasir Hassan Bhat serves as a Senior Assistant Professor in the Department of Economics at Lalit Narayan Mithila University, Darbhanga, Bihar, bringing over eight years of teaching and research experience. He holds an M.A. and Ph.D. in Economics from Aligarh Muslim University, an MBA in Financial Services from Bharathiar University, and a Post Graduate Diploma in Data Analytics with SPSS from AMU. Dr. Bhat has actively participated in numerous national and international conferences, UGC-MMTTC programs, and contributes to academic development as a member of Boards of Studies and course development committees. He mentors Ph.D. scholars and guides student research projects. His multidisciplinary academic background and research expertise contribute significantly to the scholarly value and analytical rigor of this volume, making his involvement an asset to the academic community.

Dr. Sanjay Khajuria, Chief Scientist and Head of Krishi Vigyan Kendra (KVK), Samba, located at Sumb Road, Arazi Samba, Jammu & Kashmir, is a dedicated agricultural scientist committed to enhancing rural livelihoods through innovative research and extension services. Under his leadership, KVK Samba has actively contributed to the Viksit Krishi Sankalp Abhiyan, a national initiative aimed at transforming Indian agriculture through sustainable practices, farmer awareness, and modern technologies. Dr. Khajuria's research focuses on improving crop productivity, soil health, and climate-resilient farming. He regularly engages with farmers through field demonstrations, training programs, and awareness campaigns to promote scientific farming methods. His efforts have significantly impacted the socio-economic development of the farming community in the region, making him a key contributor to agricultural progress in Jammu & Kashmir.

Dr. Nandini Vithalrao is currently serving as a Guest Lecturer in the Department of Zoology at Government (Autonomous) Degree College, Kalaburagi. She has previously held the position of Vice-Principal and Lecturer in Biology at St. Xavier's Pre-University College, Kalaburagi. She holds a Ph.D. and M.Sc. in Zoology, along with B.Ed. and B.Sc. degrees from Gulbarga University. With nine years of teaching experience, Dr. Vithalrao has published two research papers and presented a poster at academic forums. She has actively participated in various workshops, seminars, and conferences. Her primary research interests lie in the fields of biodiversity and ecology. She has also completed a 21-day training program on Capacity Building in Taxonomy of Insects and Mites at the Department of Entomology, University of Agricultural Sciences, GKVK, Bangalore, further strengthening her academic and research credentials.

Dr. Sanhita Sengupta (PT) is an Assistant Professor at Brainware University, Kolkata, and currently pursuing her Ph.D. in Physiotherapy at Teerthanker Mahaveer University, Uttar Pradesh. She holds a Bachelor of Physiotherapy from IPGMER, Kolkata, and a Master's degree in Orthopaedic Physiotherapy from WBUHS. Her primary research interests include musculoskeletal disorders, cervicogenic headaches, and rehabilitation. Dr. Sengupta has published scholarly work on myofascial pain syndrome, contributed to book chapters, and actively engages in academic research. She also serves as a reviewer for the reputed journal Pain, reflecting her academic credibility and subject matter expertise. Through her teaching and research, she brings a strong clinical and evidence-based perspective to the field of physiotherapy, contributing meaningfully to both academic and professional communities.

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ISBN 978-81-992068-6-1

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