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Sustainable Agriculture: Innovations and Future Perspectives

Editor:
Dr. Samir Show



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PREFACE

Agriculture remains the foundation of human civilization, providing food, nutrition, livelihoods, and economic stability for billions of people worldwide. However, increasing population growth, climate change, land degradation, biodiversity loss, water scarcity, and the overexploitation of natural resources have created unprecedented challenges for global agricultural systems. These concerns demand innovative, resilient, and environmentally responsible approaches that ensure food security while preserving ecological balance for future generations.

Sustainable Agriculture: Innovations and Future Perspectives presents a comprehensive collection of scholarly contributions highlighting recent advances, emerging technologies, and practical solutions for sustainable agricultural development. The chapters encompass diverse themes, including climate-smart agriculture, precision farming, organic and regenerative practices, integrated nutrient and pest management, soil health restoration, water conservation, biotechnology, artificial intelligence, digital agriculture, sustainable crop production, livestock management, agroforestry, and circular agricultural systems. Collectively, these contributions demonstrate how scientific innovation, technological advancement, and traditional knowledge can be integrated to improve agricultural productivity while minimizing environmental impacts.

This volume also emphasizes the importance of multidisciplinary research, evidence-based policymaking, farmer-centered innovations, and collaborative partnerships among researchers, educators, industry professionals, and policymakers. By encouraging sustainable resource utilization and resilient farming systems, the book aims to support the achievement of global sustainable development goals and strengthen food systems under changing environmental conditions.

We hope this book serves as a valuable resource for researchers, academicians, students, agricultural professionals, extension workers, policymakers, and all those committed to advancing sustainable agriculture. It is our sincere expectation that this volume will inspire further research, innovation, collaboration, and practical action toward building productive, resilient, environmentally sustainable, and food-secure agricultural systems for present and future generations.

- Editors

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PRESENT STATUS OF PRODUCTION, MARKETING, TRADE AND AVAILABILITY OF EDIBLE OILS IN INDIA

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Abstract

Vegetable oil constitutes an important part of our daily diet as a source of energy and essential fatty acids. India is the fifth largest producer of oilseeds in the world after Brazil, USA, China, and Argentina, and the oilseed sector occupies an important position in the agricultural economy of the country. India was a net exporter of oilseeds, meals, extractions, and edible oils till the 1960s, but with stagnation in production and increasing demand, it became a net importer of edible oils by the late 1970s. By the mid-1980s, edible oils became the largest import item after petroleum products despite India having the world's second largest area under oilseeds. India is now heavily dependent on imports and is among the largest importers of vegetable oils globally. This huge import bill led to the initiation of various oilseed development programmes to enhance domestic edible oil production. Consequently, oilseed production increased due to expansion in cultivated area, improved productivity, greater irrigation coverage, availability of quality seed, and technological interventions under programmes such as TMO, TMOP, ISOPOM, NMOOP, and NFSM-Oilseeds. Although the Minimum Support Price (MSP) of oilseeds showed remarkable growth, procurement by government agencies remained low compared to production. Per capita availability of oilseeds improved during 2001–2021, mainly because of increased imports. Therefore, awareness among oilseed growers should be enhanced through training camps, demonstrations of improved production technologies, and timely availability of quality seed. Adequate procurement should ensure MSP benefits to farmers, while a balance between domestic and import prices must be maintained to safeguard growers' interests and strengthen the country's edible oil security through higher domestic production.

Keywords: Growth rate, Import-Export, MSP, Oilseeds, Production program, Productivity.

Production Program for Oilseeds in India

Oilseed crops are mainly grown for edible oils all over the world and are considered important crops due to their economical value (Joseph and Karunakaran, 2022). With its rich agro-ecological diversity, India is ideally suited for growing all the major annual oilseed crops (Bansil, 1997, Thapa *et al.*, 2019). The major oilseeds cultivated in India are groundnut, rapeseed-mustard, castor, sesamum, nigerseed, linseed, safflower, sunflower and soybean (Rai *et*

al., 2016). Among the nine oilseed crops grown in the country, seven are of edible oils and two are of non-edible oils. Out of them, groundnut, rapeseed-mustard, soybean, sunflower, sesamum, safflower and nigerseed are edible but castor and linseed are non-edible oilseed crops (Meena and Sharma, 2019).

Table 1: Major programs for enhancing oilseeds production in India

S. No.	Programs	Period	States/ Locations
1.	All India Coordinated Research Projects	1967	-
2.	Intensive Oilseed Development Program	1974-1984	-
3.	National Oilseeds Development Project (NODP)	1984-1990	17
4.	Technology Mission on Oilseeds (TMO)	1986-1990	17
	Oilseeds Production Thrust Project (OPTP)	1987-1988	17
	Integrated Policy on Oilseeds	1989	
5.	Technology Mission on Oilseeds, Pulses and Maize (TMOP&M)	1990-2004	14
6.	Integrated Scheme of Oilseeds, Pulses, Oil Palm and Maize (ISOPOM)	2004-2014	14
7.	National Mission on Oilseeds and Oil Palm- Oilseeds (NMOOP)	2014-15	26
8.	National Food Security Mission (Oilseeds & Oil Palm)	2018-19	25
9.	NFSM-(OS&OP)	2019-20	25
10.	NFSM-(OS&OP)	2020-21	27- 3UT
11.	National Mission on Edible Oils-Oil Palm (NMEO-OP)	2021-22	-

India is heavily dependent on imports to meet its edible oil requirements and is the largest importer of vegetable oils in the world followed by China and USA. Of all the imported edible oils, share of palm oil was about 62 percent followed by soybean oil (22%) and sunflower (15%) in 2020-21. Import growth in respect of edible oils during the last decades was about 174 percent. The import figure of edible oils during 2020-21 revealed that India imported a total of 13.45 million tonnes of vegetable oils costing Rs.81682 crore. Almost 75 percent of the total oilseeds area is confined to rainfed farming (DES, 2021). Lack of appropriate technologies, cultivation under input-starved conditions, combating the biotic and abiotic stresses are some of the major causes for poor productivity of oilseeds in India. The huge drain on the import bill coupled with the above factors led to initiation of various program for enhancing the domestic production of edible oils and given in table 1.

Directorate of Oilseeds Development: Directorate of Oilseeds Development, Hyderabad was set up in the year 1942 as Project for Intensification of Regional Research on Cotton, Oilseeds &

Maize (PIRCOM) centre which was looking after research and development of oilseed crops in the country. Subsequently, in the year 1966, this office was re-organized and research and development functions were bifurcated and the research work has been assigned to ICAR institute “Directorate of Oilseeds Research” and it was renamed as “Directorate of Oilseeds Development”. Presently Directorate of Oilseeds Development (DOD) looks after the monitoring of Oilseeds and Oil Palm Development Program/schemes being implemented in the country and also central sector/sponsored schemes of Ministry of Agriculture and Farmers Welfare in the assigned states of Andhra Pradesh, Karnataka, Kerala, Tamil Nadu, Telangana and Pondicherry (DOD, 2018).

All India Coordinated Research Projects: All India Coordinated Research Projects (AICRP) on soybean, groundnut, rapeseed-mustard, sunflower, sesamum, castor, safflower, nigerseed and linseed have been working since 1967 under ICAR for conducting extensive research for achieving self-sufficiency in vegetable oils. The mandate of AICRP is development of new cultivars, production and protection technologies for a particular oilseed crops (ICAR-IIOR, 2023).

Technology Mission on Oilseeds (TMO): The Technology Mission on Oilseeds (TMO) was launched by the GoI in May 1986. Its basic objective was to substantially reduce the import of edible oils by the end of the 7th Plan, *i.e.*, by March 1990 and ultimately to achieve self-reliance during the course of 8th Plan. The mission was necessitated on account of the fact that, after petroleum products, edible oils accounted for the largest drain on India's foreign exchange resources. In fact, during the period 1981-86, the country imported Rs.3,884 crores worth of edible oils. The TMO has four micro-missions as Micro-mission-I for crop production technology, Micro-mission-II for post-harvest technology, Micro-mission-III for inputs and service support and Micro-mission-IV for price support, storage, processing and marketing (Kumar, 2001).

Considering the importance of oilseeds various development schemes like, Intensive Oilseed Development Program (1974–84), National Oilseeds Development Project on Oilseeds (1984-90), Oilseeds Production Thrust Project (1987-91), Oilseeds Production Program (1991-2004) and Oil Palm Development Program (1991-2004) were launched. These programs were subsumed under Technology Mission on Oilseeds (Sharma, 2014).

Under this program National Oilseeds Development Project (NODP) was launched in 180 districts located in 17 states, to step up various services to the farmers. These services included distribution of seeds, chemical fertilizers and bio-fertilizers, pesticides, implements and credit. The project also financed demonstrations on large plots (50 ha) so that the farmers could learn a location-specific technology for increasing the productivity. The activities like Research Project,

National Demonstrations conducted by ICAR/SAUs were supported (Shenoi, 2003). Krishi Vigyan Kendras also joined in the demonstration of improved technology.

Since four oilseed crops, namely, groundnut, mustard, soybean and sunflower contributed about 85 percent of the total oilseeds therefore Oilseed Production Thrust Project (OPTP) was initiated in 1987-88 to accelerate the production of these major crops. The project provided 100 percent assistance to the states in order to strengthen the key components such as seed production, plant protection, demonstration, proper application of inputs and market support (Shenoi, 2003). The project was implemented in a total of 246 districts of 17 states, including 151 NODP districts. NODP and OPTP had since been merged into Oilseed Production Program (OPP). The 4th micro-mission deals with the support to farmers in terms of incentive prices and support to industry in cooperative as well as private sector for processing, storage and marketing (Kumar, 2001).

In January 1989, the government announced an "Integrated Policy on Oilseed" (IPO) with five important elements which included support to farmers with technology, inputs, etc to increase productivity, review of PDS prices and issue prices to vanaspati industry, fixation of a price band, appointment of NDDB as the Market Intervention Agency (MIA) and an Empowered Committee headed by cabinet secretary to monitor the implementation of the Integrated Policy. Imported oils were supplied at a price not below the cost of production of domestic oils. PDS oils would be released at reasonable prices without determinant to the legitimate interests of farmers.

As a result of TMO interventions area, production, productivity and irrigation coverage of oilseeds increased in the country. Area increased from 18.38 to 20.50 million ha, production increased from 11.42 to 13.94 million tonnes with productivity enhancement from 621 to 680 kg ha⁻¹ from 6th Five-Year Plan to 7th Five-Year Plan. Irrigated area coverage under oilseeds also increased from 15.60 to 20.68 percent from 6th Five-Year Plan to 7th Five-Year Plan (Ghosh *et al.*, 2016)

Technology Mission on Oilseeds, Pulses and Maize (TMOP&M): Pulses (1990), oil palm (1992-93) and maize (1995) were also brought under the ambit of the mission and renamed as Technology Mission on Oilseeds, Pulses and Maize (TMOP&M). The developmental program continued in like Oilseed Production Program (OPP), National Pulses Development Project (NPDP), Oil Palm Development Project (OPDP) and Accelerated Maize Development Project (AMDP) were merged under TMOP&M and it was implemented with four-pronged approach through four Mini Missions as in case of TMO (Nethrayini and Mundinamani, 2013).

Integrated Scheme of Oilseeds, Pulses, Oil Palm and Maize (ISOPOM): The ministry winded-up individual developmental schemes on oilseeds (OPP), pulses (NPDP), oilpalm (OPDP) and maize (AMDP) and conglomerated into a common scheme named ISOPOM (2004-

05) and remained under implementation till March, 2014. The objective of the scheme was to increase the production and productivity of oilseeds. The cost of scheme was shared between GoI and state governments in the ratio of 75: 25 for most of the components of the scheme. The states had the flexibility in scheme implementation on the basis of annual action plan, area specific project approach and involvement of private sector. The scheme had innovative features like contractual research for development of drought tolerant varieties, hybrids etc.

Central agencies were also involved in implementation of some of the components like foundation and certified seed production/distribution, frontline demonstrations (FLDs), seed minikits program, etc. Major strategies of the scheme were i) increasing Varietal Replacement Rate (VRR) & Seed Replacement Rate (SRR) through minikits/FLDs, intercropping, ii) increasing irrigation coverage under oilseeds from 26 percent to 36 percent, iii) area expansion under oil palm including watersheds and wastelands, iv) increasing availability of quality oilpalm planting material through seed gardens and imports and v) enhancing procurement of oilseeds through NAFED & other agencies.

The major states (14), involved in implementation of ISOPOM-Oilseeds were Andhra Pradesh, Bihar, Chhattisgarh, Gujarat, Haryana, Karnataka, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Tamil Nadu, Uttar Pradesh and West Bengal. The pulses component was detached from ISOPOM and became part of National Food Security Mission (NFSM) *w.e.f.* April, 2010 (DPD, annual report, 2022).

Oil Palm Area Expansion (OPAE) Program: A sub-scheme of RKVY implemented during 2011-12 to 2013-14 made significant contribution in increasing the oilseeds production and area expansion under oil palm. The program was implemented in 12 states *viz.* Andhra Pradesh, Assam, Gujarat, Goa, Karnataka, Kerala, Maharashtra, Mizoram, Orissa, Tamil Nadu, Tripura and West Bengal.

National Mission on Oilseeds and Oil Palm (NMOOP): The centrally sponsored schemes of Integrated Scheme of Oilseeds, Oil Palm and Maize (ISOPOM), Tree Borne Oilseeds (TBOs) and Oil Palm Area Expansion (OPAE) program were restructured into National Mission on Oilseeds and Oil Palm (NMOOP) in 2014-15 with budgetary provision of Rs.3507 crores for 12th Plan. The mission was implemented in 28 states except Kerala comprising of three Mini Mission (MM) one each for Oilseeds (MM-I) in 27 states, Oil Palm (MM-II) in 13 states and TBOs (MM-III) in 10 states. NMOOP scheme was implemented on sharing of expenditure between central and state government in the ratio of 60:40 for general category states and 90:10 for North Eastern and Himalayan states.

The mission was implemented in 2017-18 comprising of three Mini Missions *i.e.* MM-I (Oilseeds) in 27 states, MM-II (Oil palm) in 13 states and MM-III (Tree Borne Oilseeds) in 10 states involving 5 central seed producing agencies. Mini Mission-I on Oilseed was implemented

in Andhra Pradesh, Assam, Arunachal Pradesh, Bihar, Chhattisgarh, Gujarat, Haryana, Jammu & Kashmir, Jharkhand, Karnataka, Madhya Pradesh, Maharashtra, Manipur, Meghalaya, Mizoram, Nagaland, Odisha, Punjab, Rajasthan, Sikkim, Tamil Nadu, Telangana, Tripura, Uttar Pradesh, Uttarakhand and West Bengal.

Under the Mission, financial assistance was provided for seed components (production & distribution of certified seeds & minikits, variety specific targeted seed production); inputs (plant protection equipments/eco-friendly light-trap, bio-pesticides, distribution of micronutrients, bio-transfer of technology (block demonstrations, frontline demonstrations, farmers and extension workers training etc.)). However, few interventions like purchase of breeder seeds by both state and central seed producing agencies, supply of seed minikits to the farmers through central seed producing agencies, development of seed infrastructure at SAUs/KVKs farms, front line/cluster demonstrations through ICAR/KVKs, R&D activities and Kisan Mela etc. with 100 percent central assistance. Mini Mission-I also supported ICAR institutes for undertaking FLDs on oilseed crops and ICAR-KVKs for organizing cluster demonstration on oilseeds.

The strategy for implementing the proposed mission was increasing seed replacement rate (SRR) with focus on varietal replacement, increasing irrigation coverage under oilseeds from 26 to 36 percent, diversification of area from low productivity cereal crops to oilseeds crops, intercropping of oilseeds with cereals/pulses/sugarcane, use of fallow land after paddy/potato cultivation, expansion of cultivation of Oil Palm & TBOs in watersheds and wastelands, increasing availability of quality planting materials of Oil Palm & TBOs, enhancing procurement of oilseeds and collection & processing of TBOs. The scheme was implemented in a mission mode through active involvement of all the stakeholders' throughout the country (DA&FW, annual report, 2022).

Research and Development projects under National Mission on Oilseeds and Oil Palm (NMOOP): Many technological interventions need for location-specific refinements for ensuring their effectiveness at the grass root level. A good number of innovations made by the farmers/extension functionaries need scientific validation before their large scale promotion. Keeping this in view, a provision was made under NMOOP for supporting R&D projects crucial for attaining goals of the Mission during the 12th Plan. So far, projects implemented were i) productivity enhancement of rapeseed-mustard crops through technology implementation and their refinement under farmer's field conditions in the state of Uttarakhand implemented through GBPUA&T, Pantnagar Uttarakhand for the period 2015-16 to 2016-17, ii) Block Demonstrations and training of raised bed technique of soybean cultivation implemented through IGKVV, Raipur for the period 2015-16 to 2016-17, iii) Bridging the production gaps in potential districts of sunflower and sesame through dynamic technology transfer implemented through IIOR, Hyderabad for the period 2015-16 to 2016-17, iv) Release of high oil and oleic groundnut

varieties implemented through ICRISAT, Hyderabad for the year 2016-17. These projects were continued in 2017-18 also.

New initiatives for Oilseeds from 2017-18 onwards

➤ **Targeting Rice Fallow Areas (TRFA):** A project to cover 4.5 million ha area, 1.5 million ha every year for three years (2017-18 to 2019-20) targeting rice fallow areas under pulses and oilseeds. It was implemented in six eastern states *viz*; Assam, Bihar, Chhattisgarh, Jharkhand, Odisha and West Bengal covering 40 districts and 4000 villages. TRFA was implemented under NMOOP with a production target of 2.43 lakh tonnes of oilseeds every year.

Alternate crop plan to combat wheat blast: The action plan for alternate crops to replace wheat by oilseed crops a project 'Alternate crop plan to combat wheat blast' was approved for West Bengal state during 2017-18 crops for implementation in Murshidabad and Nadia districts of West Bengal. The action plan was also continued in 8 districts of West Bengal to replace wheat by oilseeds and pulses over an area of 1.92 lakh ha. This Action Plan continued under NFSM-Oilseeds with an amount of Rs. 904.00 lakh comprising central share of Rs.542.40 lakh and state share of Rs.361.60 lakh was during year 2019-20.

➤ **Seed production, distribution, minikits and FLDs on Oilseeds during 2015-16:** In order to encourage the adoption of newly released varieties and improved agro-techniques in oilseed crops. Financial support was provided under NMOOP to central agencies *viz*. NSC, KRIBHCO, HIL, NAFED and IFFDC for procurement of breeder seed (BS), production of foundation seed (FS) and certified seed (CS), distribution of certified seed and supply of seed minikits. Assistance was also provided to conduct Front Line Demonstrations (FLDs) in the country through ICAR/SAUs network.

During kharif-2015 and rabi 2015-16, a total of 3.35 lakh quintal and 82.91 thousand quintal of various categories of seeds (BS/FS/CS) were produced and 1.68 lakh quintal seeds were distributed. Seed minikits (2.03 lakh) of six oilseeds crops in kharif 2015 and for 8 oilseed crops (8.39) in rabi 2015-16 were supplied through central seed producing agencies, while for summer 2015-16 (4.28 thousand) minikits supplied for groundnut and sunflower. During kharif-2016 and rabi 2016-17, a total of 2.80 lakh quintal and 88.36 thousand quintal of various categories of seeds (BS/FS/CS) were produced and 70.99 thousand quintal seeds were distributed. A large number of seed minikits of seven oilseed crops were supplied in kharif-2016 (16.58 lakh) and rabi 2016-17 (14.27 lakh) through central seed producing agencies. During 2017-18 (kharif and rabi) a total of 3.27 lakh quintal of various seeds (BS/FS/CS) were produced. Seed minikits of 8 oilseeds crops (18.09 lakh) were supplied during kharif, rabi and summer 2017-18 through central seed producing agencies.

A total of 2.8 thousand FLDs in kharif-2015 on improved varieties and agro-techniques of five oilseeds and 2.44 FLDs in rabi 2015-16 on seven oilseeds were conducted through ICAR-AICRP

network covering groundnut, rapeseed-mustard, linseed, sesame and sunflower crops. A total of 2.62 thousand FLDs in kharif-2016 on improved varieties and agro-techniques of five oilseeds and 4.66 thousand FLDs in rabi 2016-17 on seven oilseeds were conducted through ICAR-AICRP network. A total of 51.66 thousand cluster FLDs conducted through 423 KVKs of ICAR in different states covering groundnut, soybean, rapeseed-mustard, sunflower, safflower, linseed, sesamum, nigerseed and castor during kharif/rabi/summer 2016-17 oilseeds. During kharif/rabi/summer 2017-18 a total of 73.28 thousand cluster FLDs conducted through 516 KVKs of ICAR in different states covering groundnut, soybean, rapeseed-mustard, sunflower, safflower, linseed, sesamum, nigerseed and castor crops.

National Food Security Mission (Oilseeds & Oil Palm) -NFSM (OS&OP): NMOOP mission was merged with the National Food Security Mission (NFSM) in 2018-19 and implemented as NFSM (OS&OP). It comprised of three sub-missions namely, NFSM-Oilseeds, NFSM-Oil Palm and NFSM-TBOs. Assistance for various interventions was focused to benefit farmers and had direct impact on increasing the income of farmers involved in oilseeds and oil palm cultivation. Most of the components were in the ratio of 60:40 percent (GoI: State) sharing for general states and 90:10 percent for North East and hilly states. A few components were 100 percent funded by GOI to Central agencies, ICAR, KVKs/SAUs. NFSM (OS) program was implemented in 27 states and 3 UTs comprising of 7 central seed producing agencies with Budgetary Estimate (BE) of Rs.536 crore. Under restructured program, all the interventions suitable for integrated farming system depending on the climatic condition and natural resource base for optimizing farm returns in a sustainable manner were included. The components were classified broadly in three broad categories namely, seed components, production components and transfer of technology. The funds allocated for various components like seed components (30%), demonstration, farmers field school (FSS) & Training (27%), distribution of inputs including farm machinery and irrigation system/tools (30%), flexi funds (10%) and project management expenses (3%).

The strategies adopted under the mission were i) horizontal (area expansion) and vertical (productivity increase) expansion of oilseeds crop, ii) increasing seed production and distribution of newly released varieties, iii) low cost technologies with high impact on productivity resulting in higher income, iv) technologies with high impact that involve reasonable investment with high return on investment (ROI), with emphasis on eco-friendliness and high input use efficiency, v) strategies with emphasis on quality improvement and value addition leveraging technologies with a bearing on employment through skill/entrepreneurship development, vi) strategies to increase additional area and production of oilseeds through rice fallow, intercropping and crop diversification. Newer opportunities to explore non-traditional seasons and regions for crops were also projected that have proven a success for area expansion and integration into the major cropping systems.

Under this mission, financial assistance was provided for seed components (production & distribution of certified seeds, seed hubs and minikits), inputs (plant protection equipments, bio-pesticides, distribution of micro-nutrients, bio-fertilizers, improved farm implements, pipes, sprinklers, seed storage bins, seed treatment drums) and transfer of technology through Block demonstrations, frontline demonstrations (FLDs), cluster frontline demonstrations (CFLDs), farmers and extension workers training etc. NFSM-Oilseeds also supported ICAR institutes for undertaking FLDs on oilseed crops and ICAR-KVKs for organizing cluster demonstration on oilseeds.

In order to encourage the adoption of newly released varieties and improved agro techniques in oilseed crops, support was provided under NFSM-Oilseeds to central agencies *viz.* NSC, KRIBHCO, HIL (include NFL), NAFED and IFFDC for procurement of breeder seed (B/S), production of foundation seed (F/S), production of certified seed (C/S), supply of seed minikits (kharif/rabi/TFRA/summer) for inspirational districts notified by NITI Aayog & TRFA. From the figure 4.64 it is evident that seed production increased from 120 to 147 tonnes in 2018-19 to 2020-21 but distribution of seed increased from 160 to 187 tonnes in 2018-19 to 2019-20 but declined to 121 tonnes in 2020-21.

Demonstrations conducted under NFSM-oilseeds were categorized under two sub heads *i.e.* block demonstration and block demonstration of groundnut on polythene mulch. In the first year of NFSM-OS area covered under demonstrations was 197 ha, which declined to 133 ha in 2020-21. Integrated nutrient management/integrated pest management was demonstrated in 472 thousand ha area in 2018-19 declined to 375 and 347 thousand ha in subsequent years. Machineries head includes distribution of plant protection equipments and supply of improved farm implements. During 2018-19 highest numbers of machineries distribution was done *i.e.* 453 hundred declined but declined to 206 hundred in 2019-20 and increased slightly in 2020-21 (253 hundred). Under NFSM-oilseeds 32, 18 and 20 hundred officers/farmers trainings were organized in 2018-19, 2019-20 and 2020-21, respectively. To increase the irrigation area under oilseeds water carrying pipes were distributed of 49, 29 and 13 lakh meters of length (DA&FW, annual report, 2022).

Seed hub Program: Under the NFSM (Oilseeds), Government of India has set up 37 oilseeds seed hubs during 2018-19 and 2019-20 with an objective to increase the availability of high yielding quality seed. National Seed Corporation and State Seed Corporations were primarily responsible for producing and supplying of seeds of oilseeds. In order to supplement these agencies, seed hubs created at selected KVKs/SAUs and institutes of ICAR through Indian Institute of Oilseeds Research (IIOR), Hyderabad. These seed hubs had seed processing and seed storage facilities. Each seed hub took up seed production of oilseeds through farmers and made arrangement of buy back the produce from the farmers from its revolving fund. Each seed hub

had given one time grant up to Rs.50 lakh for creating seed processing and storage facilities and one time revolving fund upto Rs. 1.00 crore. Financial assistance to these seed hubs was as per NFSM-Pulses seed hub (DOD, 2022). The detail of seed hubs covering oilseed crops and state is presented in table 2.

Table 2: Crop-wise distribution of seeds hubs for quality seed production of oilseeds under NFSM

Sr. No.	Crop	State	No. of seeds hubs
1.	Groundnut	Andhra Pradesh (1), Gujarat (1), Karnataka (2), Odisha (1), Rajasthan (2), Tamil Nadu (1), Telangana (1)	9
2.	Rapeseed-mustard	Assam (1), Haryana (1), Madhya Pradesh (1), Rajasthan (3), Uttar Pradesh (2)	8
3.	Linseed	Bihar (1), Madhya Pradesh (1), Odisha (1),	3
4.	Soybean	Chandigarh (1), Karnataka (1), Madhya Pradesh (2), Maharashtra (1), Rajasthan (1), Telangana (1),	7
5.	Castor	Gujarat (1), Tamil Nadu (1), Telangana (1)	3
6.	Nigerseed	Karnataka (1), Madhya Pradesh (1), Odisha (1)	3
7.	Safflower	Maharashtra (1)	1
8.	Sunflower	Telangana (1), West Bengal (1)	2
9.	Sesamum	West Bengal (1)	1
Total			37

Source: Directorate of Oilseeds Development, GoI, Hyderabad

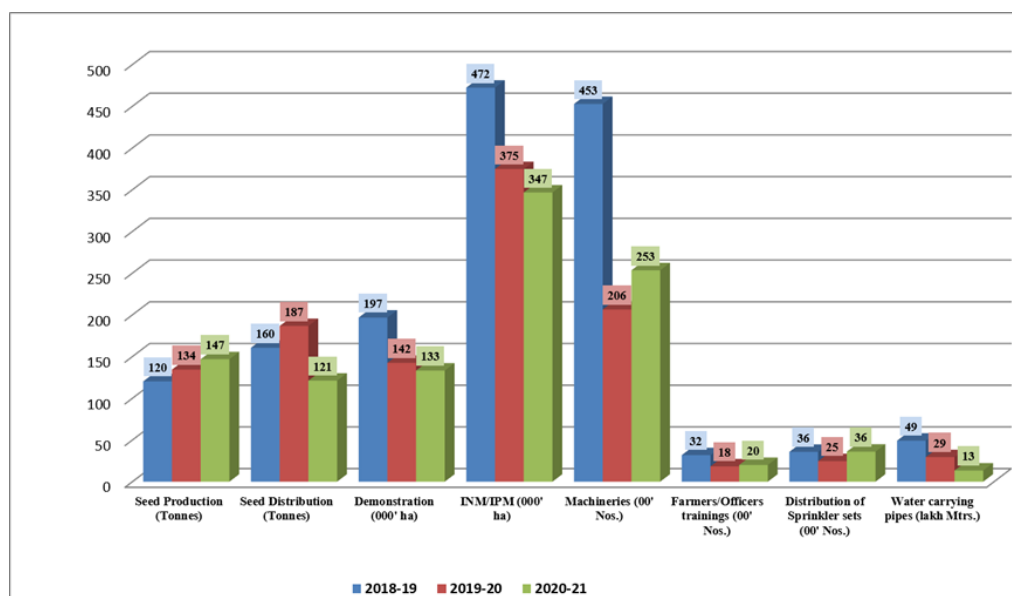


Figure 1: Progress in implementation of NFSM–Oilseeds: 2018-19 to 2020-21

Source: NFSM cell, Ministry of Agriculture and Farmers Welfare, GoI, New Delhi

National Mission on Edible Oils-Oil Palm (NMEO-OP): Considering the growing domestic demand for edible oils, the staggering deficiency and the cost to the exchequer on account of import, the urgency of scaling up the oil palm area is of national interest. Therefore, to fulfill the national interest, National Mission on Edible Oils - Oil Palm (NMEO-OP) was launched in 2021-22 with the aim to enhance the edible oilseeds production and oils availability in the country by harnessing Oil Palm area expansion, increasing Crude palm oil (CPO) production and to reduce import burden on edible oils. The State Department of Agriculture, State Department of Horticulture, Central University, ICAR Institutions, CDDs, SAUs, KVKs, Central Agencies/Cooperatives, Oil palm processors/associations etc. are the implementing stake holders of the NMEO-Oil palm. The target fixed for oil palm area expansion by 2025-26 is to increase area of oil palm to 10 lakh ha from 3.5 lakh ha during 2019-20 by 2025-26, to increase in Crude Palm Oil production from 0.27 lakh tonnes during 2019-20 to 11.20 lakh tonnes by 2025-26 and 28 lakh tonnes by 2028-29 and to increase consumer awareness to maintain consumption level of 19.00 kg per person per year till 2025-26.

The strategy to implement NMEO-OP includes increasing production of seedlings by establishment of seed gardens and nurseries of oil palm to assure domestic availability of seedlings as per target fixed under NMEO-OP. Improving productivity of FFBS, increasing drip irrigation coverage under oil palm, diversification of area from low yielding cereals crops to oil palm, inter-cropping during gestation period of 4 years. The scheme would be implemented in a mission mode through active involvement of all the stakeholders (NMEO, 2023).

Marketing policies for oilseeds in India

Minimum Support Price of Oilseeds: Seven major oilseeds, namely groundnut, rapeseed-mustard, sunflower, soybean, safflower, sesamum and nigerseed were covered under minimum support price (MSP) system. To study temporal variations in MSPs of oilseeds, the study period was divided into the following five periods: overall study period (20001-02 to 2020-21) was divided into four sub-periods, as period-I (2001-02 to 2005-06), period-II (2006-07 to 2010-11), period-III (2011-12 to 2015-16) and period-IV (2016-17 to 2020-21).

It can be elucidated from the table 3 and figure 2 that minimum support price (MSP) of oilseeds increased with positive and significant growth rate during the study period except for period-I in case of nigerseed (1.58%). But the highest growth rates was observed during period-II in groundnut (11.99%), sunflower (13.67%), sesamum (20.08%), nigerseed (22.84%) and soybean black (13.63%). Highest growth was observed in case of rapeseed-mustard (8.57%) during period-I, soybean yellow (10.46%) in period-III and safflower (10.18%) in period-IV. During overall period, all the seven oilseeds exhibited positive and highly significant growth rate; groundnut (8.88%), rapeseed-mustard (7.26%), sunflower (9.69%), soybean black (10.01%) & yellow (9.18%), safflower (8.32%), sesamum (10.08%) and nigerseed (10.70%). It reflects that

GoI has given special emphasis to increase MSP of oilseed crops to improve their productivity at farmer's field for reducing dependency on import of edible oils.

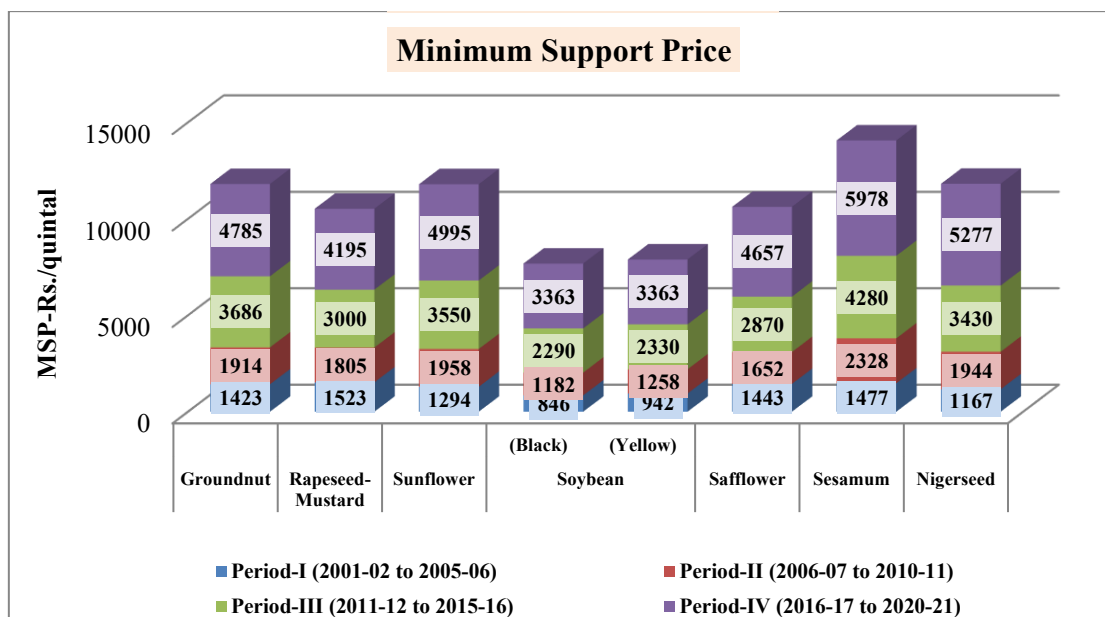


Figure 2: Trend of Minimum Support Price oilseeds crops in India: 2001-2021

Price Deficit Payment Scheme (PDPS): This scheme is aimed to ensure remunerative price to the producers of oilseeds where MSP are notified by GoI and when sold in the harvest season without procurement by the government agencies. The scheme envisaged direct payment of difference between MSP and market price realized farmers selling their produce in the notified APMC market through a transparent auction process. The state government/UT has to send option for implementation of PDPS for one or more oilseeds for the marketing season for the whole state in place of Price Support Scheme.

Pulses are procured under PSS, while states/UTs can choose either PSS or PDPS for a particular oilseed in a given procurement season for the entire state. The PSS is implemented at the request of the concerned state/UT subject to certain conditions. Under the scheme, GoI provides 100 percent support for compensation of 25 percent of production of the commodity. But if state/UT intends to procure over 25 percent of production, the total responsibility including finances shall be of state/UT government.

❖ **Price Support Scheme (PSS):** All the six major oilseeds, namely groundnut, rapeseed-mustard, sunflower, soybean, safflower and sesamum were covered under price support scheme. To study trends in procurement of oilseeds by central nodal agencies, the study period was divided into the following four periods, as period-I (2001-02 to 2005-06), period-II (2006-07 to 2010-11), period-III (2011-12 to 2015-16) and period-IV (2016-17 to 2020-21).

Table 3: Growth of Minimum Support Prices of Oilseeds in India: 2001-2021

Period	Groundnut	Rapeseed-Mustard	Sunflower	Soybean		Safflower	Sesamum	Nigerseed
				(Black)	(Yellow)			
Period-I	3.60***	8.57**	6.03**	3.79* *	3.94* *	5.62**	2.40** *	1.58 ^{NS}
Period-II	11.99**	1.69**	13.67* *	13.63**	10.19**	3.57**	20.08* *	22.84*
Period-III	9.19*	6.38**	6.44*	10.93* *	10.46* *	7.83**	7.67**	5.00*
Period-IV	5.98***	5.74***	11.83* *	9.05* **	9.05* *	10.18* *	8.69** *	16.21* *
Overall period	8.88***	7.26***	9.69** *	10.01***	9.18**	8.32** *	10.08* **	10.70* **

Note1: **Period-I** (2001-02 to 2005-06), **Period-II** (2006-07 to 2010-11), **Period-III** (2011-12 to 2015-16), **Period-IV** (2016-17 to 2020-21) and **Overall period** (2001-02 to 2020-21).

Note2: ***, ** and * are significant at 1, 5 and 10 per cent respectively

As it is evident from the table 4 during period-I, procurement made for oilseeds was groundnut (0.49%), rapeseed-mustard (10.33%), sunflower (0.12%), soybean (0.12%), safflower (4.10%) and sesamum (0.07%). During period-II, negligible procurement was made for groundnut and soybean but for rapeseed-mustard (6.31%), sunflower (0.37%), safflower (5.17%) and sesamum (0.07%) were procured in very small amount. During period-III, procurement was made for groundnut (0.97%), sunflower (0.62%) and safflower (5.17%) but negligible in case of rapeseed-mustard, soybean, safflower and sesamum. During period-IV, procurement was made for all the oilseeds except safflower as groundnut (4.53%), rapeseed-mustard (6.26%), sunflower (5.28%), soybean (0.17%) and sesamum (0.10%).

Thus, very little procurement of oilseeds was done by NAFED during the study period and the trend was irregular in procurement as seen from the figure 3. The cheap import of edible oils mainly crude and refined palm oil resulted into low domestic price for edible oils (Renjini and Girish, 2019). Poor and fluctuating procurement of oilseeds acts as a barrier and discourages farmers from producing more oilseeds, which in turn restricts the national production of edible oils (Singh & Singh, 2021).

Table 4: Procurement of oilseeds by NAFED under PSS in India: 2001-2021 (000' tonnes)

Sr. No.	Crop/Period	Procurement	Procurement as %age of production	Production
1.	Groundnut			
	Period-I (2001-02 to 2005-06)	167.37	0.49	34042.40
	Period-II (2006-07 to 2010-11)	0.16	0.00	34908.40
	Period-III (2011-12 to 2015-16)	347.39	0.97	35506.53
	Period-IV (2016-17 to 2020-21)	1977.66	4.53	43637.38
2.	Rapeseed/Mustard			
	Period-I (2001-02 to 2005-06)	3200.53	10.33	30978.10
	Period-II (2006-07 to 2010-11)	2223.80	6.31	35258.90
	Period-III (2011-12 to 2015-16)	1.72	0.00	35588.40
	Period-IV (2016-17 to 2020-21)	2815.16	6.26	44936.39
3.	Sunflower			
	Period-I (2001-02 to 2005-06)	5.67	0.12	4745.60
	Period-II (2006-07 to 2010-11)	19.56	0.37	5350.40
	Period-III (2011-12 to 2015-16)	14.28	0.62	2295.10
	Period-IV (2016-17 to 2020-21)	59.63	5.28	1130.18
4.	Soybean			
	Period-I (2001-02 to 2005-06)	4.17	1.24	33586.10
	Period-II (2006-07 to 2010-11)	0.007	0.00	52425.30
	Period-III (2011-12 to 2015-16)	0.00	0.00	57685.00
	Period-IV (2016-17 to 2020-21)	102.61	0.17	61195.37
5.	Safflower			
	Period-I (2001-02 to 2005-06)	38.44	4.10	936.20
	Period-II (2006-07 to 2010-11)	50.79	5.17	983.20
	Period-III (2011-12 to 2015-16)	0.00	0.00	510.28
	Period-IV (2016-17 to 2020-21)	0.00	0.00	253.38
6.	Sesamum			
	Period-I (2001-02 to 2005-06)	2.16	0.07	3236.40
	Period-II (2006-07 to 2010-11)	2.35	0.07	3497.00
	Period-III (2011-12 to 2015-16)	0.00	0.00	3887.80
	Period-IV (2016-17 to 2020-21)	3.74	0.10	3666.12

Source: Agriculture statistics at a Glance, GoI, New Delhi

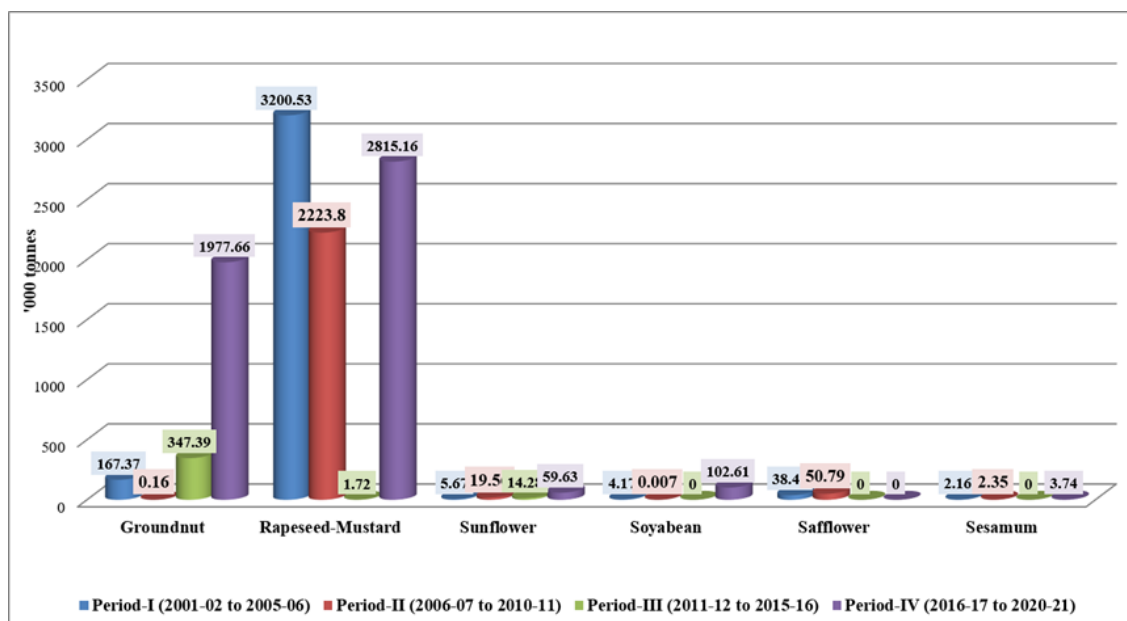


Figure 3: Procurement of Oilseeds under PSS: 2001-2021

Trade Policies for Oilseeds in India

In order to harmonize the interests of farmers, processors and consumers as well as regulate large import of edible oils to the extent possible, import duty structure on edible oils had been reviewed from time to time. Import of edible oils was under negative list and controlled through canalization until mid-1990s. In 1994-95, India liberalized edible oil imports in a phased manner and import of palm oil was placed under Open General License (OGL) subject to 65 percent import duty. Subsequently, import of other edible oils were also placed under OGL and import duty was as high as 80 percent on crude oil and 90 percent on refined edible oil during early-2000s. The import duties on edible oils were reduced to zero percent for crude oils and 7.5 percent for refined oil with effect from 1st April, 2008. The import duty on crude edible oils was increased to 2.5 percent in 2013, which was further increased to 7.5 percent in December 2014 and 12.5 percent in September 2015. Import duty on refined edible oils was increased from 7.5 percent to 10 percent in January 2014, which was further increased to 15 percent in December 2014 and 20 percent in September 2015. However, in the case of palm oil, import duty that was imposed at 65 percent in 1994, was reduced on crude palm oil to 7.5 percent and on refined palm oil to 15 percent September, 2016. GoI increased import duty on crude soybean oil from 12.5 to 17.5 percent in August 2017. Similarly, on crude palm oil, import duty was raised from 7.5 to 15 percent and on refined palm oil from 15 percent to 25 percent in August 2017.

The Negative list consists of goods whose import or export is prohibited, restricted through licensing or otherwise canalized. Canalization of import-export means import- export only through the agencies designated by the Central Government. Crude, unrefined means just exactly that, crude vegetable oil resulting from the method used to extract the oil, be it chemical,

expelled or expressed. The crude from the extraction stage carries with it many of the undesirable non-oil materials that are produced by the plant in the seed during growth and maturation, manufactured by the plant to make the seeds less palatable to bacteria, mold, fungus, insects and animals. These compounds include Free Fatty Acids, tyrosin inhibitors, urease, waxes, tocopherols, sterols, esters as well as the breakdown products of fatty acids decomposition, aldehydes, ketones and glycerols. Refined vegetable oils are those that have impurities removed mechanically and chemically. Generally refined vegetable oils have higher smoke points than unrefined vegetable oils making them more suitable for high-heat cooking. Refined vegetable oils tend to have neutral flavours.

In order to improve self-sufficiency in edible oils and ensure remunerative prices to oilseeds farmers in the country, major changes in the import duty structure of edible oils were introduced in November, 2017. Import duty on crude soybean oil was enhanced from 17.5 to 30 percent and it was further increased to 35 percent in June 2018, while import duty on refined soybean oil was raised from 20 to 35 percent in November 2017 and 45 percent in June 2018. Similarly, import duty on crude sunflower oil was increased to 35 percent in June 2018 while that on refined sunflower oil it was increased to 35 in March 2018 and 45 percent in June 2018. Import duty on crude cottonseed oil was also raised from 30 percent to 35 percent in June 2018 and on refined cottonseed oil from 35 to 45 percent in June 2018. Import duty on crude palm oil (CPO) of edible grade was raised from 15 percent to 30 percent in November 2017 and 44 percent in March 2018 but reduced to 40 percent in January 2019. Similarly, import duty on Refined Bleached and Deodorized (RBD) palm oil was increased from 25 percent to 40 percent in November 2017 and 54 percent in March 2018 but reduced to 45 percent for import of palm oil from Malaysia and 50 percent for shipments from Indonesia in January 2019. However, a safeguard duty of 5 percent was imposed on imports of RBD palm oil from Malaysia under India-Malaysia Comprehensive Economic Cooperation Agreement (IMCECA) from 4th September, 2019 but import under Association of Southeast Asian Nations (ASEAN) agreement did not attract 5 percent safeguard duty (CACP, 2022).

With effect from 1st January, 2020, the import duty on refined palm oil was lowered by the Government from 50 to 45 percent while that on crude palm oil it was reduced from 45 to 37.5 percent under ASEAN agreement and MICECA agreement. With effect from 8th January, 2020, import policy of refined palm oil was amended from 'Free' to 'Restricted' category. Further vide notification dated 27th November, 2020 the Basic Custom Duty (BCD) rate on crude palm oil was reduced to 27.5 percent from the previous rate of 37.5 percent in order to control the rise in price of palm oil and allow greater availability of edible oil in the market for consumption. This was the second time in the year 2020 that the government has cut import duty on palm oil.

Table 5: Tariff schedule of India in crude and refined oil: 2001-2021

Sr. No.	Month/Year	Import duty (%)	
		Crude oil	Refined oil
1.	2000	80	90
2.	April 2008	0	7.5
3.	2013	2.5	7.5
4.	January 2014		10
5.	December 2014	7.5	15
6.	September 2015	12.5	20
7.	September 2016	7.5 (palm oil)	15 (palm oil)
8.	August 2017	17.5 (soybean) 15 (palm oil)	20 (soybean) 25 (palm oil)
9.	November 2017	30 (soybean) 30 (palm oil)	35 (soybean) 40 (palm oil)
10.	March 2018	44 (palm oil)	35 (sunflower) 54 (palm oil)
11.	June 2018	35 (soybean) 35 (sunflower)	45 (soybean) 45 (sunflower)
12.	January 2019	40 (palm oil)	45 (for imports from Malaysia) and 50 (from Indonesia)
13.	January 2020	37.5 (palm oil)	45 (palm oil)
14.	November 2020	27.5 (oil palm)	
15.	February 2021	15 (palm oil, soybean and sunflower) 35 (rapeseed-mustard)	54 (palm oil) 45 (soybean, sunflower and rapeseed-mustard)

Source: Annual reports of CACP, GoI, New Delhi

The export of edible oils was initially prohibited for a period of one year in March 2008, which was extended from time to time. With effect from 6th February, 2015, export of rice bran oil in bulk had been permitted. With effect from 6th April, 2018, export of all edible oils except mustard oil was made free without quantitative ceiling; pack size etc, till further orders. Export of mustard oil was permitted in packs of up to 5 kg with a Minimum Export Price (MEP) of US\$900 per tonne. Oilseed export continued to be under ‘free category’ except breeder/foundation/wild variety seeds that are not allowed for export from India. The country has chosen to levy lesser than the bound tariff in the larger interests of the consumers and to keep a

sort of balance between consumer“ and producer“ interests (Singh *et al.*, 2017, Renjini & Girish, 2019).

Domestic Production, Import and Availability of Edible Oils in India

Domestic production, import and availability of edible oils is presented in table 6 and figure 4. The country imported nearly 55 percent of annual consumption of 24.62 million tonnes of edible oils in 2020-21. Increasing demand for edible oils necessitated the import in large quantities leading to a substantial drain on foreign exchange. Edible oil import increased from around 41.34 percent of total edible oils consumption in 2001-02 to 63 percent in 2015-16 but declined to 54.63 percent in 2020-21. In India, edible oil consumption was growing steadily over the years. From 10.45 million tonnes in 2001-02, the aggregate consumption of edible oils went up to 24.62 million tonnes in 2020-21. This clearly indicated the increasing dependence on import of edible oils and could be attributed to the fact that during the recent period, production of edible oils grown at a meagre rate of 2.77 per cent per annum which was very low compared to the 5.61 per cent per annum rate of growth in their demand. This resulted in 8.21 per cent growth in imports of edible oils noticed. At aggregate level, total and per capita consumption of edible oils were increasing with highly significant growth rate of 4.50 and 5.61 per cent, respectively. Consumption of all edible oils per year augmented from 8.8 to 19.7 kg during 2001-2021 translated into an increase of 124 percent. Similar results were observed by Thapa *et al.* (2019), Singh and Singh (2021).

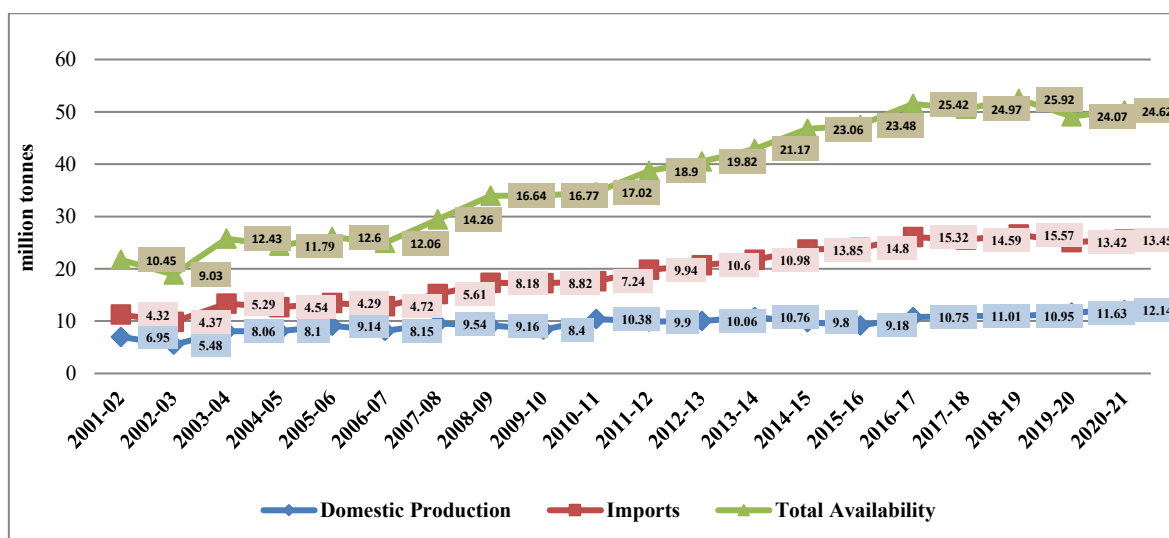


Figure 4: Domestic production, imports and total availability of edible oils in India: 2001-2021

Table 6: Domestic production, import and availability of edible oils in India: 2001-2021

Year	Domestic production (million tonnes)		Import (million tonnes)	Export & Industrial Use (million tonnes)	Total availability (million tonnes)	Share of import (%)	Per capita availability oil (kg/year)
	Edible Oilseeds	Edible oils					
2001-02	20.66	6.95 (66.50)	4.32	0.8	10.45	41.34	8.8
2002-03	14.84	5.48 (60.69)	4.37	0.82	9.03	48.39	7.2
2003-04	25.19	8.06 (64.84)	5.29	0.92	12.43	42.56	9.9
2004-05	24.35	8.10 (68.70)	4.54	0.85	11.79	38.51	10.2
2005-06	27.98	9.14 (72.54)	4.29	0.82	12.60	34.05	10.6
2006-07	24.29	8.15 (67.58)	4.72	0.78	12.06	39.14	11.1
2007-08	29.76	9.54 (66.90)	5.61	0.8	14.26	39.34	11.4
2008-09	27.72	9.16 (55.05)	8.18	0.7	16.64	49.16	12.7
2009-10	24.88	8.40 (50.09)	8.82	0.45	16.77	52.59	13.3
2010-11	32.48	10.38(60.98)	7.24	0.59	17.02	42.54	13.6
2011-12	29.80	9.90 (52.38)	9.94	0.95	18.90	52.59	13.8
2012-13	30.94	10.06(50.76)	10.6	0.84	19.82	53.48	15.8
2013-14	32.75	10.76(50.83)	10.98	0.71	21.17	51.87	16.8
2014-15	27.51	9.80 (42.50)	13.85	0.59	23.06	60.06	18.3
2015-16	25.25	9.18 (39.10)	14.8	0.55	23.48	63.03	17.7
2016-17	31.28	10.75(42.29)	15.32	0.65	25.42	60.27	18.2

2017-18	31.46	11.01(44.09)	14.59	0.63	24.97	58.43	19.5
2018-19	31.52	10.95(42.25)	15.57	0.6	25.92	60.07	18.1
2019-20	33.22	11.63(48.32)	13.42	0.98	24.07	55.75	19.2
2020-21	35.95	12.14(49.30)	13.45	0.98	24.62	54.63	19.7
CAGR	2.53***	2.77***	8.21***	-0.66	5.61***		4.50***

Source: Agriculture statistics at a Glance, GoI, New Delhi

Note 1. Figures in parentheses represent domestic oilseeds production and export as a percentage of total edible oilseeds availability

Note 2. ***, ** and * are significant at 1, 5 and 10 per cent respectively

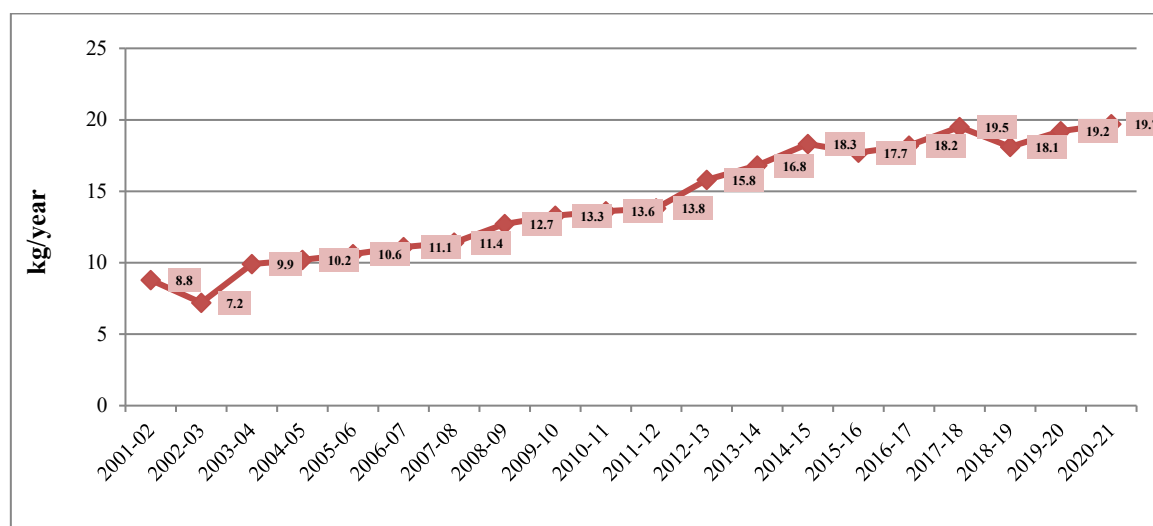


Figure 5: Per-capita availability of edible oils in India: 2001-2021

Performance overview of oilseeds in India

For comparative analysis, the average area covered, the production, productivity and percentage of oilseeds area under irrigation have been taken into consideration on the basis of Five-Year Plan and after that on annual plans. Annual plans (1966-69, 1979-80 and 1990-92), during which the Five-Year Plans could not be implemented, had been excluded for the purpose of analysis. The analytical review of oilseeds status prior to TMOP, post-TMOP, ISOPOM, and NMOOP and during NFSM period was briefly analyzed as in table 7 and figure 6.

➤ **Area expansion of oilseeds:** During the 1st Five-Year Plan (1951-56), the average oilseeds acreage of 6.77 million ha maintained an increasing trend and reached to 13.61 million ha in 4th Plan (1969-74) registering highest growth of 5.46 million ha. The inkling trend continued in subsequent periods also and reached to 20.50 million ha during TMO-Period and

25.95 million ha in TMOP-Period (1992-1997). **Table 7: Plan-wise growth in acreage, production and productivity of oilseeds in India: 1950-2021 (Area- million ha, Production- million tonnes, Productivity-kg ha⁻¹)**

Plan	Average Area	Change over (+/-)	Average Production	Change over (+/-)	Average Productivity	Change over (+/-)	Average of irrigation coverage (%)
Pre-TMO Periods							
1st Plan (1951-56)	6.77	-	1.92	-	284.00	-	2.12
2nd Plan (1956-61)	6.95	0.18	1.98	0.06	285.00	1.00	5.88
3rd Plan (1961-66)	8.15	1.20	2.28	0.30	280.00	-5.00	6.12
4th Plan (1969-74)	13.61	5.46	6.40	4.12	470.00	190.00	8.19
5th Plan (1974-79)	17.12	3.51	9.59	3.19	560.00	90.00	8.27
6th Plan (1980-85)	18.38	1.26	11.42	1.83	621.00	61.00	15.60
TMO-Period							
7th Plan (1985-90)	20.50	2.12	13.94	2.52	680.00	59.00	20.68
TMOP Period							
8th Plan (1992-97)	25.95	5.45	21.89	7.95	843.00	163.00	26.48
9th Plan (1997-02)	24.41	-1.54	21.18	-0.71	868.00	25.00	25.84
ISOPOM Period							
10th Plan (2002-07)	25.41	1.00	23.33	2.15	918.00	50.00	29.09
11th Plan (2007-12)	26.75	1.34	28.93	5.60	1082.00	164.00	28.40
NMOOP Period							
12th Plan (2012-17)	26.48	-0.27	29.55	0.62	1115.94	33.94	30.35
2017-18	24.51	-1.97	31.46	1.91	1284.00	168.06	32.75
NFSM Period							
2018-19	24.79	0.28	31.52	0.06	1271.00	-13.00	34.78
2019-20	27.14	2.35	33.22	1.7	1224.00	-47.00	-
2020-21	28.83	1.69	35.95	2.73	1247.00	23.00	-

Source: Agricultural Statistics at a Glance, GoI, New Delhi

However, there was a slight drop in area coverage *i.e.* 24.41 million ha registering negative change of 1.54 over the previous plan in 9th plan (1997-2002) but area registered increase in 10th plan of 1.00 million ha. With the introduction of ISOPOM, area augmented to 26.75 million ha. But it registered small decline of 0.27 million ha in 12th Plan and 1.97 million ha in 2017-18 in NMOOP period. After that oilseeds were included in NFSM and a program called NFSM-OS &OP was implemented in 2018-19. During NFSM period, oilseeds area exhibited continuous upsurge from 24.79 million ha in 2018-19 to 28.83 million ha in 2020-21, highest ever area registered under oilseeds cultivation. It was observed that the role of plan funds had incentivized especially in increasing area coverage under oilseeds.

➤ **Production enhancement of oilseeds:** During the 1st Five-Year Plan (1951-56), the production of oilseeds was 1.92 million tonnes and increased to 6.40 million tonnes in 4th Plan (1969-74) registering highest enhancement of 4.12 million tonnes compared to previous plan. Production of oilseeds continued to grow in TMO and TMOP-Period (21.89 million tonnes) due to area expansion under oilseeds but declined during 9th Plan by 0.71 million tonnes but again increased in subsequent plan (2002-2007). In the 8th Plan, oilseeds production recorded highest ever increase of 7.95 million tonnes. During ISOPOM period, production increased continuously to 31.46 million tonnes in 2017-18. This might be attributed to improvement in productivity even area drops in this period under oilseeds. During NFSM period, oilseeds production augmented continuously and reached to highest ever production of 35.95 million tonnes in 2020-21.

➤ **Productivity improvement of oilseeds:** Productivity of oilseeds has also improved during the Pre-TMO and TMO Plan period. The average productivity during the 1st plan (1951-56) was only 284 kg ha⁻¹ and in 4th Plan (1961- 66) productivity of it was about 470 kg ha⁻¹ whereas; maximum productivity was recorded (1284 kg ha⁻¹) in 2017-18. Approximately 168 kg ha⁻¹ increase in productivity level between the ISOPOM (2012-17) and during 2017-18 was reflected. Similarly, during the NFSM period, 2018-19, 2019-20 and 2020-21, productivity achieved was 1271, 1224 and 1247 kg ha⁻¹, respectively. Although the productivity is still below that realized under the frontline demonstrations conducted by ICAR institutes.

➤ **Oilseeds area coverage under irrigation:** The increase in production and productivity of oilseeds during Plan periods might be attributed to area expansion and adoption of modern technology based on improved package of practices, coverage of area under irrigation. These could be possible because of the launching of TMO in 350 districts of 17 states. An inadequate irrigation facility, especially the supply of critical irrigations is the main cause of low production of Indian oilseeds. During 1st Five-Year Plan (1951-56), the coverage of area under irrigation was hardly 2.12 percent. Growth was observed in area coverage under irrigation from 5.88 percent in 2nd Plan (1956-61) to 20.68 percent in TMO period and 29.09 percent in TMOP-

period (2002-07). The irrigated area coverage declined in ISOPOM-period (2007-12) initially to 28.40 percent but again increased to 32.75 percent in 2017-18.

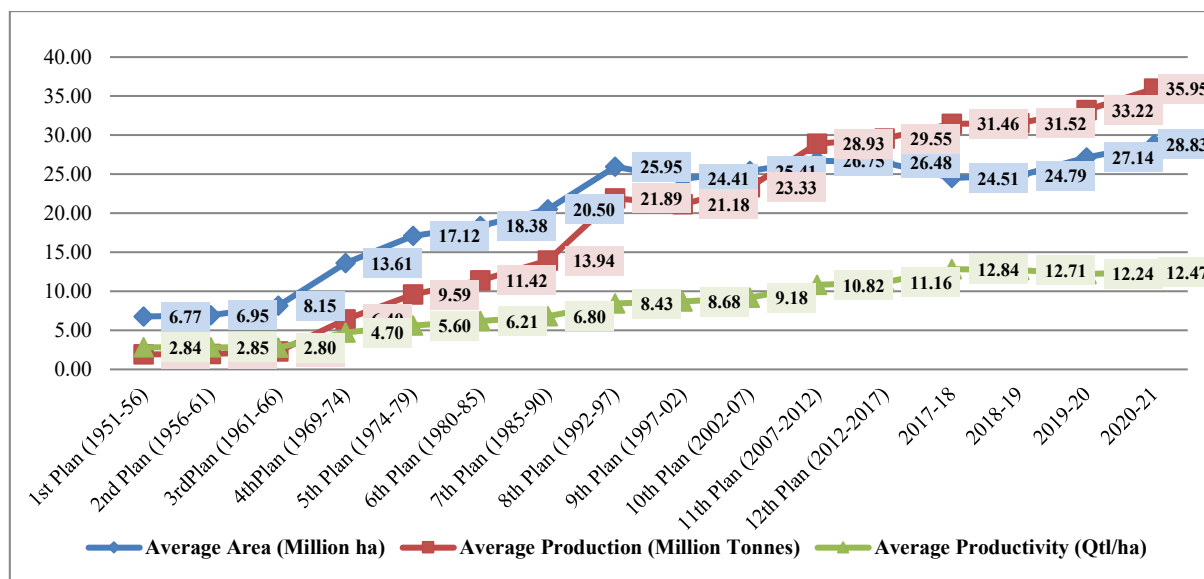


Figure 6: Trend in area, production and productivity of oilseeds in India: 1950-2021

Conclusion

With its rich agro-ecological diversity, India is ideally suited for growing all the major annual oilseed crops. Among the nine oilseed crops in the country groundnut, rapeseed-mustard, soybean, sunflower, sesamum, safflower and nigerseed are edible but castor and linseed are non-edible oilseed crops. In terms of acreage, production and economic value, these crops are next to foodgrains. India is the fifth largest vegetable oil economy in the world, next only to USA, China, Brazil and Argentina. Oilseeds cultivation is undertaken across the country in about 28.83 million ha in 2020-21 mainly on marginal lands, of which 75 per cent is confined to rainfed farming. Productivity of oilseeds (284 to 1247 kg ha⁻¹) increased during the study period (1950-51 to 2020-21) due to increased availability of inputs like seed, fertilizers, plant protection chemicals and increase in irrigated area under these crops. MSP of oilseeds showed tremendous growth but procurement by government agencies was very less compared to their production. Per capita availability of oilseeds increased during the period 2001-02 to 2020-21 and major reason for its increase was increased imports (8.21%).

It is, therefore, necessary to exploit domestic resources to maximize production to ensure edible oil security for the country. It can be achieved by strengthening existing seed hubs established for oilseeds by making arrangement for distribution of the quality seed produced to the farmers by active involvement of state seed producing agencies and private sector. Awareness and encouragement should be promoted among oilseeds growers by organizing camps, demonstrations of improved production technologies, ensure availability of quality seed etc. Adequate procurement of oilseeds should be done to insure MSP to farmers. Import and export of oilseeds should be reviewed at different intervals of time keeping in view their domestic

production. Further balance between domestic and import price of oilseeds should be maintained to safeguard the interest of pulses and oilseeds growers in the country.

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DISSEMINATING DRONE-BASED SMART SERVICES: EXTENSION BLUEPRINTS FOR SMALLHOLDER FARMING CLUSTERS

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Abstract

The integration of Unmanned Aerial Vehicles (UAVs) or drones in smallholder agriculture marks a critical shift toward precision farming. Drones offer rapid solutions for standardizing nano-urea applications and localized crop protection. However, resource fragmentation and low digital literacy present substantial barriers to widespread adoption in smallholder clusters. This chapter establishes a strategic extension blueprint designed for frontline agencies like Krishi Vigyan Kendras (KVKs) and District Agricultural Advisory and Transfer of Technology Centres (DAATTCs). The framework focuses on building rural entrepreneurship by training rural youth to establish and manage Custom Hiring Drone Hubs. By utilizing a "Train-the-Trainer" approach alongside Farmer Producer Organizations (FPOs), this model transforms precision agriculture from an elite technology into an accessible, community-managed utility.

Keywords: Drone Diffusion, Precision Extension, Rural Youth Entrepreneurship, Custom Hiring Hubs, Nano-Fertilizers.

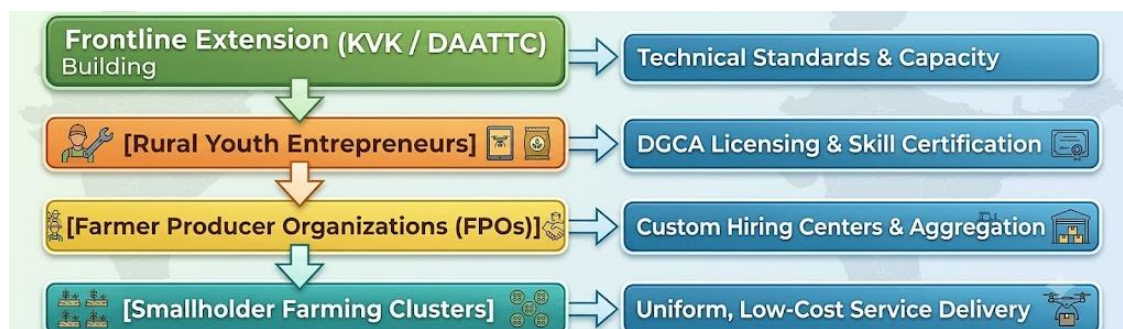
1. Introduction

Modern smallholder agriculture faces a dual challenge: rising input costs and acute agricultural labor shortages during peak operational seasons. Traditional pesticide spraying and manual broadcasting of bulk fertilizers like granular Urea and Di-Ammonium Phosphate (DAP) are inefficient and pose health risks to farm labor.

The introduction of liquid nano-fertilizers (such as Nano-Urea and Nano-DAP) and advanced crop protection chemistry requires ultra-precise delivery systems to maximize canopy coverage. Agricultural drones provide a viable solution to these efficiency demands. However, individual ownership of a drone is financially impractical for small and marginal farmers. Therefore, extension frameworks must pivot toward a institutionalized, service-led diffusion model.

2. The Extension Framework for Drone Technology Diffusion

To successfully move drone technology from a novelty to a regular field practice, frontline extension mechanisms must coordinate multiple stakeholders simultaneously.



Institutional Responsibilities

- **KVKs and DAATTCs:** Conduct method demonstrations (Frontline Demonstrations) to visually prove the saved time, water, and input quantities to skeptical farming communities.
- **Skill Development Partners:** Align training with the Remote Pilot Training Organizations (RPTOs) approved by the Directorate General of Civil Aviation (DGCA) to legitimize rural youth operations.
- **FPOs:** Act as the local aggregators, booking service windows across contiguous land parcels to optimize drone flight economics.

3. Capacity Building: Training Rural Youth as Precision Service Providers

A core element of this extension blueprint is transforming underemployed rural youth into skilled agri-entrepreneurs. Relying on external corporate drone operators is not economically sustainable for long-term rural development.

Technical and Operational Curriculum Matrix

Extension training modules managed by KVKs and DAATTCs should focus on three foundational dimensions:

Training Module	Core Technical Competencies	Extension Delivery Method
Module I: Flight Operations & Compliance	DGCA rules, airspace categorization (Green/Yellow zones), battery management, and basic maintenance.	Collaborations with certified RPTOs; simulator exercises.
Module II: Precision Agronomy	Calibration of spray discharge rates, canopy density mapping, optimal flight height, and speed according to crop architecture.	On-farm trials and live field interventions during specific crop stages.
Module III: Agro-Chemical Safety	Correct dilution rates for nano-fertilizers, compatibility of tank-mixes (pesticide + nutrients), and personal protective equipment (PPE) protocols.	Method demonstrations and diagnostic workshops.

4. Operationalizing Custom Hiring Drone Hubs (CHDH)

To achieve commercial viability in smallholder clusters, drone operations must follow a decentralized hub-and-spoke configuration.

Financial and Collective Action Mechanics

- **FPO-Linked Infrastructure:** The drone hub is housed within an existing FPO or a village-level Custom Hiring Center (CHC). This setup allows the hub to leverage subsidized procurement programs backed by state and central government schemes.
- **Cluster-Based Booking Schedules:** Random, scattered requests increase transportation overheads and waste battery life. Extension agents assist FPOs in designing contiguous spraying schedules, enabling a drone to spray 15–20 acres in a single continuous layout.
- **Economic Breakdown:** Standardizing custom hiring rates ensures that drone spraying costs remain lower than manual labor expenses per acre, while providing a clear profit margin for the youth operator.

5. Agronomic Advantages and Safety Standards

Drone-based application methods offer measurable improvements over traditional hand-spraying practices:

- **Resource Conservation:** Drone applications typically use only 10 liters of water per acre, compared to the 150–200 liters required by manual knapsack sprayers. This is a crucial advantage in rainfed and water-stressed zones.
- **Optimal Nutrient Absorption:** The fine atomization of spray droplets produced by specialized nozzles ensures uniform leaf coverage, which drastically boosts the uptake efficiency of nano-formulations.
- **Drift Management:** Operators must be trained to monitor wind velocity using hand-held anemometers, halting operations when winds exceed 15 km/h to prevent chemical drift onto non-target crops.

6. Socio-Economic Barriers to Adoption

Despite the clear technological advantages, extension networks must actively address several social and structural bottlenecks:

- **The "High Volume" Perception Bias:** Smallholder farmers often equate large quantities of water with effective chemical application. Moving them toward low-volume drone sprays requires continuous, verifiable field results.
- **Fragmented Landholdings and Boundary Disputes:** Small fields bounded by tall trees, electrical poles, and varying crop rows introduce physical flight hazards. This underscores the need for collective local village agreements.

- **Regulatory Compliance:** Navigating digital sky platforms, obtaining flight permissions, and maintaining certified equipment can overwhelm rural youth without ongoing administrative support from DAATTC and KVK scientists.

Conclusion and Policy Implications

The scale of drone adoption in smallholder farming clusters depends less on the technology itself and more on the strength of the extension delivery network. Training rural youth to manage local drone hubs addresses two challenges at once: it accelerates the adoption of precision tools like nano-urea while building stable, technology-driven jobs within rural economies. For this model to succeed across more regions, policies must focus on easing credit access for youth entrepreneurs, streamlining rural drone licensing, and expanding the capacity of frontline extension networks to deliver technical training.

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HARNESSING TECHNOLOGY FOR SUSTAINABLE AGRICULTURE

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Abstract

Sustainable agriculture has emerged as a transformative approach to food production that seeks to balance agricultural productivity, environmental conservation, economic viability, and social equity. The concept evolved in response to concerns over soil degradation, biodiversity loss, water scarcity, and climate change associated with intensive agricultural practices. Historically, traditional farming systems relied on ecological principles and local knowledge to maintain soil fertility and ecosystem stability. The Green Revolution significantly enhanced food production but also led to increased dependence on chemical fertilizers, pesticides, and monoculture systems. In the present era, sustainable agriculture integrates traditional wisdom with modern technologies such as precision farming, climate-smart agriculture, regenerative agriculture, artificial intelligence, and digital agriculture. These innovations aim to improve resource-use efficiency, reduce greenhouse gas emissions, enhance resilience to climate change, and ensure long-term food security. Emerging concepts such as carbon farming, ecosystem restoration, circular bioeconomy, and nature-based solutions are shaping the future of agriculture. This chapter discusses the historical evolution, current status, recent developments, challenges, and future prospects of sustainable agriculture, highlighting its crucial role in achieving global food security and environmental sustainability.

Keywords: Sustainable Agriculture, Traditional Farming, Precision Agriculture, Climate-Smart Agriculture, Regenerative Agriculture, Food Security.

1. Introduction

Agriculture has been the foundation of human civilization for over 10,000 years. The challenge of modern agriculture is not merely to increase food production but to produce food sustainably while preserving natural resources for future generations. Sustainable agriculture is defined as an integrated system of plant and animal production practices that satisfy human food and fiber needs, enhance environmental quality, efficiently utilize non-renewable resources, sustain farm profitability, and improve the quality of life for farmers and society (Pretty, 2021; FAO, 2025). According to the Food and Agriculture Organization (FAO), sustainable agriculture must simultaneously address food security, climate change adaptation, biodiversity conservation, and rural development (FAO, 2025). With the global population projected to approach 9.7 billion by

2050, food production must increase substantially while minimizing environmental impacts (OECD-FAO, 2025). Climate-smart agricultural approaches are increasingly recognized as essential for achieving these objectives (FAO, 2025).

2. Historical Evolution of Sustainable Agriculture

2.1 Ancient Agricultural Systems

Early agricultural societies practiced inherently sustainable methods:

- Crop rotation
- Mixed cropping
- Agroforestry
- Organic manuring
- Water harvesting systems

Examples include:

- Terrace farming in Asia
- Indigenous agroforestry systems in Africa
- Traditional rice-fish farming systems
- Ancient Indian Vrikshayurveda practices

These traditional systems maintained ecological balance, promoted nutrient cycling, and ensured stable food production through the sustainable use of natural resources (Gliessman, 2022).

2.2 Green Revolution Era (1960–1990)

The Green Revolution introduced:

- High-yielding varieties (HYVs)
- Chemical fertilizers
- Synthetic pesticides
- Irrigation expansion
- Mechanization

Achievements:

- Dramatic increases in cereal production
- Prevention of widespread famine

Limitations:

- Soil degradation
- Groundwater depletion
- Biodiversity loss
- Environmental pollution
- Increased production costs

The Green Revolution significantly increased food grain production worldwide through the adoption of high-yielding varieties, irrigation, fertilizers, and pesticides; however, it also contributed to soil degradation, groundwater depletion, and biodiversity loss (**Pretty, 2021; Lal, 2023**).

3. Principles of Sustainable Agriculture

The major principles include:

Ecological Sustainability

- Soil conservation
- Biodiversity protection

Economic Sustainability

- Farm profitability
- Reduced input costs
- Market resilience

Social Sustainability

- Rural livelihood security
- Food and nutritional security
- Community participation

Climate Resilience

- Adaptation to extreme weather
- Carbon sequestration
- Reduced greenhouse gas emissions

The principles of sustainable agriculture are based on balancing ecological integrity, economic viability, and social responsibility while enhancing resilience to climate change and environmental stresses (Pretty, 2021; FAO, 2025).

4. Present Status of Sustainable Agriculture

4.1 Climate-Smart Agriculture (CSA)

Climate-smart agriculture integrates:

- Increased productivity
- Adaptation to climate change
- Mitigation of greenhouse gas emissions

CSA includes:

- Drought-tolerant crops
- Precision irrigation
- Conservation tillage
- Integrated nutrient management

FAO identifies Climate-Smart Agriculture (CSA) as a critical pathway for improving agricultural productivity, enhancing resilience, and reducing greenhouse gas emissions under changing climatic conditions (FAO, 2025).

4.2 Organic Farming

Organic agriculture avoids synthetic inputs and emphasizes:

- Composting
- Biofertilizers
- Biopesticides
- Crop rotation

India has become one of the leading countries in organic farming area and producer participation. Organic farming contributes to improved soil health, biodiversity conservation, and reduced environmental pollution while supporting sustainable livelihoods (FAO, 2025).

4.3 Conservation Agriculture

Conservation agriculture has been widely recognized for improving soil structure, increasing water-use efficiency, and reducing erosion in agricultural landscapes (Lal, 2023).

Three key principles:

- Minimum soil disturbance
- Permanent soil cover
- Crop diversification

Benefits include:

- Reduced erosion
- Improved soil structure
- Increased water retention

4.4 Agroecology

Agroecology combines ecological science with agricultural production systems and local knowledge to develop resilient and sustainable farming systems (Gliessman, 2022).

5. Recent Trends and Innovations (2020–2026)

5.1 Regenerative Agriculture

Regenerative agriculture focuses on:

- Soil regeneration
- Carbon sequestration
- Biodiversity enhancement

Recent global assessments indicate that regenerative practices such as cover cropping, agroforestry, reduced tillage, and organic management can improve productivity while enhancing ecosystem services and soil carbon storage (Hounkpatin *et al.*, 2026).

Key Practices

- Cover crops
- No-till farming
- Agroforestry
- Managed grazing
- Compost application

5.2 Carbon Farming

Carbon farming aims to capture atmospheric carbon dioxide in soils and vegetation through sustainable agricultural practices.

Benefits:

- Climate change mitigation
- Improved soil fertility
- Additional farmer income through carbon credits

Carbon farming has gained considerable attention as a nature-based solution for climate change mitigation by enhancing carbon sequestration in soils and biomass (Priyanka *et al.*, 2026; Lal, 2023).

5.3 Precision Agriculture

Technologies include:

- GPS
- Drones
- IoT sensors
- Artificial Intelligence
- Satellite monitoring

Advantages:

- Reduced fertilizer use
- Efficient irrigation
- Improved productivity
- Lower environmental impact

Recent smart farming platforms demonstrate that the integration of artificial intelligence, satellite data, and IoT-based monitoring systems can significantly improve resource-use efficiency and sustainable decision-making (Bompotas *et al.*, 2025).

5.4 Circular Bioeconomy

Agricultural waste is increasingly converted into:

- Biogas
- Bioenergy

- Bioplastics

The circular bioeconomy promotes efficient utilization of agricultural residues and waste streams to generate value-added products while reducing environmental impacts (OECD-FAO, 2025).

6. Sustainable Agriculture in India

India has launched several initiatives to promote sustainable agricultural development through improved soil health, water conservation, organic farming, and climate resilience (Government of India, NMSA; PKVY; PM-PRANAM).

- Rainfed farming
- Water-use efficiency
- Soil health management

The Maharashtra Krishi Samruddhi Yojana (2025) emphasizes climate-resilient agriculture, crop diversification, digital technologies, and sustainable resource management.

7. Recent Global Developments and News (2025–2026)

Ecosystem Restoration:

The United Nations Environment Programme identified several large-scale ecosystem restoration projects under the World Restoration Flagships initiative to enhance food security, biodiversity conservation, and sustainable land management (UNEP, 2025).

Policy Reforms:

Recent international assessments emphasize strengthening legal and policy frameworks to accelerate the adoption of sustainable agricultural practices and biodiversity-friendly food systems (IUCN, 2026).

8. Challenges

Major constraints include:

- Climate change
- Water scarcity
- Soil degradation
- Biodiversity loss
- Limited adoption of sustainable technologies
- Financial barriers
- Knowledge gaps
- Market uncertainties

9. Future of Sustainable Agriculture

Future agriculture will increasingly rely on:

Artificial Intelligence and Machine Learning

For:

- Crop monitoring
- Pest prediction
- Resource optimization

Gene Editing and Climate-Resilient Crops

Development of:

- Drought-tolerant varieties
- Heat-resistant crops
- Disease-resistant cultivars

Carbon Markets

Farmers may receive compensation for ecosystem services and carbon sequestration.

Digital Agriculture

Real-time farm management through:

- Remote sensing
- Mobile applications
- Big data analytics

Nature-Based Solutions

Increasing use of:

- Agroforestry
- Wetland restoration
- Biodiversity corridors

Conclusion

Sustainable agriculture has evolved from traditional ecological farming practices to a sophisticated system integrating advanced technologies and environmental stewardship. Emerging innovations such as regenerative agriculture, carbon farming, precision agriculture, artificial intelligence, and climate-smart agriculture offer promising pathways toward resilient food systems (FAO, 2025; Hounkpatin *et al.*, 2026; Bompotas *et al.*, 2025). As climate change intensifies and natural resources become increasingly constrained, sustainable agriculture will play a central role in ensuring food security, environmental conservation, and rural prosperity (Lal, 2023; UNEP, 2025).

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INNOVATIVE FARMING SOLUTIONS FOR A CHANGING CLIMATE

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Abstract

Climate change presents grave risks to the world agriculture in terms of productivity, sustainability and food security. The traditional agricultural systems have been destabilised by global warming, unreliable precipitation, soil erosion, and harsh weather conditions. This chapter reviews emerging solutions of farming to enhance climate resilience and sustainability. It talks about climate-smart farming, precision farming, regenerative farming, biotechnology and digital farming as potential solutions to these problems. The chapter synthesises recent studies and case studies by explaining that by incorporating modern technologies and ecological ideas, one can improve the results of agriculture. The results suggest that to reduce climate risks and achieve long-term food security, adaptive, technology-based, and ecosystem-based strategies are critical. The chapter concludes with the importance of advocating policy, raising awareness among farmers, and interdisciplinary research in realizing sustainable agricultural transformation.

Keywords: Climate Change, Climate-Smart Agriculture, Precision Farming, Regenerative Agriculture, Food Security, Sustainable Agriculture, Iot, Artificial Intelligence, Crop Resilience.

Introduction

Agriculture remains one of the most climate-sensitive sectors, directly influenced by environmental conditions such as temperature, rainfall, and seasonal variability. Climate change has intensified these factors, leading to increased droughts, floods, and unpredictable weather patterns that adversely affect crop yields and farming livelihoods. As the global population continues to grow, the demand for food is rising, placing additional pressure on already stressed agricultural systems. At the same time, agriculture contributes to greenhouse gas emissions, creating a complex relationship between farming practices and environmental sustainability. Addressing these challenges requires innovative approaches that not only enhance productivity but also reduce environmental impact. In this context, sustainable and climate-resilient farming practices have gained prominence as essential strategies for ensuring food security and ecological balance.

Objectives

The primary objective of this chapter is to analyse the impact of climate change on agricultural systems and to explore innovative farming solutions that enhance resilience and sustainability. It also aims to evaluate the effectiveness of emerging technologies and practices in improving agricultural productivity under changing climatic conditions, while proposing strategies for future development.

Methodology

This chapter is based on a comprehensive review of recent literature published between 2020 and 2025, including peer-reviewed journal articles, institutional reports, and case studies. A qualitative approach was adopted to synthesize findings from various sources, focusing on innovations in climate-resilient agriculture. The methodology involved identifying key themes such as climate-smart agriculture, precision farming, and digital technologies, followed by a comparative analysis of their applications and outcomes. Case studies were examined to understand real-world implementations, and insights were categorized to highlight the most effective strategies for adapting to climate change.

Climate Change Impacts on Agriculture

Climate change has far-reaching impacts on agricultural systems, affecting both crop production and resource availability. Rising temperatures can accelerate crop maturation but often reduce yields by shortening growing periods. Water scarcity, resulting from irregular rainfall and prolonged droughts, limits irrigation and affects soil moisture levels. Extreme weather events such as floods, storms, and heatwaves cause direct damage to crops and agricultural infrastructure. Additionally, changing climatic conditions contribute to the spread of pests and diseases, further threatening crop health and productivity. These challenges collectively disrupt food supply chains and increase the vulnerability of farmers, particularly in developing regions where adaptive capacity is limited.

Innovative Farming Solutions

Innovative farming solutions have emerged as critical tools for addressing the challenges posed by climate change. Climate-smart agriculture integrates adaptation, mitigation, and productivity goals by promoting practices such as crop diversification, efficient irrigation, and soil conservation. These practices help farmers manage risks associated with climate variability while maintaining productivity. Precision agriculture represents another significant advancement, utilizing technologies such as sensors, GPS, drones, and data analytics to optimize resource use. By providing real-time information on soil conditions, weather patterns, and crop health, precision farming enables more efficient and sustainable agricultural practices.

Regenerative agriculture focuses on restoring soil health and ecosystem balance through methods such as cover cropping, reduced tillage, and organic inputs. These practices enhance soil fertility,

improve water retention, and increase carbon sequestration, contributing to both climate mitigation and resilience. Similarly, digital and smart farming technologies, including the Internet of Things (IoT) and artificial intelligence (AI), have transformed agricultural management. These technologies enable farmers to monitor environmental conditions, predict crop performance, and make data-driven decisions that improve efficiency and reduce environmental impact. Biotechnology also plays a crucial role in developing climate-resilient crops. Advances in genetic engineering and breeding techniques have led to the creation of drought-resistant, heat-tolerant, and pest-resistant crop varieties. These innovations help maintain productivity under adverse conditions and reduce reliance on chemical inputs. Additionally, controlled environment agriculture, such as hydroponics, vertical farming, and greenhouse cultivation, offers solutions for growing crops in controlled settings, minimizing the impact of external climatic factors and improving resource efficiency.

Discussion

The adoption of innovative farming solutions offers significant potential for enhancing agricultural resilience and sustainability. However, the effectiveness of these approaches depends on several factors, including accessibility, affordability, and farmer awareness. In many regions, particularly in developing countries, limited access to technology and financial resources poses challenges to implementation. Furthermore, the successful integration of modern technologies with traditional knowledge systems is essential for creating context-specific solutions that address local needs. Interdisciplinary collaboration among scientists, policymakers, and farmers is also critical for developing and scaling innovative practices. By combining technological advancements with ecological principles, it is possible to create farming systems that are both productive and sustainable.

Challenges and Limitations

Despite the potential benefits, several challenges hinder the widespread adoption of innovative farming solutions. High initial investment costs and lack of technical expertise can discourage farmers from adopting new technologies. Infrastructure limitations, such as inadequate internet connectivity and access to electricity, further restrict the use of digital tools in rural areas. Policy and institutional barriers, including insufficient support and incentives, also affect the implementation of sustainable practices. Addressing these challenges requires coordinated efforts from governments, research institutions, and private sectors to provide financial support, training, and infrastructure development.

Future Prospects

The future of agriculture lies in the continued development and integration of advanced technologies and sustainable practices. Artificial intelligence, big data analytics, and robotics are expected to play increasingly important roles in agricultural management. The development of

climate-resilient crop varieties and sustainable resource management strategies will further enhance the adaptability of farming systems. Additionally, the integration of nanotechnology and smart materials may lead to new innovations in soil management, crop protection, and nutrient delivery. As these technologies evolve, it is essential to ensure that they are accessible and affordable to farmers across different regions.

Conclusion

Innovative farming solutions are essential for addressing the challenges posed by climate change and ensuring global food security. Approaches such as climate-smart agriculture, precision farming, regenerative practices, and digital technologies offer effective strategies for enhancing resilience and sustainability. However, their successful implementation requires supportive policies, adequate infrastructure, and increased awareness among farmers. By adopting integrated and adaptive approaches, it is possible to create agricultural systems that are both productive and environmentally sustainable. Future efforts should focus on developing scalable and inclusive solutions that address the diverse needs of farmers and contribute to long-term agricultural transformation.

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REDOX HOMEOSTASIS AND ANTIOXIDANT DEFENSE MECHANISMS IN THE POSTHARVEST BIOLOGY OF FRUITS AND VEGETABLES

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Abstract

Postharvest deterioration of fruits and vegetables is a major challenge affecting food quality, nutritional value, and global food security. Central to this process is the regulation of redox homeostasis, which maintains a balance between reactive oxygen species (ROS) production and antioxidant defense systems. This chapter provides a comprehensive overview of the mechanisms governing redox homeostasis in postharvest biology, highlighting the dual role of ROS as signalling molecules and mediators of oxidative damage. It discusses the generation of ROS, oxidative stress, enzymatic and non-enzymatic antioxidant defense mechanisms, and the influence of storage conditions on cellular redox balance. The chapter further examines sustainable postharvest strategies, including controlled atmosphere storage, edible coatings, natural elicitors, and signalling molecules, for enhancing antioxidant capacity and delaying senescence. In addition, recent advances in nanotechnology, omics approaches, artificial intelligence, and genome editing are discussed as promising tools for improving postharvest quality. These integrated approaches provide sustainable solutions for reducing postharvest losses while improving the quality and shelf life of fresh horticultural produce.

Keywords: Antioxidant Defense Mechanisms, Oxidative Stress, Postharvest Biology, Reactive Oxygen Species (ROS), Redox Homeostasis, Sustainable Postharvest Technologies.

1. Introduction

Fruits and vegetables are essential components of a healthy diet, providing vitamins, minerals, dietary fibre and a wide range of bioactive compounds with significant health-promoting properties (Decros *et al.*, 2019). Among these compounds, antioxidants such as ascorbic acid, carotenoids, tocopherols, flavonoids and phenolic compounds play a crucial role in protecting cells from oxidative damage and reducing the risk of chronic diseases. Despite their nutritional importance, fruits and vegetables are highly perishable commodities, accounting for substantial postharvest losses worldwide due to rapid physiological and biochemical deterioration. These losses not only reduce food availability and economic returns but also pose a major challenge to sustainable agriculture and global food security.

A key factor responsible for postharvest deterioration is the disruption of cellular redox homeostasis. Under normal physiological conditions, reactive oxygen species (ROS), including superoxide radicals, hydrogen peroxide, hydroxyl radicals, and singlet oxygen, are continuously generated as natural by-products of cellular metabolism. At controlled levels, ROS function as important signalling molecules regulating growth, ripening and stress responses (Eze *et al.*, 2025). However, postharvest stresses such as mechanical injury, temperature fluctuations, dehydration and pathogen infection lead to excessive ROS accumulation, resulting in oxidative stress. This imbalance causes lipid peroxidation, protein oxidation, nucleic acid damage, membrane deterioration, accelerated senescence and loss of nutritional and sensory quality.

To maintain cellular redox homeostasis, fruits and vegetables possess an efficient antioxidant defence system comprising enzymatic antioxidants, including superoxide dismutase, catalase, ascorbate peroxidase and glutathione reductase, as well as non-enzymatic antioxidants such as ascorbic acid, glutathione, carotenoids, tocopherols, and phenolic compounds (Liu *et al.*, 2021). The coordinated action of these defence systems regulates ROS metabolism, minimizes oxidative damage and contributes to the maintenance of postharvest quality and shelf life.

This chapter discusses the mechanisms governing redox homeostasis and antioxidant defence in the postharvest biology of fruits and vegetables. It highlights the generation and physiological roles of ROS, antioxidant defence mechanisms, factors influencing redox balance and recent advances in sustainable postharvest technologies for improving quality, extending shelf life and reducing postharvest losses.

2. Redox Homeostasis in Postharvest Biology

Concept of Redox Homeostasis

Redox homeostasis refers to the dynamic equilibrium between the generation of reactive oxygen species (ROS) and their detoxification by cellular antioxidant defense systems. In postharvest fruits and vegetables, this balance is essential for maintaining normal physiological processes, preserving cellular integrity and delaying senescence. Following harvest, fruits and vegetables remain metabolically active and continue to respond to environmental and handling stresses such as mechanical injury, temperature fluctuations, dehydration and pathogen attack. These stresses disturb the cellular redox balance, leading to excessive ROS accumulation and oxidative stress (Li *et al.*, 2023). Consequently, maintaining redox homeostasis is fundamental for preserving postharvest quality, nutritional attributes and storage life.

Cellular Redox Balance

The maintenance of redox homeostasis depends on an integrated antioxidant network that regulates oxidation-reduction reactions within plant cells. Major redox buffers, including ascorbate (ASC), glutathione (GSH) and pyridine nucleotides such as NAD(P)H, maintain the intracellular reducing environment through continuous electron transfer reactions. Under normal

conditions, these molecules efficiently neutralize ROS and regenerate antioxidant compounds. However, postharvest stresses alter this equilibrium by increasing ROS production while simultaneously reducing antioxidant capacity. The resulting oxidative environment disrupts membrane integrity, enzyme function and cellular metabolism, thereby accelerating tissue deterioration and senescence.

ROS Generation and Redox Regulation

Reactive oxygen species are continuously generated as natural by-products of aerobic metabolism in mitochondria, chloroplasts and peroxisomes. During postharvest storage, mitochondrial respiration becomes the major source of ROS because photosynthetic activity is considerably reduced. Although excessive ROS cause oxidative damage, low and controlled concentrations serve as important signalling molecules that regulate stress responses, fruit ripening, defence mechanisms and programmed cell death. Therefore, cellular redox regulation depends on maintaining a balance between ROS generation and antioxidant-mediated scavenging (Alkan and Fortes, 2015). When ROS production exceeds the scavenging capacity of plant cells, oxidative stress develops, resulting in lipid peroxidation, protein oxidation, nucleic acid damage, and membrane dysfunction.

Redox Homeostasis During Ripening and Senescence

Fruit ripening is accompanied by extensive physiological and biochemical changes that are closely associated with alterations in cellular redox status. As ripening progresses, respiration and ethylene production generally increase, leading to enhanced ROS generation. Simultaneously, antioxidant defence systems gradually decline, making tissues more susceptible to oxidative damage. This imbalance contributes to membrane degradation, pigment loss, enzymatic browning, tissue softening, flavour deterioration and nutritional depletion (Hodges *et al.*, 2004). Nevertheless, controlled ROS production also acts as a developmental signal regulating pigment biosynthesis, cell wall metabolism and other ripening-related processes. Thus, maintaining redox homeostasis is essential for ensuring normal ripening while delaying premature senescence and preserving fruit quality.

Significance of Redox Homeostasis in Postharvest Quality

The capacity of fruits and vegetables to maintain redox homeostasis largely determines their postharvest performance and storage potential. Commodities possessing efficient antioxidant defence systems exhibit greater tolerance to oxidative stress and generally retain quality for longer storage periods. Recent studies have shown that signalling molecules such as nitric oxide, hydrogen sulphide, melatonin and several phytohormones regulate antioxidant metabolism and improve stress tolerance by maintaining cellular redox balance (Hossain *et al.*, 2020). Furthermore, sustainable postharvest technologies including low-temperature storage, controlled atmosphere storage, edible coatings, natural elicitors and nanotechnology-based approaches are

increasingly being developed to regulate ROS metabolism and enhance antioxidant activity. A comprehensive understanding of redox homeostasis therefore provides an important scientific foundation for designing innovative postharvest strategies that improve quality retention, extend shelf life, reduce postharvest losses and contribute to sustainable agricultural and food systems.

3. Reactive Oxygen Species (ROS):

Reactive oxygen species (ROS) are highly reactive oxygen-containing molecules that play a dual role in the postharvest biology of fruits and vegetables. Under normal physiological conditions, ROS function as important signalling molecules regulating growth, ripening, stress responses and defence mechanisms. However, excessive accumulation of ROS disrupts cellular redox homeostasis, leading to oxidative stress, accelerated senescence and quality deterioration. Therefore, maintaining an optimal balance between ROS generation and antioxidant defence is essential for preserving postharvest quality and extending shelf life.

Definition

Reactive oxygen species are partially reduced or activated derivatives of molecular oxygen that are continuously generated during normal cellular metabolism. Although they are unavoidable by-products of aerobic respiration and other metabolic processes, their concentration is tightly regulated by antioxidant defence systems to prevent cellular damage.

Types of Reactive Oxygen Species

The major ROS identified in postharvest tissues include superoxide anion (O_2^-), hydrogen peroxide (H_2O_2), hydroxyl radical ($\bullet OH$), and singlet oxygen (1O_2). Among these, superoxide anion is the primary product of electron leakage from the respiratory electron transport chain, whereas hydrogen peroxide is comparatively stable and can readily diffuse across cellular compartments. The hydroxyl radical is considered the most reactive and damaging ROS because of its ability to rapidly oxidize cellular macromolecules (Kerr *et al.*, 2025). Singlet oxygen is mainly generated during photosynthetic reactions and under light-induced stress conditions.

Sources and Sites of ROS Generation

Reactive oxygen species are continuously generated in different cellular compartments during aerobic metabolism. Mitochondria serve as the major source of ROS during postharvest storage owing to sustained respiratory activity, whereas chloroplasts and peroxisomes contribute significantly in photosynthetically active tissues. Additional ROS are produced by plasma membrane-bound NADPH oxidases, cell wall peroxidases and various oxidase enzymes during mechanical injury, pathogen attack, temperature stress, and other postharvest challenges (Kiran *et al.*, 2023). Excessive ROS production under these conditions disturbs cellular redox balance and initiates oxidative damage.

Physiological Roles of ROS

At low and tightly regulated concentrations, ROS function as signalling molecules that regulate numerous physiological and developmental processes. They participate in fruit ripening, stress perception, defence responses, hormone signalling, cell wall modification and the activation of antioxidant enzymes. Controlled ROS accumulation also contributes to the induction of protective mechanisms that enhance tolerance against environmental and biological stresses. Conversely, excessive ROS accumulation causes oxidative damage to membrane lipids, proteins, nucleic acids and pigments (Li *et al.*, 2023). Such damage disrupts membrane integrity, impairs enzyme activity, accelerates tissue softening, enzymatic browning, pigment degradation and ultimately leads to premature senescence and reduced postharvest quality. Therefore, the physiological outcome of ROS depends largely on their intracellular concentration and the efficiency of antioxidant defence mechanisms.

4. Oxidative Stress

Oxidative stress develops when the production of reactive oxygen species exceeds the antioxidant scavenging capacity of plant cells, resulting in disruption of cellular redox homeostasis. This imbalance is one of the primary causes of postharvest deterioration, as excessive ROS damage essential cellular components and accelerate senescence.

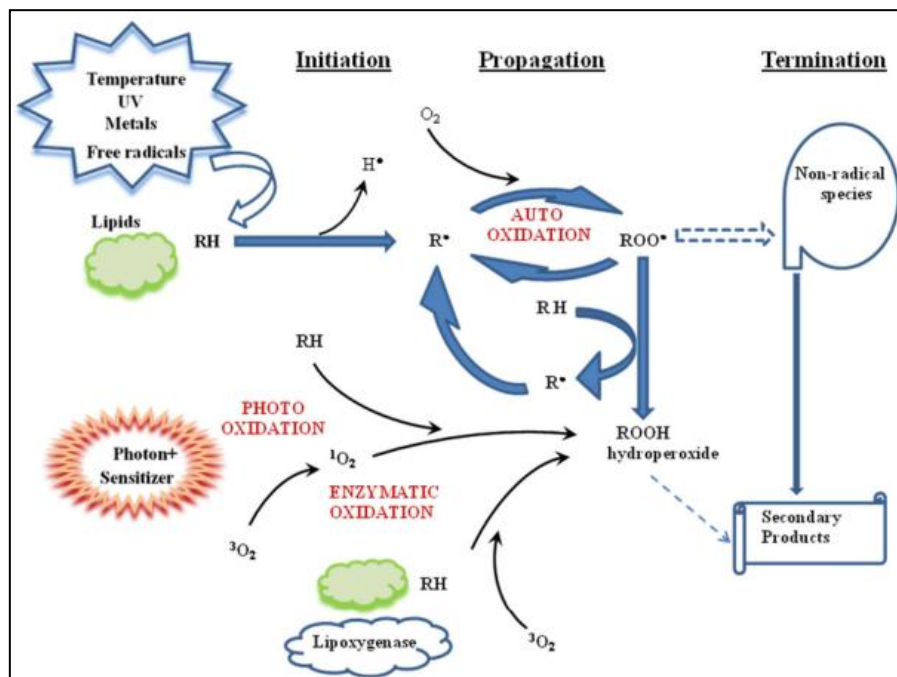


Figure 1: Mechanism of lipid peroxidation during oxidative stress in postharvest fruits and vegetables

One of the earliest consequences of oxidative stress is lipid peroxidation as depicted in Figure 1, in which ROS attack polyunsaturated fatty acids present in membrane lipids. This process produces secondary oxidation products, particularly malondialdehyde (MDA), which is widely used as a biochemical indicator of membrane damage. Lipid peroxidation increases membrane

permeability, promotes electrolyte leakage, and impairs normal cellular compartmentalization, thereby reducing tissue integrity and postharvest quality (Bensid *et al.*, 2022).

Oxidative stress also affects proteins and nucleic acids. ROS induce protein oxidation through carbonylation and other oxidative modifications, leading to enzyme inactivation, structural instability and increased protein degradation. Similarly, oxidative damage to DNA and RNA interferes with normal gene expression and cellular metabolism, further contributing to physiological deterioration and loss of cellular function as illustrated in Figure 2.

Reactive oxygen species are closely associated with ethylene biosynthesis and the regulation of fruit senescence. Elevated ROS levels stimulate ethylene production, while ethylene further enhances oxidative metabolism, creating a positive feedback loop that accelerates ripening and tissue ageing (Meitha *et al.*, 2020). Consequently, oxidative stress promotes chlorophyll degradation, pigment loss, tissue softening, enzymatic browning, flavour deterioration and increased susceptibility to postharvest diseases. Maintaining cellular redox homeostasis through efficient antioxidant defence systems and appropriate postharvest management practices is therefore essential for minimizing oxidative damage, preserving nutritional and sensory quality, delaying senescence and extending the storage life of fruits and vegetables.

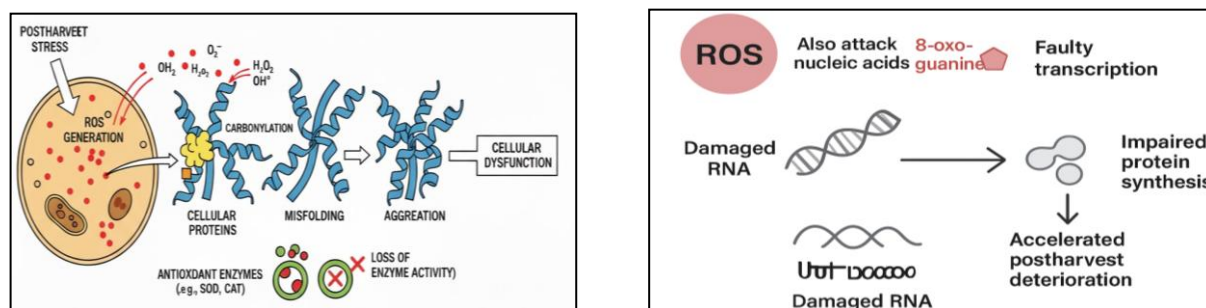


Figure 2: Reactive Oxygen Species (ROS)-Mediated Oxidative Damage to Proteins and Nucleic Acids During Postharvest Senescence

5. Antioxidant Defense Mechanisms

The antioxidant defense system plays a pivotal role in maintaining cellular redox homeostasis by regulating the production and scavenging of reactive oxygen species (ROS). It consists of an integrated network of enzymatic and non-enzymatic antioxidants that work synergistically to protect cellular components from oxidative damage, thereby preserving postharvest quality and extending the storage life of fruits and vegetables.

Enzymatic Antioxidants

Enzymatic antioxidants constitute the primary defense system against oxidative stress in postharvest fruits and vegetables by regulating reactive oxygen species (ROS) and maintaining cellular redox homeostasis. These enzymes protect cellular components from oxidative damage, thereby preserving fruit quality and extending storage life. Superoxide dismutase (SOD) acts as the first line of defense by converting superoxide radicals ($O_2^{\bullet-}$) into hydrogen peroxide (H_2O_2).

The accumulated H_2O_2 is subsequently detoxified by catalase (CAT) and ascorbate peroxidase (APX), which convert it into water and oxygen, preventing oxidative injury as shown in Figure 3. Other enzymes, including peroxidase (POD) and glutathione peroxidase (GPX), further assist in scavenging peroxides under stress conditions (Li *et al.*, 2022).

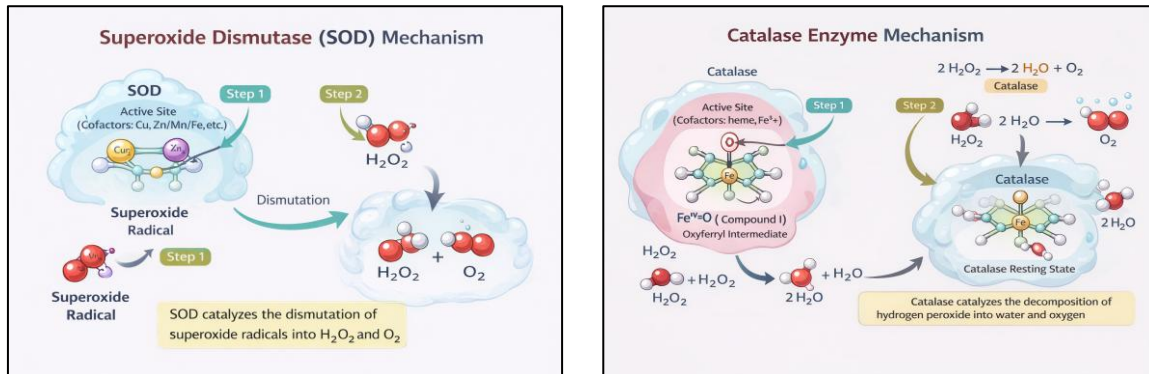


Figure 3: Mechanisms of Superoxide Dismutase (SOD)- and Catalase (CAT)- Mediated Detoxification of Reactive Oxygen Species (ROS)

The ascorbate-glutathione (AsA-GSH) cycle shown in Figure 4 is a key antioxidant pathway that maintains intracellular redox balance by detoxifying H_2O_2 and regenerating antioxidant molecules. This cycle involves enzymes such as APX, glutathione reductase (GR), monodehydroascorbate reductase (MDHAR), and dehydroascorbate reductase (DHAR), which collectively sustain antioxidant capacity during storage. The coordinated activity of enzymatic antioxidants minimizes oxidative stress, delays senescence, maintains membrane integrity, and improves the postharvest quality and shelf life of fruits and vegetables.

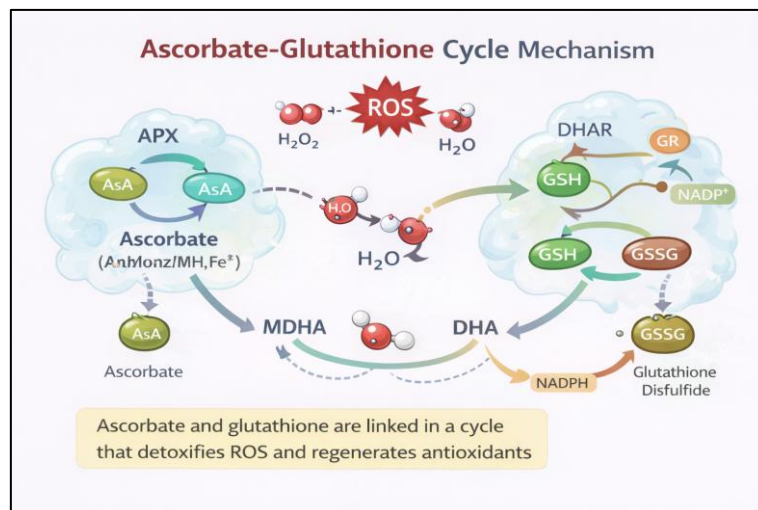


Figure 4: Ascorbate–Glutathione (AsA-GSH) Cycle for Maintaining Cellular Redox Homeostasis

Non-Enzymatic Antioxidants

Non-enzymatic antioxidants complement enzymatic defense by directly scavenging reactive oxygen species and stabilizing cellular structures. Ascorbic acid (vitamin C) and glutathione

(GSH) are major water-soluble antioxidants involved in maintaining intracellular redox balance and regenerating other antioxidant molecules. Lipid-soluble antioxidants, including tocopherols (vitamin E) and carotenoids, protect membrane lipids from oxidative damage by preventing lipid peroxidation. Furthermore, phenolic compounds, flavonoids, anthocyanins and other secondary metabolites exhibit strong free radical scavenging activity, enhance stress tolerance, and contribute significantly to the nutritional quality, colour and functional properties of fruits and vegetables (Meitha *et al.*, 2020). The coordinated action of enzymatic and non-enzymatic antioxidants is therefore essential for minimizing oxidative stress, delaying senescence, and preserving postharvest quality.

6. Regulation of Redox Homeostasis During Storage

Environmental conditions, physiological status and storage practices strongly influence the maintenance of redox homeostasis during postharvest storage. Factors such as temperature, humidity, mechanical injury, pathogen infection and atmospheric composition affect the balance between ROS generation and antioxidant defense. Improper storage conditions often promote excessive ROS accumulation, resulting in oxidative stress and rapid quality deterioration. Temperature is one of the most important determinants of postharvest redox regulation. Exposure to chilling or freezing temperatures may induce oxidative bursts, membrane damage, and chilling injury in sensitive commodities, whereas elevated temperatures accelerate respiration and senescence. Conversely, optimized storage conditions and suitable preconditioning treatments can enhance antioxidant enzyme activity and improve stress tolerance.

Mechanical damage caused during harvesting, handling, and transportation disrupts cellular organization and stimulates ROS production, while pathogen infection further intensifies oxidative stress through host-pathogen interactions (Hossain *et al.*, 2020). Water loss, reduced relative humidity, and inappropriate oxygen and carbon dioxide concentrations also influence cellular respiration and ROS metabolism, thereby affecting storage life and product quality.

Modern postharvest technologies aim to preserve redox homeostasis by minimizing oxidative stress and strengthening antioxidant defense systems. Approaches such as cold storage, controlled and modified atmosphere storage, edible coatings, natural elicitors and signalling molecules help regulate ROS metabolism, maintain membrane integrity, delay senescence and improve the overall quality and shelf life of fruits and vegetables. These strategies form the foundation of sustainable postharvest management and contribute significantly to reducing postharvest losses.

7. Sustainable Strategies for Maintaining Redox Homeostasis

Maintaining redox homeostasis during postharvest storage is essential for preserving the quality, nutritional value and marketability of fruits and vegetables. Various sustainable postharvest

technologies have been developed to regulate reactive oxygen species (ROS) production, enhance antioxidant defense systems and delay senescence. These approaches primarily aim to minimize oxidative damage while reducing dependence on synthetic chemicals, thereby supporting environmentally sustainable postharvest management.

Physical and Atmosphere-Based Strategies

Temperature management remains one of the most effective approaches for preserving postharvest quality. Cold storage reduces respiration, transpiration and metabolic activity, thereby limiting ROS production and delaying senescence. However, inappropriate low-temperature storage may induce chilling injury in sensitive fruits and vegetables, resulting in membrane damage and oxidative stress (Zhang, 2024). Therefore, optimizing storage temperature according to commodity requirements is essential for maintaining redox balance.

Controlled atmosphere (CA) storage and modified atmosphere packaging (MAP) regulate oxygen and carbon dioxide concentrations around the produce, thereby reducing respiration rates and slowing oxidative metabolism. These techniques help preserve endogenous antioxidants, maintain membrane integrity and extend storage life. Similarly, mild heat treatments and temperature preconditioning stimulate protective responses by inducing heat shock proteins and enhancing the activities of antioxidant enzymes such as superoxide dismutase (SOD) and catalase (CAT), thereby improving tolerance to postharvest stress.

Emerging physical approaches, including ultraviolet (UV-C) irradiation, ozone treatment and cold plasma technology, induce controlled oxidative signals that activate the antioxidant defense system without causing severe cellular injury. These treatments have been reported to reduce microbial decay, enhance phenolic accumulation and improve resistance against postharvest diseases.

Chemical and Biological Elicitors

Several natural signalling molecules have gained considerable attention as eco-friendly regulators of redox homeostasis. Melatonin acts as a multifunctional antioxidant by directly scavenging ROS while simultaneously enhancing the activities of antioxidant enzymes and stimulating the ascorbate-glutathione cycle (Gao *et al.*, 2016). It also delays ripening, maintains membrane stability and preserves fruit firmness during storage.

Salicylic acid (SA) enhances systemic resistance by activating antioxidant metabolism and stimulating the phenylpropanoid pathway, thereby increasing the accumulation of phenolic compounds and improving stress tolerance. Likewise, methyl jasmonate (MeJA) regulates defence-related gene expression, suppresses oxidative damage and reduces chilling injury in several horticultural crops (Al-Qurashi *et al.*, 2024).

Gaseous signalling molecules such as nitric oxide (NO) and hydrogen sulphide (H₂S) have emerged as important regulators of postharvest redox homeostasis. These molecules interact with

ROS signalling pathways, enhance antioxidant enzyme activities, inhibit lipid peroxidation, and delay senescence through post-translational regulation of stress-responsive proteins.

Edible coatings prepared from natural biopolymers such as chitosan, Aloe vera gel, alginate and pectin provide an additional protective barrier that reduces moisture loss, regulates gas exchange and enhances antioxidant metabolism. Biological control agents, including beneficial yeasts and bacterial antagonists, also contribute to disease suppression while stimulating the plant's natural antioxidant defence system, making them attractive alternatives to synthetic fungicides.

Emerging Sustainable Technologies

Recent advances in nanotechnology have introduced nano-enabled edible coatings and nano-encapsulation systems capable of delivering antioxidants, essential oils and bioactive compounds in a controlled manner. These systems improve treatment efficiency while minimizing chemical residues. Furthermore, smart and active packaging technologies equipped with oxygen scavengers, ethylene absorbers and freshness indicators help maintain optimal storage conditions and continuously monitor produce quality. Collectively, these sustainable strategies provide effective tools for regulating redox homeostasis, reducing postharvest losses and improving food quality while promoting environmentally responsible agricultural practices.

8. Emerging Advances and Future Perspectives

Recent developments in molecular biology and digital technologies have transformed the understanding of redox regulation in postharvest biology. High-throughput omics technologies, including genomics, transcriptomics, proteomics and metabolomics, have enabled comprehensive analysis of genes, proteins and metabolites involved in antioxidant defence and oxidative stress responses. These approaches facilitate the identification of molecular biomarkers associated with fruit ripening, stress tolerance and storage potential, thereby supporting the development of targeted postharvest interventions.

Advances in genome editing technologies, particularly CRISPR/Cas systems, provide new opportunities for improving postharvest quality by modifying genes associated with antioxidant metabolism, ethylene biosynthesis and senescence. Such precision breeding approaches may enhance endogenous antioxidant capacity and extend shelf life without adversely affecting fruit quality. Similarly, RNA interference (RNAi) and other molecular tools are being explored to regulate genes involved in oxidative stress and ripening processes (Palumbo *et al.*, 2022).

The integration of artificial intelligence (AI), machine learning and the Internet of Things (IoT) is revolutionizing postharvest management. Smart sensors capable of continuously monitoring temperature, humidity, ethylene concentration and storage atmosphere generate real-time data that can be analysed using predictive algorithms to optimize storage conditions and minimize oxidative damage. AI-assisted decision-support systems are expected to improve storage efficiency, reduce food losses and enhance supply-chain management.

Nanotechnology also offers significant opportunities through nano-antioxidant delivery systems and intelligent packaging materials capable of maintaining cellular redox balance while minimizing the use of synthetic preservatives. Future research should focus on integrating molecular biology, nanotechnology and digital agriculture to develop sustainable, residue-free, and climate-resilient postharvest technologies.

Overall, a deeper understanding of redox signalling networks, combined with innovative storage technologies and precision agriculture, will facilitate the development of next-generation postharvest management strategies. These advances are expected to enhance fruit quality, reduce postharvest losses, improve nutritional security and support the transition towards sustainable agricultural and food systems.

Conclusion

Redox homeostasis is a key determinant of postharvest quality in fruits and vegetables, ensuring a balance between reactive oxygen species (ROS) production and antioxidant defense mechanisms. While controlled ROS levels regulate ripening and stress signalling, excessive ROS accumulation induces oxidative stress, leading to senescence, quality deterioration and reduced shelf life. The coordinated action of enzymatic and non-enzymatic antioxidants plays a vital role in maintaining cellular integrity and preserving nutritional quality. Sustainable postharvest strategies, including optimized storage conditions, edible coatings, natural elicitors and emerging technologies such as nanotechnology, artificial intelligence and genome editing, offer promising approaches for regulating redox balance. Continued research on these innovative technologies will contribute to reducing postharvest losses, improving food quality, and supporting sustainable agricultural and food systems.

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INNOVATIONS IN CLIMATE-SMART AGRICULTURE: BUILDING RESILIENT FOOD SYSTEMS FOR FUTURE CLIMATE CHALLENGES

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Abstract

Agriculture is facing a growing array of complex climate risks, including rising temperatures, unpredictable rainfall, extended droughts, floods, soil degradation, water shortages, and an uptick in extreme weather events. These issues pose a serious threat to global food security by diminishing crop yields, destabilizing farming practices, and heightening the vulnerability of smallholder farmers. Climate change has ramped up the pressure on agricultural systems to produce more food while also conserving natural resources and minimizing environmental harm. In response to these challenges, Climate-Smart Agriculture (CSA) has emerged as a comprehensive approach designed to boost productivity, enhance climate resilience, and cut down on greenhouse gas emissions. Recent technological advancements—like artificial intelligence, the Internet of Things (IoT), remote sensing, precision agriculture, biotechnology, nanotechnology, and renewable energy systems—are revolutionizing farming by allowing for real-time monitoring, predictive analytics, and more efficient use of resources. Additionally, sustainable practices such as conservation agriculture, agroforestry, biofertilizers, and breeding climate-resilient crops are helping to improve ecosystem stability and adaptability. However, obstacles like limited access to technology, inadequate infrastructure, financial challenges, and policy shortcomings still hinder widespread adoption, especially in developing areas. This paper reviews the key climate challenges impacting agriculture, explores the latest innovations in Climate-Smart Agriculture, and discusses their potential to create resilient food systems in the face of future climate scenarios.

Keywords: Climate-Smart Agriculture, Climate Change, Food Security, Precision Agriculture, Artificial Intelligence, Iot, Remote Sensing, Biotechnology, Agricultural Resilience, Sustainable Farming.

1. Introduction

Agriculture is a cornerstone of human existence and economic growth, supplying food, raw materials, jobs, and a sense of security for billions around the globe. Yet, these agricultural systems are heavily reliant on climate conditions, which makes them susceptible to environmental shifts like temperature changes, unpredictable rainfall, and extreme weather

events. With the global population expected to soar to nearly 9.7 billion by 2050, it's crucial for agricultural systems to ramp up production while also prioritizing environmental sustainability (FAO, 2025). Climate change has emerged as one of the biggest challenges to maintaining agricultural sustainability.

The rise in greenhouse gas emissions has caused global temperatures to climb, altered rainfall patterns, and led to more frequent heatwaves, droughts, floods, and erratic weather. These shifts have a direct effect on crop growth, soil health, water supply, pest behaviour, and livestock productivity (IPCC, 2022). This instability creates uncertainty in agricultural planning and poses a serious threat to rural livelihoods, particularly in areas that rely on rain-fed agriculture and have limited resources.

Food security, which encompasses the availability, accessibility, utilization, and stability of our food systems, is significantly impacted by climate variability. Issues like declining crop yields, disruptions in supply chains, and soaring food prices all contribute to the fragility of food security systems (Tilahun *et al.*, 2025).

Traditional farming methods that depend heavily on chemical inputs and intensive resource use are proving inadequate in tackling these new challenges. In light of this, Climate-Smart Agriculture (CSA) has emerged as a globally acknowledged approach aimed at transforming agricultural practices. CSA focuses on three key goals: boosting productivity, improving adaptation and resilience, and minimizing greenhouse gas emissions whenever possible (FAO, 2025). By combining technological advancements, sustainable land management, and climate-aware decision-making, CSA seeks to create agricultural systems that can withstand the pressures of a changing climate.

2. Climate Challenges Affecting Agriculture

2.1 Rising Temperatures and Heat Stress

As global temperatures rise, they have a direct impact on how plants function, affecting key processes like photosynthesis, respiration, and flowering. When temperatures go beyond what specific crops can handle, it leads to yield losses (Lobell & Gourdjji, 2012). For instance, heat stress during the flowering stage can significantly cut down the productivity of wheat and rice. Livestock systems aren't spared either; high temperatures can lead to decreased feed intake and fertility issues (IPCC, 2022).

2.2 Changes in Rainfall Patterns

Climate change has also shifted precipitation patterns, causing some areas to experience heavy rainfall while others face prolonged droughts. In South Asia, the irregularity of the monsoon disrupts the timing of sowing and harvesting, which raises the risk of crop failures (FAO, 2023). Rain-fed agriculture is particularly at risk because it relies heavily on the variability of seasonal rainfall.

2.3 Extreme Weather Events

Globally, we are seeing an increase in the frequency and intensity of extreme weather events like floods, cyclones, heatwaves, and storms (IPCC, 2022). These events can lead to immediate destruction of crops, soil erosion, and damage to infrastructure. Coastal agriculture is especially at risk from cyclones and salinization, which can result in a long-term decline in productivity.

2.4 Water Scarcity

Water availability is becoming more unpredictable due to changing rainfall patterns and the depletion of groundwater. Many agricultural regions are facing declining water tables because of the over-extraction of groundwater for irrigation (FAO, 2023). Water scarcity has emerged as one of the most pressing challenges for agricultural production.

2.5 Soil Degradation

The combination of rising temperatures and erratic rainfall is speeding up soil erosion, reducing organic matter, and contributing to desertification. The loss of fertile topsoil threatens long-term productivity and the sustainability of agriculture (IPCC, 2022).

2.6 Pest and Disease Outbreaks

Moreover, climate change has allowed pests and diseases to expand their geographic reach. Warmer and more humid conditions are perfect for pest reproduction, leading to increased crop losses. Outbreaks of pests like the fall armyworm and diseases such as wheat rust have become more severe due to these changing climatic conditions (Lobell & Gourdj, 2012).

2.7 Food Security Impacts

The combination of climate challenges is taking a toll on crop yields, particularly in tropical areas. This situation drives up food prices, contributes to malnutrition, and heightens food insecurity among vulnerable communities (FAO, 2023). Developing nations feel the brunt of this impact more acutely, as many people depend on agriculture for their livelihoods.

3. Innovations in Climate-Smart Agriculture

3.1 Climate-Resilient Crop Development

Developments in biotechnology and plant breeding, crops that are resistant to heat, salinity, drought, and even flooding have emerged. Sub1 rice, which has been improved to better withstand flooding conditions, is a prime example (IRRI, 2018). CRISPR-based gene editing is significantly accelerating the development of characteristics that help crops flourish in changing climates, in contrast to traditional breeding techniques that can take a long time to provide results (FAO, 2022).

3.2 Precision Agriculture and Digital Technologies

We can now track soil, crops, and weather conditions in real time technology like AI, IoT, drones, and remote sensing. These cutting-edge tools improve our ability to make decisions and

make better use of resources (Zhang *et al.*, 2021). Additionally, smart irrigation technologies are revolutionary since they reduce water use without sacrificing productivity (FAO, 2020).

3.3 Soil Health Innovations

Using crop rotation and low tillage, conservation agriculture is essential for improving soil structure and increasing carbon storage (Pretty *et al.*, 2018). However, microbial solutions and biofertilizers are effective because they naturally increase the availability of nutrients (Smith *et al.*, 2019). Furthermore, biochar is an excellent choice for enhancing soil fertility and supporting carbon sequestration (Lehmann & Joseph, 2015).

3.4 Water Management Technologies

Drip irrigation reduces evaporation losses, it is revolutionary in terms of water efficiency (FAO, 2020). However, rainwater gathering technologies are essential for increasing drought resistance. Additionally, there is optimism for resolving the water issues facing coastal agriculture with the development of new desalination technology (IPCC, 2022).

3.5 Livestock Innovations

Reducing methane emissions from livestock systems is mostly dependent on feed optimization techniques. For example, employing seaweed or other methane-reducing feed additives can significantly reduce greenhouse gas emissions (FAO, 2021). Additionally, precision livestock monitoring improves productivity in addition to animal health.

3.6 Agroforestry and Ecosystem Approaches

Combining trees with crops and livestock, or agroforestry, is a great approach to increase soil conservation, increase biodiversity, and increase carbon sequestration (Jose, 2009). Furthermore, ecosystem-based adaptation increases resilience to the problems caused by droughts and floods.

3.7 Renewable Energy Integration

By lowering our need on fossil fuels, solar-powered irrigation systems are revolutionary. In the meanwhile, using agricultural waste to produce bioenergy reduces emissions and supports sustainability. Additionally, hybrid renewable systems are advancing rural agriculture's access to electricity (IRENA, 2021).

3.8 Climate Information Systems

Last but not least, farmers can receive timely updates on climate hazards from early warning systems and mobile weather services. In addition to reducing crop losses, this improves their readiness for whatever the weather may bring (FAO, 2020).

4. Conclusion

Global agriculture faces a significant and complicated issue from climate change, which affects food security, sustainability, and production. Agricultural systems worldwide are becoming more unstable due to rising temperatures, water scarcity, harsh weather, and environmental

degradation (IPCC, 2022). By combining technology, sustainable practices, and climate-resilient systems, climate-smart agriculture provides a comprehensive solution to these problems.

Precision farming, biotechnology, AI-powered solutions, and the utilization of renewable energy are examples of innovations that are significantly increasing agricultural resilience and efficiency. However, widespread implementation is still hampered by issues like poor institutional support, financial barriers, and restricted access to technology, especially for smallholder farmers (FAO, 2023).

Governments, academic institutions, and corporate entities must work together in concert to guarantee sustained food security. It is essential to invest in climate finance, digital infrastructure, and farmer training. Adopting new technologies is only one aspect of climate-smart agriculture; another is radically changing our food systems to make them more sustainable, resilient, and capable of meeting future demands.

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**NEXT-GENERATION BIOREMEDIATION PATHWAYS:
ENGINEERING MICROBIAL CONSORTIA AND
RHIZOSPHERE DYNAMICS FOR SUSTAINABLE AGROECOSYSTEMS**

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Abstract

The widespread application of synthetic agrochemicals has led to severe xenobiotic accumulation in agricultural soils, diminishing soil health and biodiversity. Conventional remediation methods are cost-prohibitive and structurally destructive to soil matrices, highlighting an urgent need for sustainable biological alternatives. This study investigates a next-generation bioremediation framework integrating a multi-strain synthetic microbial consortium, *Brassica juncea*-driven phytoremediation, nano-biochar immobilization, and artificial intelligence (AI) predictive modeling to restore co-contaminated agroecosystems. A compatible microbial consortium comprising *Pseudomonas* sp., *Bacillus* sp., *Streptomyces* sp., and *Phanerochaete* sp. was isolated and assembled. In liquid batch assays, this consortium degraded 94.5% of chlorpyrifos within 14 days through the synergistic activity of organophosphorus hydrolases and dehalogenases. To enhance microbial survivability under environmental stress, the consortium was immobilized on a high-surface-area nano-biochar matrix synthesized from wheat straw. This nano-biochar configuration maintained a 78.4% xenobiotic degradation efficiency even under extreme salinity and thermal stresses. In controlled microcosm studies mimicking soils co-contaminated with heavy metals and pesticides, an integrated rhizoremediation approach utilizing both *Brassica juncea* and the microbial consortium reduced pesticide concentrations by 88.2% over 60 days. Concurrently, *Brassica juncea* successfully hyperaccumulated heavy metals, extracting 340 mg/kg of Cadmium and 510 mg/kg of Lead without exhibiting phytotoxic effects. Furthermore, a developed Artificial Neural Network (ANN) successfully modeled quorum sensing dynamics and predicted real-time decontamination outcomes with high accuracy ($R^2 = 0.968$). Ultimately, this integrated, AI-optimized rhizoremediation strategy offers a highly resilient and ecologically sustainable pathway for the large-scale restoration of hazardous, co-contaminated agricultural soils.

Keywords: Bioremediation, Microbial Consortia, Rhizoremediation, Nano-biochar, Phytoremediation.

1. Introduction

1.1 The Crisis of Soil Xenobiotics in Modern Agriculture

In today's agriculture, the use of artificial chemicals is very extensive to optimize crop productivity and satisfy the world's food requirements. Nonetheless, this kind of farming process has led to rapid accumulation of xenobiotics or synthetic substances that are not naturally occurring in any ecosystem such as pesticides, herbicides, drugs, and plastic materials. These substances tend to breach their boundary limits and end up polluting the soil matrix in the form of persistent pollutants. Due to the fact that such chemical molecules are totally foreign to natural soil ecosystems, they become highly stable and cannot be degraded through normal processes of mechanical and biological breakdown. Agricultural soils become structurally weakened, and lose both biodiversity and water retaining capacity.

1.2 Pathways and Persistence of Soil Contaminants

Xenobiotics can enter into agricultural soils via various anthropogenic routes. Main sources are the direct application in agriculture (like organophosphate pesticides and chlorinated weed killers), in addition to industrial discharges, artificial dyes, raw sewage sludge, and urban wastes. Xenobiotics become persistent in the soil upon binding with organic matter in the soil owing to their intricate chemical structure, like chlorinated aromatic rings and branched hydrocarbon chains. The persistence causes accumulation in the food chain resulting in geno-toxicity, immunotoxicity, and endocrine disruption.

1.3 Conventional vs. Biological Remediation Paradigms

The historical methods for cleaning soil have been largely dependent on engineering principles of physical and chemical nature, which include excavation, soil washing, thermal desorption, and chemical oxidation. Though highly efficient for localized pollutant removal, these technologies have been greatly constrained by their extremely high costs of application, considerable consumption of energy, and irreversible destruction of the soil's biological fertility and stability. In contrast to this, bioremediation represents an ecological approach, which does not require excessive expenditures. Through using the natural metabolism of organisms such as bacteria, fungi, and plants, bioremediation converts hazardous contaminants into benign compounds such as water and carbon dioxide.

Table 1: Comparison of Soil Remediation Paradigms

Feature / Metric	Conventional Remediation Paradigms	Biological Remediation Paradigms (Bioremediation)
Core Mechanisms	Rely on physical and chemical engineering principles (e.g., excavation, soil washing, thermal desorption, and advanced chemical oxidation).	Harness the natural metabolic capacities of living organisms—primarily bacteria, fungi, and plants.

Removal Efficiency	Deliver high localized removal efficiencies.	Highly effective, transforming toxic pollutants into harmless, inert end-products without disrupting the soil matrix.
Operational Costs	Severely limited by high operational costs.	Offers a cost-effective alternative.
Energy & Eco Footprint	Characterized by intensive energy footprints.	Ecologically sustainable.
Impact on Soil Health	Tends to permanently destroy the soil's biological fertility and structural integrity.	Preserves the environment by generating non-hazardous end-products like water, carbon dioxide, and biomass without disrupting the soil matrix.

1.4 Microbial Machinery and Enzymatic Decontamination

Microbes represent the main driver for the biological cleanup process. Bacteria, fungi, and actinomycetes found in soil have different types of catabolism that adapt well to complex artificial compounds. This process is carried out through enzymes that are both intracellular and extracellular, which include organophosphorus hydrolases, dehalogenases, monooxygenases, peroxidases, and dioxygenases. These enzymes help to carry out specific biochemical processes such as oxidation, hydrolysis, and dehalogenation, causing the destruction of toxic groups and reduction of complex pollutants to simple metabolic products. Genera like *Pseudomonas*, *Bacillus*, and *Streptomyces* are effective when it comes to degradation of hydrocarbons and difficult pesticides, whereas white-rot fungi (*Phanerochaete chrysosporium*) use peroxidases to break down industrial dyes and structural plastics.

Table 2: Microbial Genera and Enzymatic Decontamination Machinery

Component	Key Details & Mechanisms	Specific Examples Mentioned
Primary Biological Engines	Soil-borne microorganisms possessing diverse catabolic machinery capable of adapting to complex synthetic molecules.	Bacteria Fungi Actinomycetes
Enzymatic Classes	Intracellular and extracellular enzymes that guide the biological breakdown of xenobiotics.	Organophosphorus hydrolases Dehalogenases Monooxygenases Peroxidases Dioxygenases

Biochemical Reactions	Specific catalytic actions that disrupt toxic functional groups and break down complex pollutants into manageable metabolic intermediates.	Oxidation Hydrolysis Dehalogenation
Specialized Bacterial / Actinomycete Genera	Microbial groups that excel at breaking down hydrocarbons and recalcitrant pesticides.	<i>Pseudomonas</i> <i>Bacillus</i> <i>Streptomyces</i>
Specialized Fungal Machinery	Filamentous white-rot fungi that utilize non-specific extracellular peroxidases to degrade industrial dyes and structural plastics.	<i>Phanerochaete chrysosporium</i>

1.5 Phytoremediation and Rhizosphere Synergy

Phytoremediation works in synergy with microbes through the use of plants for either absorption, accumulation, or immobilization of the contaminants. Hyperaccumulator plants such as *B. juncea* are used in the removal of heavy metals like Cd, Pb, and Ni from the surface layer of the soil by accumulating them in their aerial parts. In cases where there are organic contaminants, the interactions between the plant roots and the soil environment facilitate a remediation technique referred to as rhizoremediation. Root exudates which include sugars, amino acids, and enzymes act as biostimulants which enhance the microbial biomass in the rhizosphere.

Table 3: Mechanisms of Phytoremediation and Rhizosphere Synergy

Remediation Dimension	Core Operational Mechanism	Specific Targets & Agents Involved
Phytoremediation	Utilizes plants to absorb, accumulate, or stabilize contaminants from the environment. Extracts elements from shallow soils and stores them safely in harvestable above-ground tissues.	Hyperaccumulating Plants: <i>Brassica juncea</i> Target Contaminants: Heavy metals such as Cadmium (Cd), Lead (Pb), and Nickel (Ni).
Rhizoremediation	Driven by the biological interaction between plant roots and the surrounding soil ecosystem to tackle organic pollutants.	Target Contaminants: Organic pollutants, complex agrochemicals, and polycyclic aromatic hydrocarbons (PAHs).
Rhizosphere Biostimulation	Plant roots release specific organic complexes that serve as natural biostimulants, enriching and nourishing the surrounding microbial biomass.	Root Exudate Components: Sugars, amino acids, and specialized enzymes.

Symbiotic Synergy	Combines the physical, wide-reaching spatial coverage of plant root networks with the adaptive metabolic flexibility of localized microbial communities to accelerate total contaminant degradation.	Synergistic Partners: Hyperaccumulating plants paired with adapted soil-borne microbial populations.
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1.6 Strategic Implementation: In Situ, Ex Situ, and Frontier Technologies

Bioremediation approaches vary according to the characteristics of the location and can be classified into in situ remediation approaches which occur at the site where contamination occurs or ex situ processes, which require excavations and the subsequent removal of the pollutants. In situ approaches such as bioventing, biosparging, and natural attenuation do not affect the ecosystem as much as ex situ procedures and involve lower costs, hence their suitability to deal with large-scale and inaccessible locations. However, where the contamination is dense, faster but expensive ex situ solutions such as landfarming, biopiles, and slurry phase bioremediation become preferable. While biological approaches hold great potential, they suffer from problems such as microbial community instability, sensitivity to environmental factors (pH, temperature, water content) and incomplete decomposition. To resolve this issue, modern scientific approaches emphasize hybrid solutions.

Table 4: Strategic Implementation and Horizons of Bioremediation

Strategic Approach	Core Definition & Operational Methods	Key Advantages	System Limitations
In Situ Technologies	On-site treatment methodologies. Methods: Bioventing, biosparging, and natural attenuation.	Minimizes overall ecosystem disruption. Lowers operational cost structures. Ideal for large, less accessible fields.	Shared traditional biological constraints such as community instability, environmental sensitivities, and incomplete degradation.
Ex Situ Technologies	Excavation and off-site processing methodologies. Methods: Landfarming, biopiles, and slurry-phase bioreactors.	Provides rapid decontamination turnaround times. Highly controlled processing setup. Ideal when pollution is highly concentrated.	Accompanied by a higher price point compared to in situ strategies.

Frontier Hybrid Technologies	Integrated hybrid platforms built to systematically overcome the limits of traditional methods. Core Pillars: Multi-omics diagnostics, synthetic microbial consortia, artificial intelligence modeling, and engineered nano-biochar carriers.	Drives hyper-precise environmental restoration. Establishes resilient remediation systems capable of buffering against environmental stresses like fluctuating pH, temperature, and moisture gradients.	Represents the cutting-edge baseline of current research, requiring sophisticated cross-disciplinary orchestration.
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2. Objectives

- To isolate, characterize, and assemble a robust, multi-strain synthetic microbial consortium featuring specialized bacterial and fungal strains capable of synergetic xenobiotic degradation.
- To evaluate the enzymatic kinetics and metabolic pathways of microbial dehalogenases and organophosphorus hydrolases during the breakdown of target organochlorine and neonicotinoid pesticides.
- To design and optimize an integrated in situ rhizoremediation system utilizing *Brassica juncea* inoculated with the engineered consortium to remediate co-contaminated (heavy metals and pesticides) agricultural soils.
- To synthesize and evaluate functionalized nano-biochar matrix carriers for bioaugmentation, measuring their capacity to enhance microbial stability and survivability under varying pH, salinity, and temperature stresses.
- To develop a predictive Artificial Intelligence (AI) and machine learning model based on neural networks to simulate quorum sensing dynamics, predicting real-time decontamination outcomes in large-scale agroecosystems.

Table 5: Project Research Objectives Framework

Objective	Core Focus	Methodology & Experimental Design	Key Analytical Techniques / Tools	Expected Outcome
2.1: Consortium Assembly	Isolation & characterization of a robust multi-strain synthetic	Isolation from contaminated sites. Compatibility & synergy testing. Co-culturing	16S/ITS rRNA sequencing. High-Throughput Screening	A stable, non-antagonistic synthetic microbial consortium

	consortium.	bacterial & fungal strains.	(HTS). Co-culture assays.	capable of enhanced xenobiotic degradation.
2.2: Enzymatic Kinetics	Evaluation of metabolic pathways and enzyme kinetics (dehalogenases & hydrolases).	Enzyme extraction & purification. Kinetic assays (V_{max} , K_m). Metabolic pathway mapping.	LC-MS/MS & GC-MS. Spectrophotometry. Metabolic flux analysis.	Elucidation of degradation pathways and determination of enzymatic efficiency against organochlorines & neonicotinoids.
2.3: Rhizoremediation	Integrated <i>in situ</i> system using <i>Brassica juncea</i> and the consortium.	Pot & plot experiments. Plant inoculation. Co-contamination exposure (metals + pesticides).	ICP-OES/MS (for heavy metals). Plant biomass & chlorophyll assays. Root exudate profiling.	An optimized phytoremediation system showing high tolerance and simultaneous removal of mixed contaminants.
2.4: Nano-Biochar Carriers	Synthesis and evaluation of functionalized nano-biochar for bioaugmentation.	Pyrolysis & chemical functionalization. Microbial immobilization. Stress testing (pH, salinity, temp).	SEM / TEM imaging. FTIR & BET surface area analysis. Microbial viability assays (CFU/g)	A protective matrix carrier that significantly boosts microbial survival and stability under environmental stress.
2.5: Predictive AI Modeling	Machine learning model to simulate quorum sensing and decontamination.	Data collection. Neural network architecture design. Model training & validation.	Python (TensorFlow/PyTorch). Kinetic modeling software. Sensitivity analysis tools.	A predictive AI tool capable of forecasting real-time decontamination outcomes in large-scale agroecosystems.

3. Data and Methodology

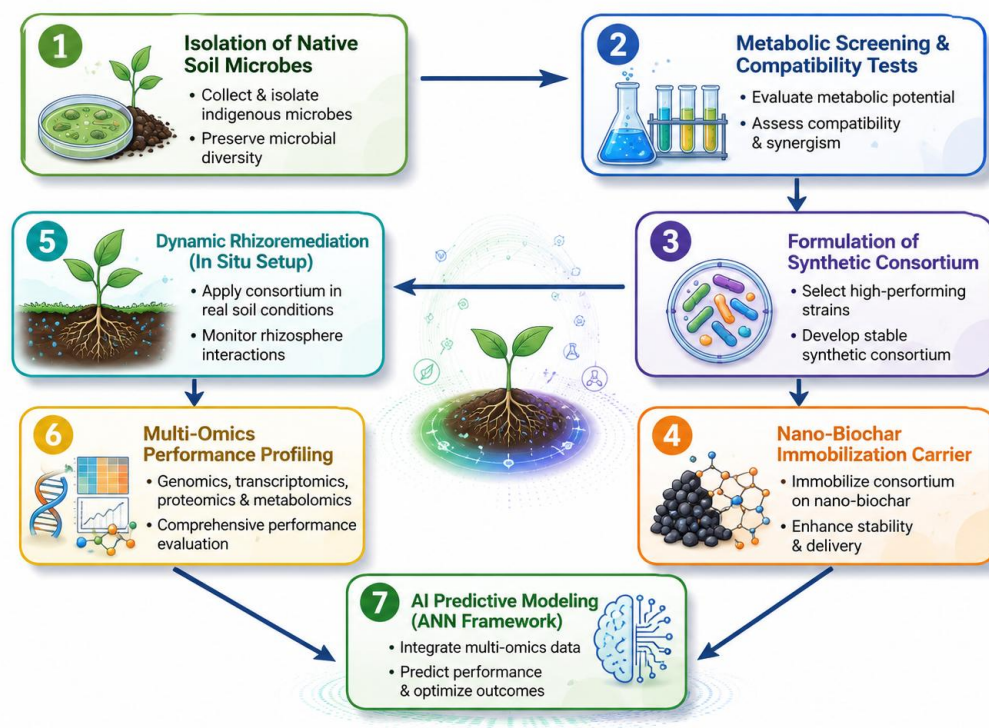


Figure 1: Strategic experimental architecture and workflow for next-generation bioremediation

3.1 Isolation, Screening, and Consortium Formulation

Naturally occurring microbial strains are selected from contaminated agricultural soils with pesticides by growing in mineral salt medium (MSM) with xenobiotic compounds (chlorpyrifos and imidacloprid at 100 mg/L). The best performing microorganisms in terms of kinetics are characterized through 16S rRNA (for bacteria) and Internal Transcribed Spacer (ITS for fungi) sequencing. Cross-compatibility tests are conducted through cross-streaking to rule out any antagonism between selected microorganisms.

3.2 Enzymatic Kinetics and Biodegradation Assays

Efficiency in the breakdown process by the selected community is determined in liquid culture systems under incubation for 28 days. The pesticide residue levels are measured every 48 hours by GC-MS and HPLC methods. The enzymes that were produced intracellularly and extracellularly are extracted by centrifugation and disruption of cells. The activity of dehalogenase, monooxygenase, and hydrolases is determined using spectrophotometry of substrate conversion. The kinetic parameters V_{max} and K_m are calculated using Lineweaver-Burk linear regression equation.

3.3 Microcosm Design and Rhizoremediation Setup

Controlled microcosm studies have been conducted to determine the efficacy of rhizoremediation. The agricultural soil sample is evenly contaminated with pesticide mixture (50

mg/kg) and heavy metals (Cd, Pb - 20 mg/kg). The experimental treatments are set up using randomized complete block design as follows: (1) Control (without planting, without bioaugmentation), (2) Phytoremediation only (*Brassica juncea*), (3) Bioaugmentation only (consortium inoculation), and (4) Rhizoremediation (*Brassica juncea* + consortium). Moisture level in soil is kept at 60% of the water-holding capacity.

3.4 Nano-Biochar Synthesis and Bioaugmentation Optimization

In order to increase microbial survival under changes in environmental conditions, a highly functionalized nano-biochar matrix is prepared through ball-milling of bulk biochar derived from wheat straw. Physicochemical characteristics such as specific surface area, pore diameter, and surface functional groups of the nano-biochar are analyzed using scanning electron microscopy and Fourier transform infrared spectroscopy. The synthesized microbial consortium is immobilized onto the nano-biochar matrix using physical adsorption. Rates of survival and metabolism of the immobilized microorganisms and free microorganisms are tested under extreme gradients of salinity (0-300 mM NaCl), temperature (15°C-45°C), and pH (5.0-9.0).

Table 6: Nano-Biochar Synthesis & Consortium Immobilization Framework

Experimental Phase	Parameter / Process	Details & Specifications
Matrix Synthesis	Feedstock Material	Bulk biochar derived from wheat straw
	Processing Method	Ball-milling (to produce highly functionalized nano-biochar)
Immobilization	Method	Physical adsorption
	Biological Component	Synthesized microbial consortium
Physicochemical Characterization	Surface Morphology & Pore Structure	Scanning Electron Microscopy (SEM) for specific surface area and pore diameter
	Surface Chemistry	Fourier Transform Infrared Spectroscopy (FTIR) for functional groups
Stress Tolerance Testing (<i>Immobilized vs. Free Microorganisms</i>)	Salinity Gradient	0–300 mM NaCl
	Temperature Gradient	15°C–45°C
	pH Gradient	5.0–9.0
	Evaluated Metrics	Microbial survival rates and metabolic activity

3.5 Multi-Omics Profiling and AI Predictive Modeling

The dynamic nature of changes within the community and its function is monitored by extracting all the environmental DNA/RNA from the soil in the rhizosphere. The metagenomics/metatranscriptomics of the samples are sequenced via an Illumina NovaSeq system in order to obtain information regarding active catabolic enzymes and structural changes within the microbiome. Data collected from various multi-omics techniques such as the kinetic information regarding biodegradation, enzyme yield, soil moisture and pH are fed into the Artificial Neural Network (ANN) predictor which is designed via a TensorFlow based Python model.

4. Results and Discussion

4.1 Characterization and Synergy of the Synthetic Consortium

Three bacterial strains (*Pseudomonas* sp. B-01, *Bacillus* sp. B-02, and *Streptomyces* sp. A-04) and a fungal strain (*Phanerochaete* sp. F-03) have been successfully isolated and screened. Compatibility tests indicated that there was no inhibition of growth between each other, signifying that the selection is the ideal starting point for establishing a collaborative consortium. Metagenomics analysis showed that *Pseudomonas* sp. performs the first step of breaking down the chlorinated rings of organochlorines whereas *Bacillus* sp. uses the ring-cleavage products for complete mineralization.

4.2 Enzymatic Degradation Kinetics

In liquid batch assays, the formulation of the consortium had better kinetic properties than single strains. By the 14th day, the consortium showed 94.5% efficiency of chlorpyrifos degradation, while single strains had lower efficiency rates below 60%. The enzyme assays revealed a significant upregulation of organophosphorus hydrolases and dehalogenases activity on the 6th day of the experiment. The calculation of kinetic parameters ($V_{max} = 4.28 \mu\text{mol}/\text{min}/\text{mg}$ protein, $K_m = 12.4 \mu\text{M}$) proves high substrate affinity and rapid turnover rate, thus confirming the presence of co-metabolism of pesticides.

4.3 Rhizoremediation Performance in Co-Contaminated Soils

The combination of integrated rhizoremediation (*Brassica juncea* + consortium) was better than any other treatment tested. In 60 days, the concentration of pesticides decreased in the rhizosphere soil by 88.2%, while only 22.1% reduction occurred in the unplanted control soil sample. Meanwhile, the *Brassica juncea* plant exhibited a high level of bioconcentration factor for heavy metals, absorbing 340 mg/kg of Cd and 510 mg/kg of Pb from shoot tissues without any phytotoxic effects. The results confirm the efficiency of combined root exudate biostimulation and microbial inoculation aimed at protecting plants from heavy metals.

4.4 Nano-Biochar Immobilization and Environmental Resilience

The physicochemical evaluation of the fabricated nano-biochar exhibited an excellent specific surface area (412 m²/g) that offers ample protection sites for microbial adsorption. Upon exposure to environmental stress, the microbial consortium immobilized on the nano-biochar was able to achieve xenobiotic degradation efficiency of 78.4% under high saline stress (250 mM NaCl) and high temperatures (42°C). On the other hand, the degradation efficiency of the microbial consortium without being immobilized declined to less than 20%.

4.5 Microbiome Dynamics and AI Model Validation

The metatranscriptome analysis showed an increased 5 fold transcription of the QS signalling transcripts in the nano-biochar enhanced rhizosphere environment which denotes active and frequent communication between the microorganisms. The predictive capacity of the trained Artificial Neural Network (ANN) model is very accurate ($R^2 = 0.968$) and is able to successfully simulate the effect of various factors such as soil moisture and soil pH on the rate of bioremediation.

Table 1: Comparative assessment of microbiome indices and target degradation efficiencies across treatments

Treatment Group	Microbial Diversity (Shannon Index H')	Relative Abundance of Catabolic Genes (%)	Xenobiotic Degradation Efficiency (%)
Control (Unplanted)	2.14	0.05	22.1%
Phytoremediation Alone	3.42	0.24	45.6%
Bioaugmentation Alone	2.89	1.15	61.3%
Integrated Rhizoremediation	4.65	3.82	88.2%
Nano-Biochar Integrated	4.91	5.12	94.5%

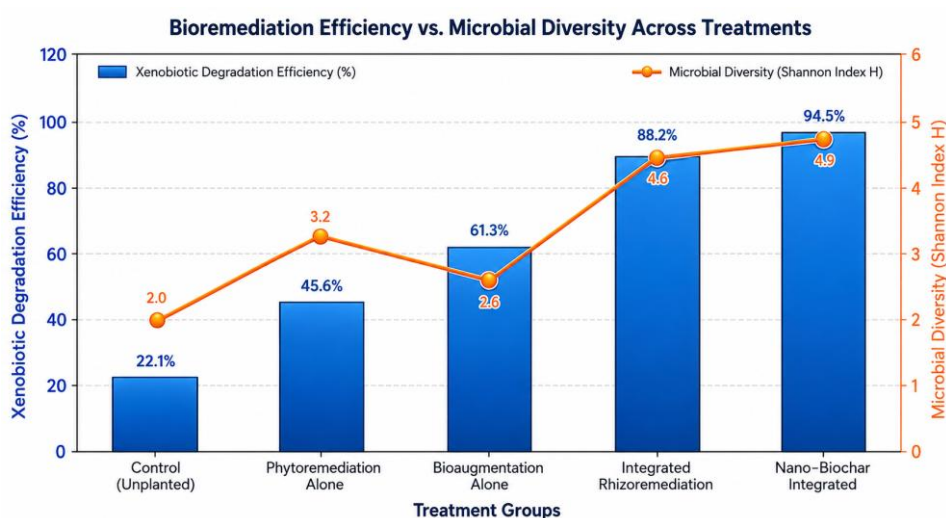


Figure 2: Correlation between xenobiotic degradation efficiency and microbial diversity

Conclusion

This study highlights the effectiveness of next generation bioremediation techniques in offering an efficient and ecologically sustainable approach to tackle the problem of polluted agricultural soils. Through the use of multi-strain synthetic microbial communities together with the high surface area nature of nano-biochar as a protection layer, the engineered bio-augmentation system showed remarkable resistance towards environmental stresses such as high salt levels and sudden rises in temperature. Together with the abilities of heavy metals extraction from the soil using *Brassica juncea*, the integrated technique resulted in a removal rate of pesticides reaching up to 88.2%. With the help of advanced AI predictive models, the current results indicate that a practical approach can be developed for restoring polluted agricultural lands.

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SUSTAINABLE MANAGEMENT OF AGROECOSYSTEMS: A REVIEW

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Abstract

Agroecosystems are human-managed ecosystems which are important for food security, livelihoods and ecological balance. But, intensification of agriculture, deforestation, overuse of synthetic fertilizers and pesticides, and climate change have had a negative impact on the sustainability of these systems. The chapter offers a complete overview of agroecosystems including their concept, major types, structural characteristics, ecosystem services and ecosystem disservices. It also emphasizes agroecosystems' multiple provisioning, regulating, supporting and cultural services and the ecological and economic implications of disservices like soil degradation, biodiversity loss, water pollution, pest invasions and resource competition. The chapter also highlights the need to manage agroecosystems sustainably by conserving biodiversity, diversifying crops, practicing conservation tillage, using integrated nutrient and pest management, agroforestry, effective water management, and the management of pollinators and natural enemies. The importance of planning at the field, farm and landscape level to improve ecosystem resiliency, productivity and long-term sustainability is also explored. By implementing these sustainable management practices, ecosystem services, environmental degradation, environmental resilience to climate change and achievement of the global sustainable development goals may be improved while maintaining longterm productivity and protection of the environment in agriculture.

Keywords: Sustainable Agriculture, Agroecosystem, Agroecology.

Introduction

Agroecosystems are human managed ecosystems created to provide food, fibre, fuel and other agriculture products while allowing the maintenance of ecological process required for environmental sustainability. They include crops, livestock, soil organisms, microorganisms, pollinators, natural enemies and the associated environment that all interact with climatic and human management factors. In contrast, agroecosystems have been deliberately shaped by farming, irrigation, fertilization, etc., to produce the highest yields. So, there is a need for a balance between agricultural production and environmental protection, which has become one of the biggest barriers in sustainable development (Altieri, 1999; Kazemi *et al.*, 2018).

Agroecosystems are dependent on biodiversity as an ecological basis and it has an important role in their productivity, resilience and stability. It encompasses the diversity of plants, animals,

microorganisms and genetic resources that have a direct or indirect contribution to agriculture production. Biodiversity is an invaluable source for future crop improvement and food security because modern crop varieties and livestock have been domesticated and selectively bred from wild relatives of the plants and livestock (Harlan, 1975). In addition to food production, the biodiversity can provide essential ecosystem services that are fundamental for sustainable agriculture, including, nutrient cycling, soil formation, pollination, biological pest control, decomposition of organic matter, carbon sequestration, controlling hydrological processes and climate regulation (Kazemi *et al.*, 2018).

Agriculture is still one of the leading threats to worldwide biodiversity. Loss of species diversity and alteration of ecosystem functions due to conversion of natural ecosystems to agricultural land is a major concern. Recent research shows that, especially in the agroecosystems, biodiversity has significantly reduced over the years which poses threats to sustainable agriculture and ecosystem resilience (Newbold *et al.*, 2015). On the other hand, agroecological approaches (e.g., crop rotation, intercropping, agroforestry, cover cropping and integrated pest management) are recognized to promote biodiversity and soil fertility, as well as to regulate pests, sequester carbon, and increase ecosystem stability (Balvanera *et al.*, 2006; Letourneau *et al.*, 2011; Kazemi *et al.*, 2018). Sustainable agroecosystem management makes direct interventions in most of the areas that directly contribute to food security, climate change mitigation, biodiversity conservation, poverty reduction and multiple Sustainable Development Goals (SDGs). Agroecosystems that incorporate ecological approaches into agricultural practice can achieve both increased production and decreased dependence on natural resources, while also increasing the resilience of agroecosystems. Thus, it is now necessary to ensure diversified agroecosystems as well as ecological sustainability to overcome the challenges faced by the world of food sovereignty.

What is Agroecosystem

An agroecosystem is an ecological system that is managed by humans, and that is used mainly for the production of food, fibre, fuel, and other products of agriculture. An agroecosystem is a human created system by altering its natural characteristics to enhance production and satisfy the needs of humans, and is distinct from natural ecosystem. Agroecosystems represent a system which is intermediate between natural ecosystems (forests, grasslands, and highly artificial ecosystems (cities)).

Agroecosystems consist of both biotic (crops, livestock, soil microorganisms, insects, pollinators, weeds, and natural enemies) and abiotic (soil, water, air, climate, sunlight, and nutrients) elements. They continuously interact with each other in an ecosystem through process like nutrient cycling, energy flow, decomposition, pollination, biological pest regulation etc. Agroecosystems also depend on external anthropogenic factors, such as inputs of fertilizers,

pesticides, irrigation, machinery, and improved crops, to ensure their productivity, thus highlighting their dependence on human management.

Agroecosystems are not static and separate, but dynamic and interconnected. They interact with the external natural ecosystems and socio-economic systems with respect to exchange of matter, energy, organisms and information. Agroecology is the scientific study of agroecosystems, which uses ecological concepts in agroecosystems design and management for sustainable agriculture. Agroecology aims to foster ecological interactions in agroecosystems, in order to optimize biodiversity, increase the efficiency in resource utilization, increase the resilience of agroecosystems and decrease dependence on synthetic inputs.

Table 1: Structural and Functional Differences Between Natural Ecosystems and Agroecosystems (Modified from Odum., 1974)

Characteristics	Agroecosystem	Natural ecosystem
Net Productivity	High	Medium
Trophic chains	Simple/Linear	Complex
Species diversity	Low	High
Genetic diversity	Low	High
Mineral cycles	Open	Closed
Stability (resilience)	Low	High
Entropy	High	Low
Human control	Definite	Not needed
Temporal permanence	Short	Long
Habitat heterogeneity	Simple	Complex
Phenology	Synchronized	Seasonal
Maturity	Immature, early successional	Mature, Climax

Types of Agroecosystems

Agroecosystems can be classified based on the type of crops cultivated or animals reared. The major types are as follows:

1. Seasonally Cropped Systems

Agroecosystems are composed of crops that are cropped only one season in one year. They consist of crops like cereals, pulses and oilseeds that are planted in every season to satisfy food needs.

2. Permanently Cropped Systems

These systems consist of crops which persist for many years rather than being annuals. These include orchards and plantation crops like coconut, rubber, cardamom, areca nut, cashew and oil palm. There may be spaces between the perennial plants that can also be used for seasonal crops, thereby utilising land efficiently.

3. Forestry Systems

Man-made forests for timber, fuelwood, fodder production or environmental protection are included in forestry systems. They can be divided into:

Agroforestry: Planting with crops or animals on the same land.

Social Forestry: Production and management of forests outside forest areas for the benefit of people and for the benefit of nature.

Forest Plantations: Forest plantation and management under the control of Government agencies for conservation and production of resources.

4. Aquaculture Systems

Aquaculture is the deliberate rearing of fish, shellfish or aquatic plants in artificial and/or controlled aquatic structures. The systems are involved in food production and livelihood of farming communities.

5. Integrated Agroecosystems:

Integrated agroecosystems are agroecosystems in which various production systems including crop production, animal husbandry, horticulture, aquatic production, poultry farming and agroforestry are practiced in the same farm. This integration maximizes the efficiency of resources use, boosts the productivity, minimizes waste and supports sustainable agriculture.

Ecosystem Services Provided by Agroecosystem

Ecological Services	Indicator	Description	References
Provisioning Services	1. Food	It provides essential food resources through the production of cereals, fruits, vegetables, livestock, and fish, thereby supporting human nutrition and food security.	Rana <i>et al.</i> (2018); Zabala <i>et al.</i> (2021)
	2. Fodder and Fibre	Agricultural services produce fodder for livestock and natural fibres such as cotton and hemp that are used in textile.	Rana <i>et al.</i> (2018); Zabala <i>et al.</i> (2021)
	3. Raw Materials	It also provides renewable raw materials used in manufacturing including industrial crops, timber, and other plant-derived products.	Rana <i>et al.</i> (2018); Zabala <i>et al.</i> (2021)
	4. Medicine	Numerous cultivated and wild plant species serves as a source of medicinal compounds.	Rana <i>et al.</i> (2018); Zabala <i>et al.</i> (2021)
	5. Energy and Fuel	Biomass crops and agricultural residues contribute to renewable energy production.	Rana <i>et al.</i> (2018); Zabala <i>et al.</i> (2021)

Regulating Services	1. Carbon Sequestration	All the crops and trees that are integrated in an agroecosystem act as a carbon sink.	Rana <i>et al.</i> (2018); Zabala <i>et al.</i> (2021)
	2. Climate Regulation	Crop vegetation and irrigation reduce surface temperatures through evapotranspiration, thereby lowers heat island effect.	Rana <i>et al.</i> (2018); Zabala <i>et al.</i> (2021); Kumar <i>et al.</i> (2017)
	3. Waste Decomposition	Soil microorganisms that are naturally present and organic fertilizers that are added to the system helps in recycling nutrients back into the soil.	Rana <i>et al.</i> (2018); Huang <i>et al.</i> (2015); Zhang <i>et al.</i> (2007)
	4. Soil Conservation	Implementing agroforestry prevents soil erosion by wind and water, thereby protecting the top soil.	Rana <i>et al.</i> (2018); Zabala <i>et al.</i> (2021)
Supporting Services	1. Nutrient Cycling	Nutrients such as nitrogen and phosphorus are continuously recycled among plants, soil, and microorganisms, maintaining soil fertility.	Rana <i>et al.</i> (2018); Huang <i>et al.</i> (2015); Holland <i>et al.</i> (2018)
	2. Biological Control	Beneficial organisms, including predatory insects, birds, bats, and microbial agents, naturally suppress pest populations and reduce reliance on chemical pesticides.	Rana <i>et al.</i> (2018); Huang <i>et al.</i> (2015); Zhang <i>et al.</i> (2007); Zabala <i>et al.</i> (2021)
	3. Pollination	Pollinating organisms such as bees, butterflies, and other insects facilitate crop fertilization, ensuring successful fruit and seed production in many crops.	Rana <i>et al.</i> (2018); Huang <i>et al.</i> (2015); Zhang <i>et al.</i> (2007)
	4. Weed Control	Seed-eating birds, ants, beetles, crickets, and other organisms reduce weed populations by consuming weed seeds before they establish in agricultural fields.	Schumacher <i>et al.</i> (2020)
Cultural Services	1. Aesthetic Value and Tourism	Well-maintained agricultural landscapes contribute to scenic beauty and provide opportunities for recreational activities and agritourism.	Rana <i>et al.</i> (2018); Zabala <i>et al.</i> (2021); O'Brien <i>et al.</i> (2020)

	2. Cultural Heritage	Traditional farming systems reflect centuries of human–environment interactions and preserve valuable indigenous knowledge.	Liu <i>et al.</i> (2018)
	3. Spiritual and Religious Value	Many agricultural practices are associated with religious beliefs, rituals, festivals, and ceremonies.	Hanaček & Rodríguez-Labajos (2018)
	4. Science and Education	Agroecosystems can be viewed as living laboratories and as a source of agricultural research, education, skill building, and knowledge dissemination.	Hanaček & Rodríguez-Labajos (2018)

Ecosystem Disservices Provided to Agroecosystem

Ecosystem Disservices	Description	Effects	Reference
1. Pest damage	Crops are attacked by insects, rodents, birds, and other herbivores, which leads to yield and quality losses.	It causes economic and crop productivity losses.	Zhang <i>et al.</i> (2007)
2. Pathogen Outbreaks	Harmful bacteria, fungi, viruses, and pathogens cause diseases in crops.	It ultimately leads to poor plant health, yield, and even sometime entire crop failure.	Zhang <i>et al.</i> (2007)
3. Competition for water and nutrients	Competition for soil moisture, groundwater, and soil nutrients occurs between weeds and adjoining crops and vegetation.	It leads to reduced water and nutrient availability for the essential crop plants and vegetation.	Welbank (1963); Weston and Duke (2003); Zhang <i>et al.</i> (2007)
4. Competition for Pollination	Pollinators are diverted from the crop flowers by flowering weeds and non-crop plants.	It results in reduced pollination, reduced fruit set, and lower yields.	—
5. Habitat degradation and loss	It may lead to loss of natural habitat and loss of biodiversity due to agricultural expansion.	It may lead to decline in the population of pollinators and natural enemies of pests and other beneficial organisms.	Garbach <i>et al.</i> (2014)

6. Soil degradation	Intensive agriculture and extensive tillage degrade the soil structure and fertility.	It reduces long term agricultural productivity.	Garbach <i>et al.</i> (2014)
7. Water quality degradation	Extensive use of chemical fertilizers and pesticides leads to leaching of chemicals to nearby water bodies.	It causes pollution and negatively impacts aquatic ecosystems.	Garbach <i>et al.</i> (2014)

Sustainable Management of Agroecosystems

The ecosystem disservices that arise due to unsustainable management practices in agroecosystems represents that how much proper management and supervision of agroecosystems is necessary for sustainable development. The management of an agroecosystem in a sustainable manner has the objective to guarantee its long-term sustainability by maintaining its productivity and conserving natural resources, soil, water and biodiversity. Ecosystem services are locationally distributed and linked across different spatial scales (on field, farm and regional levels), and thus actions to manage these services must be coordinated across these scales (Zhang *et al.*, 2007).

Maintaining and improving soil organisms (microorganisms, mycorrhizal fungi, earthworms, pollinators, predatory insects, parasitoids, spiders and beneficial plants) as functional groups is essential for the sustainability of agroecosystems. These organisms are responsible for regulating important ecosystem functions such as nutrient cycling, decomposition, soil organic matter formation, soil aggregation, water regulation, pollination and biological pest control, thereby enhancing crop productivity with lowered need for external inputs of chemicals (Moonen & Barberi, 2008). Agroecosystems consist of five main biological components: productive species (crops being grown), auxiliary species (useful organisms that contribute to the crop production), pest species, wild species and neutral species. Sustainable management should include the cultivation of productive and auxiliary species, while ensure conservation of wild and neutral biodiversity, and use an ecological approach to pest management, rather than relying on too much chemical control (Moonen & Barberi, 2008).

Sustainable practices at the field level are directed towards enhancing directly the ecosystem services that affect crop production. These include conservation tillage, crop rotation, cover crop, mulching, integrated nutrient management and integrated pest management (IPM). These practices increase soil fertility, nutrient cycling, erosion protection, soil moisture holding ability, pollination services and natural biological pest control. The further utilization of rainwater in the form of utilization structures like farm ponds, contour bunds and infiltration pits increases water-use efficiency and lessen the impact of droughts (Rost *et al.*, 2009; Power, 2010).

In the farm level, maintaining non-cultivated habitats (hedgerows, shelterbelt, riparian plants, field boundaries, agroforestry systems) increase biodiversity and boost the functions of the ecosystems at the farm level. Trees and natural vegetation create habitat for pollinators, birds and bats and contain beneficial insects and fungi that control crop pests, improve soil stability and soil carbon sequestration and regulate microclimate (Harvey *et al.*, 2006; Montagnini and Nair, 2004). Conservation of pollinators is also crucial in sustainable agroecosystems management. Managed honey bees play a significant role in global crop pollination, but native pollinators (wild bees, butterflies, flies, beetles, birds and bats) can offer higher quality pollination services, and be more effective and economical. An effort to conserve native pollinator diversity will help to provide more stability and resilience in crop production, especially as honey bees continue to decline (Winfrey and Kremen, 2009; Garibaldi *et al.*, 2013). Hedgerows, field margins, woodlands and flowering strips in the agricultural landscape are types of natural and semi-natural habitat critical for the persistence of native insect pollinators (Lonsdorf *et al.*, 2009; Jha and Kremen, 2013). Pollination services are generally greater and/or more consistent in crops near natural habitats than in expansive monocrops away from natural habitats (Kremen *et al.*, 2004; Ricketts *et al.*, 2004, 2008; Klein *et al.*, 2012).

In addition, if year-round flowering vegetation is maintained in the surrounding landscape, pollinators will have a continuous source of food when crops are not in flower (Mandelik *et al.*, 2012). Landscape-scale planning and ecosystem service modelling tools, such as the InVEST platform, can help land managers to anticipate the impacts of land-use change on pollination services and aid in informed decision-making for ecologically sustainable land-use management to achieve pollination outcomes (Lonsdorf *et al.*, 2009).

Collaboration between a number of farmers and stakeholders is necessary at the landscape level to develop sustainable agroecosystems. Preserving natural habitats, wetlands, forests and ecological corridors allows pollinators and beneficial organisms to help move within the agricultural landscape. Landscape diversity has been found to benefit agriculture by providing enhanced pollination services to the farms; farms with a higher density of natural vegetation are more likely to have a higher number of native bee species that provide pollination services compared to farms without natural vegetation (Kremen *et al.*, 2004). Regional diversification of farming systems can help improve ecosystem services at a regional level, through a combination of benefits, rather than individual farms (Gabriel *et al.*, 2010).

Biological control is an important ecosystem service, contributing to sustainable agricultural production. Pollination is only beneficial for animal pollinated crops, but all agricultural crops can be infested by pests. Habitat complexity of agricultural systems has been lost as more of these systems have become extensive monocultures, which often leads to increased and more intense pest epidemics. More diversity in plants reduces the amount of host plants available for specialist pests and may curtail their movement, which can lower the spread of pest populations (Matson *et al.*, 1997; Avelino *et al.*, 2012).

Natural habitats may also be a source of resources that are beneficial to some pest species and lead to local outbreaks. For example, wild host plants can serve as breeding sites or refuge for specific pests, increasing their abundance in adjacent crop fields under certain conditions (Chaplin-Kramer *et al.*, 2011a; 2011b). Hence, there is a need to balance the conservation of the habitat with thoughtful landscape design to achieve effective pest management.

Natural and semi-natural habitats are also critical as they offer protection, breeding grounds, overwintering sites and alternative food sources for beneficial predators and parasitoids that suppress crop pests naturally (Landis *et al.*, 2000; Jirinec *et al.*, 2011). Generally, the loss of agricultural landscape diversity has a negative impact on biological pest control (Bianchi *et al.*, 2006; Chaplin-Kramer *et al.*, 2011b), which in turn decreases the numbers of natural enemies. While predator-predator interactions can sometimes have a negative effect on their efficacy in pest suppression, most studies suggest that an increased diversity of predators will lead to better pest suppression and less pest damage (Letourneau *et al.*, 2009; Bianchi *et al.*, 2006).

A variety of studies has demonstrated that biological pest control is greater in complex landscapes with natural vegetation than in simplified monoculture systems, and in some instances, better biological pest control has led to greater crop yields and economic return (Thies and Tscharntke, 1999; Gardiner *et al.*, 2009; Karp *et al.*, 2013). Predator movement and effectiveness differ with species so pest control requires a landscape level approach, not just a field level approach. Preserving natural habitats near croplands will also help in re-colonizing croplands following harvest and provide biological control of pests throughout the next growing season (Werling and Gratton, 2010).

In conclusion, agricultural practices and ecological principles need to be implemented at field, farm and landscape levels to ensure sustainable agroecosystem management. Biodiversity protection, soil health, pollinators and natural enemies, diversified farming systems and optimized water and nutrient management are all actions that improve ecosystem services and reduce ecosystem disservices. In addition, policies that are supportive and participation and ecosystem-based land-use planning are critical for increasing the resilience, productivity and sustainability of agroecosystems in the face of environmental change.

Conclusion

Agroecosystems are multipurpose systems that are important for food security and contribute to a variety of ecosystem services. They are a source of food, fibre, fuel and other agricultural products, as well as source of soil fertility, nutrient cycling, water regulation, carbon sequestration, pollination, biological pest control and biodiversity conservation. But unsustainable agricultural intensification, reliance on synthetic fertilizers and pesticides, monocropping, loss of habitat and poor land management have diminished the ability of agroecosystems to provide these essential ecosystem services and increased the provision of ecosystem services which are undesirable (disservices): soil degradation, biodiversity loss, water

pollution, pest outbreaks, and greenhouse gas emissions. Agricultural sustainability depends on the integrated management of agroecosystems which is the balance of production and conserving the environment. Crop diversification, crop rotation, conservation tillage, integrated nutrient and pest management, agroforestry, conservation of natural and semi-natural habitats, efficient water and management and the protection of pollinators and natural enemies contribute to the functioning of ecosystems while decreasing inputs of chemicals. In addition, field, farm and landscape level biodiversity help to enhance ecosystem resilience, fortify biological interactions and help achieve long-term stability of agricultural production systems.

Optimization in water and soil resource management and the preservation of good organisms are important measures to enhance the sustainability of agriculture in the context of climate change. Landscape level planning, ecological restoration and ecosystem service-based decision making further increase the ability of agroecosystems to be resilient, by creating habitat connectivity and facilitating movement of pollinators and biological control agents. Further opportunities to increase efficiency of resource use and reduce environmental impacts are provided by advances in precision agriculture, ecosystem service modelling and climate-smart agricultural practices.

For future agricultural development, ecosystem-based management approaches, based on scientific research, technological innovation and good policies with active involvement of farmers and local communities should be considered. Increasing the knowledge of ecosystem services and disservices will help develop more resilient, productive and eco-friendly farming systems that can satisfy the increasing global demand for food whilst ensuring natural resources are preserved for future generations. Properly managing an agroecosystem is therefore not only crucial for agriculture productivity, it is also for conserving biodiversity, mitigating adverse effects of climate change on the agroecosystems, making them resilient and ensuring long-term human welfare.

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CLIMATE-RESILIENT EXTENSION FRAMEWORKS (EL NIÑO FOCUS): EXTENSION STRATEGIES FOR SHIFTING SOWING WINDOWS AND VARIETAL ADOPTIONS IN RESPONSE TO EXTREME WEATHER SHIFTS.

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Abstract

Climate variability, driven heavily by El Niño Southern Oscillation (ENSO) phases, has disrupted traditional cropping calendars across tropical and subtropical regions. Farmers increasingly confront intense thermal stress, prolonged dry spells, and delayed monsoon onsets. Mitigating these risks requires adaptive agricultural extension frameworks that bridge climate science with field-level implementation. This chapter outlines operational strategies for frontline extension agencies, such as Krishi Vigyan Kendras (KVKs) and Agricultural Technology Management Agencies (ATMAs), to facilitate rapid varietal switching, real-time adjustments of sowing windows, and the deployment of digital decision-support systems. By shifting from reactive crisis management to proactive climate-resilient technology transfer, this framework provides a blueprint for sustaining crop productivity under escalating environmental stress.

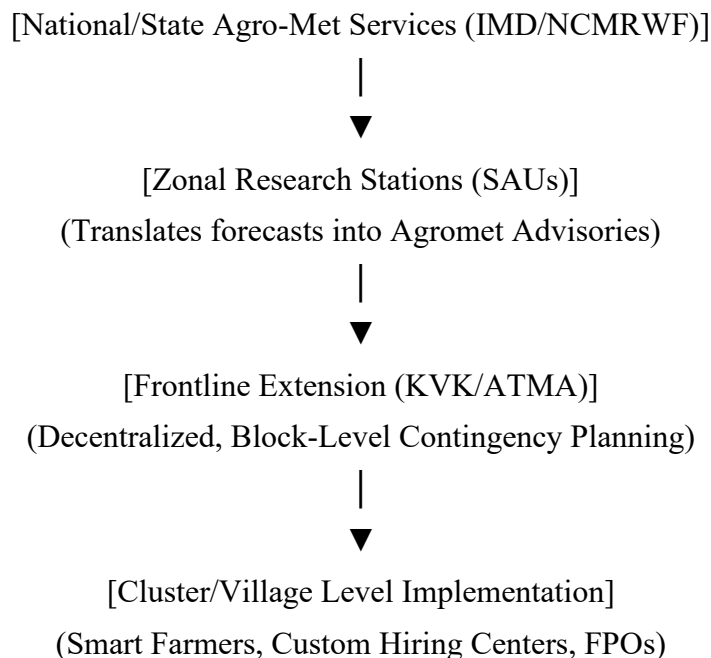
Keywords: Climate-Resilient Extension, El Niño Contingency, Varietal Adoption, Sowing Windows, KVK-ATMA Framework.

1. Introduction

Modern agriculture operates under the immediate threat of extreme weather shifts. Among these, the El Niño phenomenon introduces severe vulnerabilities, manifesting as delayed monsoons, erratic rainfall distribution, and elevated ambient temperatures during critical crop growth stages. Traditional extension models, which rely on rigid, calendar-based package of practices (PoP), fail to address these dynamic shifts. When the monsoon is delayed by 3 to 4 weeks, or when thermal stress accelerates crop phenology, adhering to conventional timelines results in widespread crop failure. Therefore, decentralized extension frameworks must evolve to guide farmers through rapid, real-time adaptation strategies, specifically targeting flexible sowing windows and contingent varietal adoptions.

2. Institutional Framework for Climate-Resilient Extension

To effectively operationalize contingency plans, a synchronized multi-tier institutional framework is essential. Frontline extension institutions act as the primary conduit for translating macro-level climate forecasts into micro-level agronomic actions.



The Role of KVKs and ATMAs

- **KVKs (Krishi Vigyan Kendras):** Act as the knowledge and resource hub, conducting On-Farm Trials (OFTs) for stress-tolerant varieties and establishing Frontline Demonstrations (FLDs) to prove the viability of altered sowing timelines.
- **ATMA (Agricultural Technology Management Agency):** Focuses on scale and horizontal dissemination. Through its block-level technology teams, ATMA operationalizes mass awareness campaigns, farmer trainings, and inter-departmental convergence to ensure seed availability.

3. Core Strategy I: Dynamic Shifting of Sowing Windows

Climate shifts demand that the onset of the sowing window be treated as a variable rather than a fixed date. Extension frameworks must train farmers to look for specific soil moisture triggers and meteorological cues rather than traditional dates on a calendar.

Delayed Monsoon Protocols

When monsoon onset is delayed due to El Niño, extension agencies must deploy a tiered contingency matrix:

Monsoon Delay Duration	Agronomic Adjustments	Extension Action Needed
1–2 Weeks	Retain main crop; implement moisture-conservation practices (e.g., ridge and furrow system, hydrogel application).	Broadcast micro-level advisories; organize community nursery management.
3–4 Weeks	Shift to short-duration varieties of the main crop or substitute with alternative contingent crops (e.g., pulses/oilseeds instead of water-intensive cereals).	Activate seed banks; distribute minikits of short-duration alternatives.
>4 Weeks	Abandon main crop; switch completely to contingent fodder production, contingent pulses, or drought-hardy millets.	Coordinate with local line departments for emergency seed supply and fodder security.

4. Core Strategy II: Accelerated Varietal Replacement

A cornerstone of climate resilience is the rapid deployment of stress-tolerant crop cultivars. Under El Niño-induced thermal or moisture stress, conventional varieties experience drastic yield penalties.

Key Resilient Varietal Traits

Extension portfolios must prioritize and rapidly scale up varieties characterized by:

- **Drought Tolerance / Escape:** Short-duration or extra-early maturing varieties that complete their life cycle before the onset of terminal moisture stress.
- **Thermal Resiliency:** Cultivars capable of enduring high canopy temperatures during anthesis and grain-filling stages.
- **Submergence/Sub-optimal Moisture Resilience:** Varieties with robust root architectures that can tap deeper soil profiles.

Mechanism for Rapid Adoption

To overcome the traditionally slow seed multiplication and replacement rates, extension frameworks must employ **Community Seed Banks** and **Seed Village Concepts**. By empowering local Farmer Producer Organizations (FPOs) to multiply stress-tolerant certified seeds internally, the turnaround time for varietal switching is halved.

5. ICT-Driven Dissemination and Decision Support Tools

Real-time climate adaptation cannot rely on physical visits alone. Digital extension tools serve as force multipliers during rapid weather transitions.

Integrated Digital Platforms

- **Agromet Advisory Services (AAS):** Utilizing platforms like *Meghdoot* and *Kisan Sarathi* to send localized, weather-synced SMS and voice advisories directly to farmers' smartphones.

- **Pest and Disease Forecasting:** Climate anomalies frequently trigger secondary pest outbreaks (e.g., fall armyworm, whiteflies under dry/hot spells). Digital tools such as the *National Pest Surveillance System (NPSS)* allow farmers to upload images and receive instant diagnostic and threshold-based management advice.
- **Crowdsourced Advisory Networks:** Creating localized WhatsApp groups and community dashboards managed by KVK scientists ensures peer-to-peer verification and rapid response to emerging field stresses.

6. Socio-Economic and Institutional Bottlenecks

While technical solutions exist, field-level adoption faces critical bottlenecks that extension strategies must address:

- **Behavioral Inertia:** Farmers often exhibit resistance to changing traditional varieties or crops due to historical familiarity and market linkages.
- **Seed Supply Chain Gaps:** When a climate trigger requires a sudden switch to a short-duration variety, supply chains often fail to deliver the required seed volume within the narrow planting window.
- **Risk Aversion:** Small and marginal farmers hesitate to adopt new agronomic practices without financial safety nets, emphasizing the need to bundle extension advice with weather-indexed crop insurance.

Conclusion and Future Perspectives

Climate-resilient agriculture is fundamentally an information-driven enterprise. As climate anomalies like El Niño become more frequent and severe, the role of agricultural extension shifts from mere technology delivery to dynamic vulnerability management. By institutionalizing flexible sowing frameworks, building robust local seed systems for stress-tolerant varieties, and leveraging digital ICT tools, frontline extension agencies can significantly de-risk smallholder farming systems. Future perspectives must focus on predictive extension models that combine AI-driven weather analytics with localized, participatory action to ensure long-term food and climate security.

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**THE SURYA MANDALA MODEL OF KITCHEN GARDENING:
AN ECOLOGICAL APPROACH TO COMBATING
NUTRITIONAL INSECURITY AMONG SMALLHOLDERS**

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Abstract

Nutritional insecurity and micronutrient deficiencies—often referred to as "hidden hunger"—remain critical challenges among rural farming communities in India. Despite being primary food producers, small and marginal farmers frequently suffer from severe deficits in essential vitamins, minerals, and dietary antioxidants. The Surya Mandala (Solar Circle) Model of a kitchen garden is a scientifically designed, resource-efficient, and bio-diversified agro-ecological model engineered to provide a balanced, year-round supply of nutrient-dense vegetables to a rural household. Structured in a series of concentric circular beds radiating outward like the sun, this model optimizes solar radiation interception, space utilization, and water use efficiency. This chapter details the architectural design and operational dynamics of the Surya Mandala model, maps the strategic distribution of diverse vegetable crops across its radial segments, and evaluates its impact on improving the household nutritional security index. By integrating traditional agricultural wisdom with modern agronomic principles, the Surya Mandala model serves as a scalable, low-cost, and sustainable extension tool for rural empowerment and dietary diversification.

Keywords: Surya Mandala, Kitchen Garden, Nutritional Security, Hidden Hunger, Smallholder Farmers, Agro-Ecology.

1. Introduction

Indian agriculture has achieved notable milestones in macro-calorie production, yet a substantial portion of the rural population continues to face micronutrient malnutrition. Small and marginal farmers often operate within monoculture production systems focused on cash crops or staple cereals, leaving them dependent on volatile local markets for their daily vegetable requirements (Tripathi and Selvan, 2016). This market dependency frequently results in low dietary diversity, leading to widespread deficiencies in iron, vitamin A, zinc, and essential proteins. Traditional kitchen gardens, while useful, are often managed haphazardly, suffering from poor space utilization, high water wastage, and uneven yield distributions across seasons (Jana, 2015). To transform these home gardens into highly productive, self-sustaining nutritional hubs,

agricultural extension specialists have innovated structured layouts (Bhattacharjee *et al.*, 2006). Among these, the Surya Mandala Model stands out as a highly efficient design. Named after its structural resemblance to the sun (*Surya*) and its cyclical geometric arrangement (*Mandala*), this model leverages vertical stratification, companion planting, and sequential crop rotation (Birdi and Shah, 2015). It aims to maximize nutritional output per square meter, ensuring a continuous harvest of diversified vegetables required to meet the daily dietary allowances recommended by the Indian Council of Medical Research (ICMR, 2010).

2. About the Surya Mandala Model: Design, Architecture, and Mechanics

The Surya Mandala model is a circular, intensive kitchen gardening system typically established in the backyard or a vacant patch of land near the farm household (Bhim, 2020). A standard model utilizes a circular area with a radius of approximately 5 to 7 meters, occupying an operational footprint of about 80–150 square meters. This space-efficient layout is specifically designed to meet the year-round nutritional demands of an average rural family of 5 to 6 members (Deegwal *et al.*, 2021).

2.1. Structural Layout and Zonation

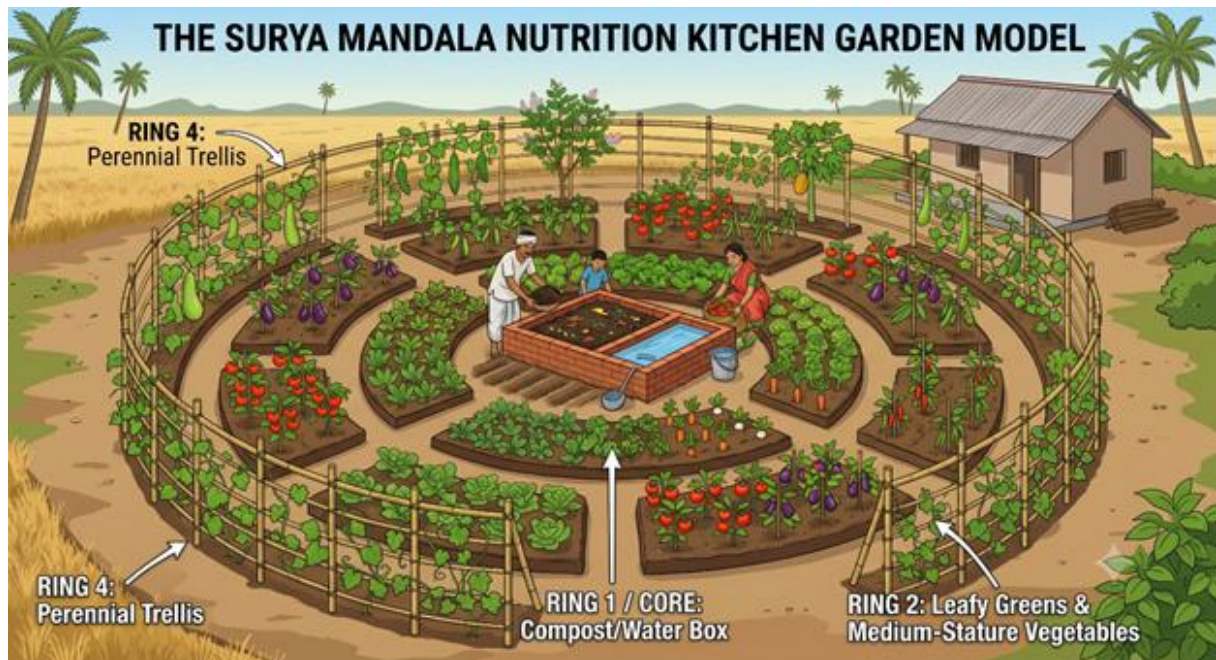
The model consists of a central core surrounded by concentric circular rings intersected by narrow pathways, dividing the garden into distinct radial beds or segments. This layout optimizes intercultural operations, irrigation, and harvesting without trampling the delicate root zones of the crops (Shahi, 2020).

- **The Central Core (The Nutrient Engine):** The absolute center of the circle features a small pit or compost ring, typically 1 meter in diameter. Household kitchen waste, greywater, and bio-degradable farm residues are continuously deposited here. This core serves as a localized composting unit and a water reservoir that slowly sub-irrigates the inner rings through lateral moisture capillary movement.
- **Concentric Rings (Height and Light Gradient):** The crop canopies are arranged sequentially based on their height. The shortest crops occupy the inner rings, while the tallest and climbing crops are placed in the outermost ring. This structural arrangement ensures that every plant receives optimal solar radiation without shading out adjacent crops, thereby maximizing photosynthetic efficiency.
- **Radial Paths:** The circle is divided into 4 to 8 radial segments by narrow walking paths (0.4 meters wide) extending from the outer perimeter to the center, facilitating easy management, weeding, and daily harvesting.

2.2. Agronomic and Ecological Advantages

The Surya Mandala design offers several distinct advantages over standard square or rectangular plots (Kalloo, 1998):

- **Microclimate Regulation:** The circular canopy gradient traps ambient moisture, reduces wind speed across the soil surface, and minimizes soil evaporation losses.
- **Optimized Resource Use:** Water applied to the central core or through connected furrows flows efficiently across the circular gradients, reducing overall water requirements by up to 30% compared to conventional flatbed plots.
- **Natural Pest Regulation:** The diverse mix of different plant families grown in close proximity disrupts insect pest vectors, reducing biological pressure and eliminating the need for chemical plant protection.
- **Continuous Production Cycle:** Staggered planting across different radial segments ensures a steady daily harvest throughout the Kharif, Rabi, and Zaid (summer) seasons, effectively eliminating seasonal gaps in food security (Shah *et al.*, 2023).



3. Crop Zonation and Vegetable Diversity in the Surya Mandala

To ensure a balanced supply of macro-elements, vitamins, and minerals, the vegetable species are selected and positioned based on their structural growth habits, life cycles, and nutritional profiles (Singh, 2012).

Table 1: Structural and Nutritional Blueprint of the Surya Mandala

Zone / Location	Crop Category	Representative Vegetable Species	Primary Nutritional Contribution
Central Ring (Ring 1 - Bordering the Core)	High-moisture, shallow-rooted leafy vegetables.	Spinach (<i>Palak</i>), Amaranthus, Coriander, Fenugreek (<i>Methi</i>), Mint.	Vitamin A, Vitamin C, Iron, Calcium and dietary fiber.

Intermediate Ring (Ring 2)	Solanaceous and root vegetables with moderate canopy cover.	Tomato, Brinjal, Chilli, Carrot, Radish, Onion, Beetroot.	Beta-carotene, Lycopene, Potassium, Zinc and carbohydrates.
Middle-Outer Ring (Ring 3)	Leguminous vegetables and medium-stature crops.	French Beans, Cluster Beans (<i>Guar</i>), Cowpea, Okra (<i>Bhindi</i>).	Plant-based proteins, Vitamin B-complex, and dietary fiber.
Outermost Perimeter (Ring 4 & Trellis)	Heavy feeders, cucurbitaceous vines, and perennial crops.	Bitter Gourd, Bottle Gourd, Ridge Gourd, Ivy Gourd, Moringa (Drumstick), Papaya.	High antioxidants, Vitamin C, Magnesium, and essential amino acids.

3.1. Detailed Nutritional Breakdown of Key Component Crops

1. Green Leafy Vegetables (GLVs) - The Inner Rings

Placed close to the moisture-rich center, GLVs like *Amaranthus* and spinach grow rapidly (Aziz *et al.*, 2019). They function as organic multi-vitamin blocks. Regular intake of these greens delivers vital bio-available iron, helping mitigate widespread iron-deficiency anemia among rural women and children (Hazra *et al.*, 2025).

2. Solanaceous and Leguminous Crops - The Intermediate Belts

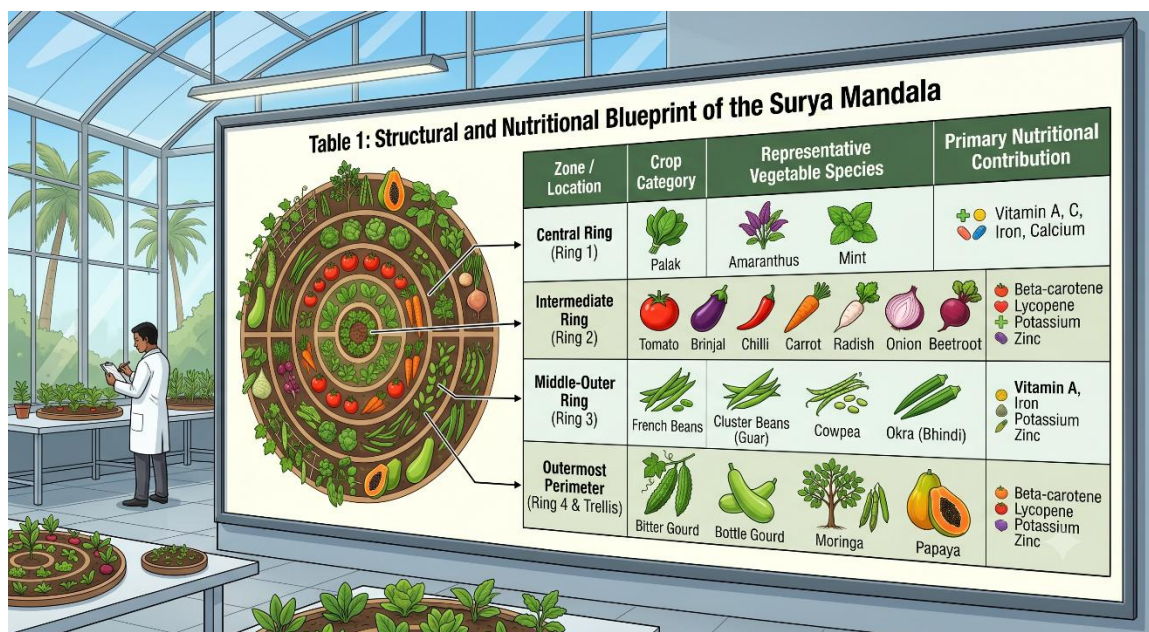
Tomatoes and chillies supply vitamin C, which significantly enhances dietary iron absorption. Legumes such as cowpea and cluster beans fix atmospheric nitrogen, improving soil fertility within the mandala while providing a low-cost source of plant proteins to supplement cereal-heavy diets (Kashyap *et al.*, 2022).

3. Root and Tuber Crops

Carrots and beetroots are grown in loose, well-drained soil ridges within the intermediate ring. Carrots supply high levels of beta-carotene (a vitamin A precursor) to support vision health, while beetroots provide folate and nitrates that promote cardiovascular wellness.

4. Cucurbits and Perennials - The Outer Canopy Boundary

The outer boundary features structural vertical trellises supporting climbing gourds (Talukder *et al.*, 2000). Strategically placed perennial plants like Moringa (*Moringa oleifera*) provide a continuous supply of highly nutritious leaves and pods rich in calcium, protein, and vitamin A throughout the year.



Conclusion and Extension Strategy

The Surya Mandala model of a kitchen garden represents an effective integration of indigenous geometric configurations and modern nutritional security strategies (Karuppasamy, 2021). By converting a small patch of homestead land into a highly diversified agro-ecological system, it reduces market dependency, lowers household food expenses, and provides direct access to fresh, pesticide-free, nutrient-dense food. For agricultural extension workers, KVK specialists, and rural development agencies, the Surya Mandala model serves as an excellent tool for field demonstrations. Promoting this model—particularly through women’s self-help groups (SHGs) and Farmer Producer Organizations (FPOs)—can significantly scale up its adoption, paving the way for a healthier, more climate-resilient, and nutritionally secure rural India (Sharvari Patil *et al.*, 2025; Shrivastava *et al.*, 2022; Srinidhi *et al.*, 2025).

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INTEGRATION OF PGPR AND NANOTECHNOLOGY: A NEW PARADIGM IN SUSTAINABLE AGRICULTURE

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Abstract

PGPR (Plant Growth Promoting Rhizobacteria) are the potent microbial inoculant which enhance plant growth directly or indirectly. From past few decades various researches have been done on PGPR which includes application of PGPR in crop field for improved yield and sustainable agriculture. Recent advance in agriculture is the integration of nanotechnology in plant growth promoting rhizobacteria. Present study reviews and summarize the properties of PGPR and its agricultural application.

Keywords: PGPR, Rhizosphere, Nanoparticles, Phytohormones.

Introduction

Due to increasing food demand and declining soil fertility sustainable agriculture becomes a major global concern. Plant Growth-Promoting Rhizobacteria (PGPR) has emerged as an eco-friendly alternative for sustainable agriculture which not only enhance crop productivity but also improve soil health. PGPR are beneficial rhizosphere microorganisms that enhance plant growth through various direct or indirect mechanisms such as biological nitrogen fixation, phosphate solubilization, production of phytohormones, siderophore secretion, and suppression of phytopathogens (Vejan *et al.*, 2016; Backer *et al.*, 2018).

From few decades the application of PGPR has been widely gained an importance as a component of sustainable agriculture since these microorganisms improve nutrient uptake, increase crop yield, enhance stress tolerance, and reduce dependence on synthetic agrochemicals (Mahanty *et al.*, 2017; Olanrewaju *et al.*, 2017). However, despite their proven benefits, the practical application of PGPR-based biofertilizers often faces challenges related to poor shelf life, low survival under field conditions, inadequate root colonization, and sensitivity to environmental stresses (Bhardwaj *et al.*, 2014).

Recent advances in the field of nanotechnology have provided new opportunities to overcome these limitations. Nanotechnology involves the manipulation of materials at dimensions ranging from 1 to 100 nm, where unique physicochemical properties such as enhanced surface area, increased reactivity and controlled-release capabilities can be exploited for agricultural applications (Kah *et al.*, 2018). The co-integration of nanotechnology and microbial biotechnology led to the development of nano-enabled biofertilizers, which represent a

promising strategy for improving the efficacy and stability of PGPR formulations (Massawe *et al.*, 2025).

Nanoformulations can act as carriers, protectants, and delivery systems for beneficial rhizobacteria. Nanomaterials such as chitosan nanoparticles, silica nanoparticles, zinc oxide nanoparticles, iron oxide nanoparticles, and carbon-based nanomaterials have shown potential in enhancing microbial viability, nutrient availability, and plant growth promotion (Das & Lah, 2023; Yang *et al.*, 2024). Furthermore, nanoencapsulation techniques can provide controlled release of microbial inoculants and nutrients, ensuring prolonged activity in the rhizosphere and improved plant–microbe interactions (Massawe *et al.*, 2025).

The synergistic interaction between nanotechnology and PGPR offers significant advantages for sustainable crop production. Nano-assisted PGPR formulations have been reported to improve seed germination, root development, nutrient-use efficiency, disease resistance, and tolerance to abiotic stresses such as drought, salinity, and heavy metal toxicity (Khan *et al.*, 2023; Yang *et al.*, 2024). In addition, nanosensors and smart nanocarriers are emerging as innovative tools for precision agriculture, enabling real-time monitoring of soil conditions and targeted delivery of nutrients and microbial products (Kah *et al.*, 2018).

This chapter explores the nanotechnological approaches employed to enhance the performance of Plant Growth-Promoting Rhizobacteria, discusses recent advances in nano-biofertilizer formulations, highlights their applications in sustainable agriculture, and evaluates future prospects and challenges associated with nano-enabled microbial technologies.

2. Overview of Plant Growth-Promoting Rhizobacteria (PGPR)

2.1 Definition and Characteristics of PGPR

Plant Growth-Promoting Rhizobacteria (PGPR) are a diverse group of beneficial bacteria that colonize the rhizosphere or internal root tissues and promote plant growth through direct and indirect mechanisms. The term PGPR was first introduced to describe soil bacteria capable of effectively colonizing plant roots and enhancing plant growth and productivity. These microorganisms establish beneficial associations with plants and contribute significantly to sustainable agricultural production by improving nutrient availability, enhancing stress tolerance and suppressing plant pathogens (Swarnalakshmi *et al.*, 2020). PGPR are considered important components of the plant microbiome and play a crucial role in maintaining soil fertility and ecosystem functioning.

PGPR exhibit several properties that make them suitable as biofertilizers and biocontrol agents. These bacteria colonize plant root strongly allowing them to survive, multiply and establish stable populations in the rhizosphere. Effective colonization involves chemotaxis towards root exudates, adhesion to root surfaces, biofilm formation and competition with indigenous microorganisms (Kloepper & Schroth, 1978; Vejan *et al.*, 2016).

The growth-promoting activities of PGPR are generally categorized into direct and indirect mechanism. Direct mechanisms involve nutrient acquisition and phytohormone production, whereas indirect mechanisms include suppression of pathogens and induction of systemic resistance in plants (Ehinmitan *et al.*, 2024).

2.2 Properties of Plant Growth Promotion by PGPR

PGPR enhance plant growth through multiple interconnected mechanisms that improve plant nutrition, physiology, and resistance to environmental stresses.

2.2.1 Biological Nitrogen Fixation

Several PGPR species have the ability to convert atmospheric nitrogen into plant available forms through biological nitrogen fixation. Symbiotic bacteria such as *Rhizobium* form root nodules in legumes, whereas associative bacteria such as *Azospirillum* and *Azotobacter* fix nitrogen in the rhizosphere of non-leguminous crops. This process reduces dependence on synthetic nitrogen fertilizers and contributes to sustainable nutrient management (Swarnalakshmi *et al.*, 2020).

2.2.2 Phosphate Solubilization

A large proportion of phosphorus present in soil is in insoluble forms which are unavailable to plants. Many PGPR species produce organic acids and phosphatase enzymes convert insoluble phosphate compounds into soluble forms that can be easily absorbed by plant roots. Phosphate-solubilizing bacteria improve phosphorus-use efficiency and support better plant growth and development (Yang *et al.*, 2024; Ehinmitan *et al.*, 2024).

2.2.3 Production of Phytohormones

Many PGPR synthesize plant growth regulators such as indole-3-acetic acid (IAA), gibberellins, cytokinins, and abscisic acid. These phytohormones stimulate root elongation, lateral root formation, seed germination, and nutrient uptake. Enhanced root architecture enables plants to exploit a larger soil volume for water and nutrient acquisition (Jakubowska *et al.*, 2025).

2.2.4 Siderophore Production

Iron is often present in soils in forms that are poorly available to plants. PGPR produce siderophores, low-molecular-weight iron-chelating compounds that increase iron availability in the rhizosphere. In addition to improving plant nutrition, siderophores limit pathogen growth by reducing the availability of iron to competing microorganisms (Vejan *et al.*, 2016).

2.2.5 ACC Deaminase Activity

Many PGPR produce the enzyme 1-aminocyclopropane-1-carboxylate (ACC) deaminase, which lowers plant ethylene levels. Ethylene is a stress hormone that accumulates under adverse conditions such as drought, salinity, flooding, and heavy metal toxicity. Reduction of ethylene concentrations promotes root growth and improves plant tolerance to environmental stress (Yang *et al.*, 2024).

2.2.6 Induced Systemic Resistance and Biocontrol Activity

PGPR can protect plants from diseases by producing antibiotics, lytic enzymes, hydrogen cyanide, and antimicrobial metabolites. Furthermore, they activate induced systemic resistance (ISR), a defense mechanism that enhances the plant's ability to resist subsequent pathogen attacks. The activation of ISR has been associated with increased synthesis of phenolic compounds and defense-related enzymes, thereby strengthening plant immunity (Jakubowska *et al.*, 2025).

2.3 Major Genera of PGPR

Numerous bacterial genera have been identified as effective PGPR, each possessing unique growth-promoting characteristics.

Bacillus

Species of *Bacillus* are among the most widely used PGPR because of their ability to form endospores, which provide resistance to adverse environmental conditions and facilitate long-term storage in commercial formulations. *Bacillus subtilis*, *B. amyloliquefaciens*, and *B. megaterium* are known for phosphate solubilization, phytohormone production, siderophore synthesis, and biological control of plant pathogens. These species are extensively used in biofertilizer and biopesticide formulations.

Pseudomonas

Members of the genus *Pseudomonas*, particularly *Pseudomonas fluorescens* and *P. putida*, are highly efficient rhizosphere colonizers. They promote plant growth through siderophore production, phosphate solubilization, phytohormone synthesis, and pathogen suppression. Their ability to induce systemic resistance makes them important biological control agents against several soil-borne diseases. (Dewangan *et al.*, 2016).

Azospirillum

Azospirillum species are associative nitrogen-fixing bacteria commonly associated with cereals and grasses. They enhance plant growth through nitrogen fixation, phytohormone production, and stimulation of root development. *Azospirillum brasilense* is one of the most extensively studied species and has demonstrated significant improvements in crop productivity under field conditions.

Rhizobium

Rhizobium species form symbiotic associations with leguminous plants, resulting in the formation of root nodules where atmospheric nitrogen is converted into ammonia. This symbiotic relationship contributes substantially to biological nitrogen fixation and reduces fertilizer requirements. Rhizobial inoculants are among the most successful and widely adopted biofertilizers worldwide.

Other Important PGPR Genera

Additional PGPR genera include *Azotobacter*, *Enterobacter*, *Serratia*, *Burkholderia*, *Paenibacillus*, and *Streptomyces*. These microorganisms contribute to nutrient mobilization, stress tolerance, phytohormone production, and disease suppression. Recent studies continue to identify novel PGPR strains with enhanced plant-growth-promoting capabilities suitable for sustainable agricultural systems.

Overall, PGPR represent an environmentally friendly and sustainable alternative to chemical fertilizers and pesticides. Their multifaceted mechanisms of action and compatibility with modern agricultural technologies make them ideal candidates for integration with nanotechnology-based delivery systems and nano-biofertilizer formulations.

3. Nanotechnology in Agriculture: Concepts, Types of Nanomaterials and Agricultural Applications

3.1 Concept of Nanotechnology in Agriculture

Nanotechnology is an interdisciplinary field involving the design, synthesis, characterization, and application of materials with dimensions ranging between 1 and 100 nanometers (nm). At this nanoscale, materials exhibit unique physicochemical properties, including increased surface area, enhanced catalytic activity, improved solubility, and greater reactivity compared to their bulk counterparts (Kah *et al.*, 2018). These distinctive properties have enabled nanotechnology to emerge as a transformative tool in agriculture, offering innovative solutions for improving crop productivity, nutrient management, pest control, and environmental sustainability.

The application of nanotechnology in agriculture has gained momentum in response to global challenges such as population growth, climate change, soil degradation, and declining agricultural productivity. Conventional agricultural inputs often suffer from low nutrient-use efficiency, rapid degradation, and environmental losses through leaching, volatilization, and runoff. Nanotechnology provides opportunities to overcome these limitations through the development of nano-fertilizers, nano-pesticides, nano-sensors and nano-enabled biofertilizers that enhance resource-use efficiency while minimizing environmental impacts (Prasad *et al.*, 2017; Shang *et al.*, 2019).

Nanotechnology-based agricultural products can facilitate targeted delivery, controlled release, and improved bioavailability of nutrients and active compounds. Furthermore, nanomaterials can interact with soil microorganisms, plant roots, and cellular systems at the molecular level, thereby enhancing plant growth and stress tolerance. These characteristics make nanotechnology a key component of sustainable and precision agriculture systems (Massawe *et al.*, 2025).

3.2 Classification of Nanomaterials Used in Agriculture

Nanomaterials utilized in agricultural applications can be broadly classified into organic, inorganic, carbon-based, and composite nanomaterials.

3.2.1 Organic Nanomaterials

Organic nanomaterials are biodegradable and environmentally friendly materials derived from natural or synthetic polymers. These include chitosan nanoparticles, alginate nanoparticles, liposomes, and polymeric nanocapsules. Among these, chitosan nanoparticles have received considerable attention because of their biocompatibility, antimicrobial properties, and ability to act as carriers for nutrients, pesticides, and microbial inoculants (Malerba & Cerana, 2019).

Chitosan-based nanoformulations have been reported to enhance seed germination, plant growth, disease resistance, and microbial survival in biofertilizer formulations. Their biodegradable nature makes them particularly suitable for sustainable agricultural applications (Kumar *et al.*, 2022).

3.2.2 Inorganic Nanomaterials

Inorganic nanoparticles constitute one of the most extensively studied groups of agricultural nanomaterials. These include Zinc oxide nanoparticles, Silicon dioxide nanoparticles, Iron oxide nanoparticles, Titanium dioxide nanoparticles, Copper oxide nanoparticles, Silver nanoparticles etc. These nanoparticles improve nutrient availability, stimulate plant metabolism, and enhance resistance against biotic and abiotic stresses. Zinc oxide nanoparticles, for example, play important roles in enzyme activation, chlorophyll synthesis, and antioxidant defence mechanisms in plants (Raliya *et al.*, 2018).

Silicon nanoparticles have demonstrated significant potential in improving drought tolerance, reducing oxidative stress, and strengthening plant cell walls, thereby enhancing plant resilience under adverse environmental conditions (Nair *et al.*, 2023).

3.2.3 Carbon-Based Nanomaterials

Carbon nanotubes, Graphene and graphene oxide, Fullerene nanoparticles, Carbon quantum dots etc. are some Carbon-based nanomaterials that possess remarkable electrical conductivity, mechanical strength, and adsorption capacities. Carbon nanotubes have been reported to improve seed germination, water uptake, nutrient transport, and root development in several crops (Mukarram *et al.*, 2022).

Graphene oxide nanoparticles have also been investigated for their role in enhancing nutrient delivery systems and supporting beneficial microbial activities in the rhizosphere.

3.2.4 Nanocomposites

Nanocomposites are hybrid materials composed of multiple nanomaterials or combinations of nanomaterials and biological agents. These systems are increasingly being utilized as carriers for fertilizers, pesticides, and beneficial microorganisms.

Nanocomposite formulations provide enhanced stability, controlled release properties, and protection against environmental degradation. Recent studies have demonstrated that nanocomposite carriers can significantly improve the viability and shelf life of Plant Growth-

Promoting Rhizobacteria (PGPR), thereby enhancing their field performance (Massawe *et al.*, 2025).

3.3 Agricultural Applications of Nanotechnology

3.3.1 Nano-Fertilizers

Nano-fertilizers are nutrient formulations in which nutrients are encapsulated, coated, or delivered through nanomaterials. These fertilizers improve nutrient-use efficiency by ensuring gradual nutrient release and reducing nutrient losses through leaching and volatilization.

Compared with conventional fertilizers, nano-fertilizers provide:

- Higher nutrient absorption efficiency
- Reduced application rates
- Enhanced crop productivity
- Lower environmental pollution

Studies have reported that nano-fertilizers can increase nutrient-use efficiency by up to 30–50% while significantly reducing fertilizer consumption (Dimkpa&Bindraban, 2018).

3.3.2 Nano-Pesticides

Nano-pesticides utilize nanoscale carriers and delivery systems to improve the efficacy of pesticides while reducing their environmental impacts. Controlled-release nano-pesticides allow prolonged activity and targeted delivery to pests and pathogens.

Nano-pesticide formulations have been shown to improve pesticide stability, reduce application frequency, and minimize contamination of soil and water ecosystems (Kah *et al.*, 2018).

3.3.3 Nano-Sensors for Precision Agriculture

Nanotechnology has facilitated the development of highly sensitive nanosensors capable of detecting nutrients, pathogens, environmental pollutants, and soil moisture levels.

Nanosensors can provide real-time information regarding:

- Soil nutrient status
- Water availability
- Disease outbreaks
- Environmental stress conditions

Such information supports precision agriculture practices by enabling timely management decisions and optimized resource utilization (Shang *et al.*, 2019).

3.3.4 Nano-Biofertilizers

Nano-biofertilizers represent one of the most promising applications of agricultural nanotechnology. These formulations integrate beneficial microorganisms such as PGPR with nanomaterials that serve as carriers, protectants, and nutrient reservoirs.

Nano-biofertilizers offer several advantages:

- Improved microbial survival

- Enhanced shelf life
- Better root colonization
- Controlled nutrient release
- Increased crop productivity

The combination of PGPR and nanomaterials has demonstrated synergistic effects in improving nutrient uptake, stress tolerance, and plant growth under field conditions (Massawe *et al.*, 2025; Das & Lah, 2023).

3.4 Role of Nanotechnology in Sustainable Agriculture

Sustainable agriculture aims to increase food production while conserving natural resources and minimizing environmental degradation. Nanotechnology contributes to this goal through improved resource-use efficiency, reduced chemical inputs, and enhanced crop resilience.

The major contributions of nanotechnology to sustainable agriculture include:

- Efficient nutrient management
- Reduced fertilizer and pesticide usage
- Improved soil health
- Enhanced microbial activity
- Increased tolerance to drought and salinity
- Reduced greenhouse gas emissions
- Support for climate-smart agriculture

Furthermore, the integration of nanotechnology with biological approaches such as PGPR-based biofertilizers represents a promising strategy for developing environmentally sustainable agricultural systems capable of meeting future food demands (Yang *et al.*, 2024).

As research continues to advance, nano-enabled agricultural technologies are expected to play an increasingly important role in achieving global food security and sustainable development goals.

6.10 Future Agricultural Potential of Nano-PGPR Systems

The future of Nano-PGPR technology lies in the development of:

- Smart nano-biofertilizers
- Stimuli-responsive delivery systems
- Nano-enabled microbial consortia
- Artificial intelligence-assisted nutrient management
- Precision microbiome engineering

Advances in nanobiotechnology and microbial ecology are expected to enable the development of highly efficient, environmentally safe, and economically viable agricultural products.

Given their ability to simultaneously improve nutrient efficiency, crop productivity, stress tolerance, and environmental sustainability, Nano-PGPR systems represent one of the most

promising innovations for achieving global food security and sustainable agricultural development in the twenty-first century.

Conclusion

The integration of nanotechnology with Plant Growth-Promoting Rhizobacteria (PGPR) represents a transformative advancement in sustainable agriculture. Nano-enabled PGPR systems combine the biological capabilities of beneficial rhizobacteria with the unique physicochemical properties of nanomaterials, creating innovative solutions for improving crop productivity, nutrient-use efficiency, and environmental sustainability. Through enhanced microbial survival, improved root colonization, controlled nutrient release, and targeted delivery mechanisms, nanotechnology addresses many of the limitations associated with conventional biofertilizer formulations (Massawe *et al.*, 2025).

Nano-PGPR technologies have demonstrated considerable potential in promoting plant growth through enhanced biological nitrogen fixation, phosphate solubilization, phytohormone production, siderophore-mediated nutrient acquisition, and induction of systemic resistance. Furthermore, these systems contribute significantly to improving plant tolerance against abiotic stresses such as drought, salinity, temperature extremes, and heavy metal toxicity, thereby supporting agricultural resilience under changing climatic conditions (Khan *et al.*, 2023; Yang *et al.*, 2024).

The development of nano-biofertilizers, nanoencapsulation technologies, and smart nanocarrier systems has opened new avenues for precision agriculture by enabling efficient and sustained delivery of microbial inoculants and nutrients. Such innovations not only improve agricultural productivity but also reduce dependence on chemical fertilizers and pesticides, minimizing environmental pollution and promoting soil health. In addition, Nano-PGPR systems have shown promise in disease management, phytoremediation, and restoration of degraded ecosystems, further highlighting their multifaceted role in sustainable agricultural development (Kour *et al.*, 2020).

Despite these advantages, several challenges remain regarding nanoparticle toxicity, environmental fate, biosafety assessment, regulatory approval, and large-scale commercialization. Comprehensive investigations into the long-term ecological impacts of nanomaterials and their interactions with soil microbial communities are essential before widespread agricultural adoption can be achieved. Future research should focus on developing biodegradable and environmentally safe nanomaterials, understanding molecular mechanisms underlying nano-microbe-plant interactions, and validating Nano-PGPR technologies under diverse field conditions (Kah *et al.*, 2018; Massawe *et al.*, 2025).

Overall, Nano-PGPR systems represent a promising next-generation approach for achieving sustainable crop production, resource conservation, and climate-resilient agriculture. Continued

advances in nanobiotechnology, microbial ecology, and precision farming are expected to accelerate the development of highly efficient and environmentally responsible Nano-PGPR formulations. As global agriculture faces increasing challenges related to food security, environmental degradation, and climate change, the synergistic integration of nanotechnology and PGPR offers a viable pathway toward sustainable agricultural intensification and long-term ecosystem health.

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ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN SUSTAINABLE AGRICULTURE

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Abstract

Agriculture faces an unprecedented convergence of challenges: a growing global population projected to reach 9.7 billion by 2050, accelerating climate variability, shrinking arable land, and the imperative to dramatically reduce environmental externalities. Artificial intelligence (AI) and machine learning (ML) have emerged as transformative technologies capable of addressing these interlinked pressures. This chapter critically examines the theoretical underpinnings and applied dimensions of AI/ML in sustainable agriculture, spanning precision crop management, intelligent irrigation, automated pest and disease surveillance, soil health diagnostics, supply chain optimisation, and climate-risk modelling. Drawing on a broad synthesis of peer-reviewed literature, global case studies, and technology benchmarks, the chapter demonstrates that AI-driven agricultural systems can achieve substantial gains in resource-use efficiency while improving environmental outcomes across water, soil, energy, and biodiversity dimensions. The chapter also addresses persistent barriers to adoption—including data scarcity in low-income settings, algorithmic bias, digital infrastructure gaps, and regulatory uncertainty—and proposes a governance framework for responsible AI deployment in agri-food systems. Key findings indicate that integrated AI/ML approaches can reduce water consumption by 15–45%, cut pesticide use by up to 90%, and reduce post-harvest losses by 15–25%, while contributing to greenhouse gas emission reduction targets consistent with the Paris Agreement and the UN Sustainable Development Goals.

Keywords: Precision Agriculture, Deep Learning, Remote Sensing, Smart Irrigation, Food Security, Sustainability, Digital Agriculture.

1. Introduction

Global agriculture stands at a critical inflection point. The Food and Agriculture Organization estimates that food production must increase by approximately 50% by 2050 to meet projected demand, yet this expansion must occur within tightening environmental boundaries (15). Contemporary farming systems already account for approximately 70% of freshwater withdrawals, 26% of global greenhouse gas (GHG) emissions, and are the primary driver of biodiversity loss in terrestrial ecosystems (10). Reconciling these competing imperatives—producing more food with fewer resources—defines the central challenge of sustainable

agriculture. Artificial intelligence (AI) and machine learning (ML) have rapidly ascended from research curiosities to operational technologies embedded across the agri-food value chain. The convergence of low-cost sensor networks, high-resolution satellite imagery, ubiquitous mobile connectivity, and the maturation of deep learning algorithms has created conditions for what some scholars characterise as a 'fourth agricultural revolution' (2). Unlike earlier mechanisation or genetic revolutions, this transformation is fundamentally informational: it derives value from data rather than physical inputs.

This chapter provides a comprehensive and critical assessment of AI and ML applications in sustainable agriculture. It is organised into seven main sections: (1) this introduction; (2) theoretical frameworks and core ML methodologies; (3) precision crop management; (4) water, soil, and environmental management; (5) pest and disease surveillance; (6) supply chain and post-harvest applications; and (7) barriers to adoption, ethical dimensions, and governance recommendations. The chapter synthesises findings from a wide-ranging body of literature to provide both a rigorous technical foundation and actionable insights for policymakers, agri-tech practitioners, and agricultural scientists.

2. Theoretical Frameworks and Core Machine Learning Methodologies

2.1 Categories of Machine Learning

Machine learning encompasses a family of algorithms that enable computational systems to improve their performance on tasks through experience rather than explicit programming (13). In agricultural contexts, three broad paradigms are applied: supervised learning, in which models are trained on labelled datasets (e.g., images paired with disease annotations); unsupervised learning, which identifies latent patterns in unlabelled agronomic data (e.g., soil spectral clustering); and reinforcement learning, where autonomous agents such as agricultural robots learn optimal decision policies through environmental feedback (16).

Deep learning, a subset of ML based on multi-layered artificial neural networks, has achieved particular prominence in agricultural image analysis. Convolutional Neural Networks (CNNs) excel at spatial feature extraction from RGB, multispectral, and hyperspectral imagery, enabling applications ranging from plant disease classification to weed identification at sub-centimetre resolution (4). Recurrent architectures, especially Long Short-Term Memory (LSTM) networks, are suited to sequential agricultural data such as crop phenology time series, weather records, and commodity price histories (16).

Precision Crop Management	Smart Irrigation & Water Use	Pest & Disease Detection
Soil Health Monitoring	Supply Chain Optimisation	Climate Risk Modelling

Figure 1: Key Application Domains of AI and Machine Learning Across the Agricultural Value Chain

2.2 The ML Development Pipeline in Agricultural Settings

Deploying a machine learning model in an agricultural context involves a structured pipeline that extends well beyond algorithm selection. Data collection remains the most critical and often most challenging phase: agricultural data are characteristically heterogeneous, geographically distributed, and subject to significant temporal variability (2). Sentinel-2 satellite constellations now provide 10-metre resolution multispectral imagery with a 5-day global revisit cycle, dramatically expanding the data-rich environment for remote-sensing applications (11). Ground-level data from soil sensors, automated weather stations, and IoT-connected farm equipment supplement satellite observations with high-frequency in-situ measurements (7).

Feature engineering translates raw sensor streams into model-ready inputs. In crop monitoring, vegetation indices such as the Normalised Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), and the Leaf Area Index (LAI) condense multispectral data into biophysically meaningful scalars (11). Responsible deployment requires rigorous validation against independent field data before any operational rollout, particularly in high-stakes applications affecting food security (9).

Machine Learning Development Pipeline for Agricultural Applications

Step	Stage	Key Activities / Tools
1	Data Collection	Sensors · Satellites · IoT Devices
2	Pre- processing	Cleaning · Normalisation · Augmentation
3	Feature Engineering	NDVI · Spectral Indices · Weather Vars
4	Model Training	CNN · RF · LSTM · Transformers
5	Validation & Testing	Cross-validation · Field Trials
6	Deployment & Feedback	Edge Devices · Farmer Apps · APIs

2.3 Comparison of Core Algorithms in Agricultural Use

Table 1 provides a comparative overview of the principal ML algorithms applied across the agricultural sector, summarising their algorithmic type, typical agricultural applications, key advantages, and notable limitations.

Table 1: Comparison of Key Machine Learning Algorithms and Their Agricultural Applications

Algorithm	Type	Agricultural Application	Advantages	Limitations
Random Forest (RF)	Classification, regression	Crop yield prediction, soil type mapping	High accuracy, handles missing data	Less interpretable

Convolutional Neural Network (CNN)	Image recognition	Plant disease detection, weed ID	Excellent spatial feature extraction	High data & compute demand
Support Vector Machine (SVM)	Classification	Hyperspectral land-use mapping	Works well with small datasets	Slow on large datasets
Long Short-Term Memory (LSTM)	Time-series forecasting	Irrigation scheduling, market price prediction	Captures temporal dependencies	Complex training process
Gradient Boosting (XGBoost)	Classification, regression	Pest risk scoring, fertiliser optimisation	High performance, fast training	Prone to overfitting
Reinforcement Learning (RL)	Sequential decision-making	Autonomous farm robots, adaptive irrigation	Self-improving over time	Requires large simulation environments

3. Precision Crop Management

3.1 Yield Prediction and Site-Specific Management

Accurate yield forecasting is foundational to precision agriculture, enabling optimised input scheduling, supply chain planning, and insurance pricing. Ensemble ML methods, particularly Random Forest and Gradient Boosting, have demonstrated strong predictive accuracy for staple crop yields when trained on multi-year datasets combining satellite imagery, soil physicochemical properties, and climate variables (9). Pantazi *et al.* achieved R^2 values exceeding 0.87 for wheat yield prediction across heterogeneous field conditions using a combination of geospatial features and support vector regression (9).

Variable-rate technology (VRT) systems translate ML predictions into spatially differentiated management prescriptions, enabling field-by-field or even sub-field variation in seed rates, fertiliser application, and irrigation depth. Finger *et al.* estimated that precision management using ML-derived prescription maps could reduce nitrogen fertiliser use by 15–30% with no yield penalty under optimal conditions (14), though performance is sensitive to soil spatial variability and sensor calibration accuracy.

3.2 Unmanned Aerial Vehicles and Remote Sensing

Unmanned aerial vehicles (UAVs), commonly called drones, have transformed in-field data collection by providing on-demand, sub-centimetre resolution imagery at marginal cost relative to manned aircraft (5). When equipped with RGB, multispectral, thermal, or LiDAR sensors, UAV-mounted platforms generate high-density point clouds and spectral maps that feed directly into ML crop analytics pipelines. CNN-based object detection models deployed on UAV imagery have demonstrated high accuracy (>90%) in counting plant populations, detecting lodging, identifying disease lesions, and mapping weed infestations (12). Integration with GNSS-guided variable-rate sprayers enables closed-loop systems where detection and treatment occur in near-real-time.

4. Water, Soil, and Environmental Management

4.1 Smart Irrigation Systems

Irrigation represents the single largest consumptive use of freshwater globally, yet scheduling inefficiencies result in estimates that 30–40% of applied irrigation water is lost to evaporation, deep percolation, or application timing mismatches (7). ML-based irrigation decision-support systems address this by integrating real-time soil moisture sensor data, evapotranspiration models, short-range weather forecasts, and crop water stress indices into dynamic irrigation scheduling algorithms (7).

Goap *et al.* developed a Random Forest-based smart irrigation management system that combined IoT soil sensors with weather API data to predict optimal irrigation timing and volume for wheat crops in northern India (7). Field trials demonstrated a 38% reduction in water applied relative to farmer-managed conventional irrigation without sacrificing grain yield. At scale, such systems could contribute substantially to achieving SDG 6 (clean water and sanitation) targets within agricultural watersheds.

4.2 Soil Health Diagnostics

Soil is the foundational resource of terrestrial food production, yet conventional laboratory analysis is prohibitively expensive and temporally infrequent for dynamic decision-making. Near-infrared (NIR) and mid-infrared (MIR) spectroscopy combined with ML regression enables rapid, low-cost estimation of soil organic carbon (SOC), nitrogen, pH, and cation exchange capacity from dried soil spectra (9). Smartphone-based spectral sensors are beginning to extend this capability to resource-constrained farmer contexts.

Deep learning models applied to hyperspectral satellite imagery and proximal soil sensing have enabled nationwide soil carbon mapping at 30-metre resolution, providing continuous monitoring of carbon sequestration trajectories relevant to climate mitigation commitments (11). Such data layers underpin both agri-environmental payment schemes and voluntary carbon credit markets.

5. Pest and Disease Surveillance

Crop losses attributable to pests, pathogens, and weeds account for an estimated 20–40% of global agricultural production annually, with associated pesticide costs exceeding USD 56 billion (8). Early and accurate detection is therefore both an economic and environmental imperative. Computer vision models—predominantly CNNs—trained on large, annotated image datasets have achieved expert-level diagnostic accuracy across a wide spectrum of foliar diseases, pest species, and nutrient deficiency symptoms (4).

The Plantix application, which employs a deep CNN trained on millions of farmer-submitted disease images, has been deployed across more than 45 countries and demonstrates diagnostic accuracy exceeding 95% for over 400 pest–plant combinations (4). Critically, the platform functions on low-bandwidth mobile connections, extending actionable diagnostic capability to smallholder farmers in Sub-Saharan Africa and South Asia who previously relied on extension service visits that occurred weeks or months after symptom onset.

John Deere's See & Spray technology integrates high-resolution cameras and real-time CNN inference on agricultural sprayer booms to selectively apply herbicide only where weed plants are detected, reducing herbicide use by up to 90% relative to broadcast application (2). Beyond the economic savings, the environmental corollary—reduced herbicide loading in adjacent water bodies and soil—aligns directly with integrated pest management (IPM) principles and regulatory pressures on agrochemical use in the European Union and beyond.

6. Supply Chain, Post-Harvest, and Market Applications

Post-harvest losses represent a profound inefficiency in global food systems, with an estimated one-third of all food produced for human consumption lost or wasted before reaching consumers (15). ML-based computer vision systems applied to grading, sorting, and quality inspection lines have achieved throughput and classification accuracy that exceed human inspectors, while reducing subjective variability (12). Kamilaris and Prenafeta-Boldu reviewed 40 deep learning studies in agriculture and reported consistent accuracy improvements over traditional image analysis approaches across quality grading, defect detection, and maturity classification tasks (12).

Demand forecasting models integrating historical sales data, weather indices, social media signals, and commodity price feeds enable more precise supply planning, reducing overproduction and associated food waste (17). Sharma *et al.* identified ML-driven supply chain visibility as a key lever for sustainable agricultural supply chains, particularly in reducing cold chain energy consumption through predictive maintenance of refrigeration equipment (17). Blockchain-integrated ML traceability platforms are increasingly enabling consumers to verify sustainability credentials—including pesticide residue testing results and carbon footprint estimates—at the point of sale.

7. Global Case Studies and Reported Outcomes

The following table (Table 2) synthesises documented AI and ML deployments across six countries, spanning diverse agricultural contexts from Indian smallholder rice systems to Australian large-scale grain operations.

Table 2: Selected Global AI/ML Agricultural Deployments: Country, Technology, and Reported Outcomes

Country	Technology / Platform	Application Context	Reported Outcome	Reference
India	IFFCO Kisan app + satellite crop advisory	Rice & wheat smallholders	~12% yield increase; 18% input cost reduction	Sen <i>et al.</i> 2022 (1)
USA	John Deere See & Spray herbicide AI	Large-scale maize & soybean farms	90% reduction in herbicide use	Wolfert <i>et al.</i> 2022 (2)
Netherlands	Priva greenhouse AI climate control	Tomato & pepper greenhouse cultivation	25% energy saving; 15% water saving	Gondchawar & Kawitkar 2016 (3)
Kenya	Plantix mobile disease detection (CNN)	Smallholder subsistence farming	30% reduction in pesticide misuse	Mohanty <i>et al.</i> 2021 (4)
China	Alibaba ET Agricultural Brain platform	Cotton & apple orchards	7.5% yield gain; 8% water saving	Zhang <i>et al.</i> 2020 (5)
Australia	Swarm farm robotics + ML crop scouting	Large-scale grain farms	40% scouting labour reduction	Duckett <i>et al.</i> 2017 (6)

These cases illustrate a consistent pattern: AI-enabled precision interventions generate measurable efficiency gains across resource use, yield stability, and environmental impact indicators. Notably, impact magnitudes are broadly comparable across very different farm scales and income contexts, though the mechanisms and enabling infrastructure differ substantially.

8. Quantified Environmental and Sustainability Impacts

Table 3 consolidates reported quantitative sustainability impacts of AI/ML across six environmental dimensions, drawing on peer-reviewed experimental and quasi-experimental evidence. The aggregate picture presented in Table 3 is one of substantial environmental co-benefits achievable from AI-enabled agricultural management. However, several methodological caveats apply: most reported figures derive from controlled trials or early-adopter settings rather than representative population averages; effect sizes are sensitive to baseline management

practices; and rebound effects—where efficiency gains stimulate intensification rather than absolute resource reduction—are not consistently accounted for in the literature (14).

Table 3: Quantified Environmental Impacts of AI/ML Interventions in Agriculture

Sustainability Dimension	AI/ML Technique Applied	Quantified Impact	Key Source
Water consumption	Precision irrigation (ML-based)	15–45% reduction in irrigation water	Goap <i>et al.</i> 2018 (7)
Pesticide use	AI-guided targeted spraying (CV)	Up to 90% reduction vs blanket spray	Partel <i>et al.</i> 2019 (8)
Fertiliser use (N)	Soil-sensor + DL optimisation	10–30% reduction in N application	Pantazi <i>et al.</i> 2016 (9)
GHG emissions	AI-optimised tillage + planting schedules	5–20% reduction in farm-level CO ₂ -eq	Lipper <i>et al.</i> 2014 (10)
Biodiversity impact	AI weed mapping & targeted biocontrol	Reduced off-target pesticide drift	Weiss <i>et al.</i> 2020 (11)
Food waste (post-harvest)	Computer vision quality grading	15–25% reduction in post-harvest loss	Kamilaris & Prenafeta-Boldu 2018 (12)

9. Barriers to Adoption, Ethical Dimensions, and Governance

9.1 Data Scarcity and the Digital Divide

The performance of ML models is fundamentally constrained by the quantity, quality, and representativeness of training data. Mehrabi *et al.* documented a substantial 'global divide in data-driven farming', in which the overwhelming majority of labelled agricultural AI training data is drawn from North American and European contexts (20). Models trained on these datasets frequently exhibit degraded performance when applied to African, South Asian, or Southeast Asian cropping systems characterised by different cultivar portfolios, agroecological conditions, and management practices (20). Addressing this structural bias requires targeted investment in annotated dataset creation within underrepresented agricultural systems, ideally through participatory citizen-science approaches that simultaneously build digital literacy among smallholder farmers.

9.2 Algorithmic Transparency and Accountability

The interpretability of ML models used in high-stakes agricultural decisions—such as credit scoring for farm loans or disease outbreak risk mapping—is a growing concern among researchers and regulators alike (18). Complex ensemble models and deep neural networks are frequently criticised as 'black boxes' whose internal decision logic cannot be readily interrogated by end users or audited for systematic bias (18). Explainable AI (XAI) methodologies, including SHAP (SHapley Additive exPlanations) value analysis and attention-map visualisation, are

increasingly integrated into agricultural AI systems to provide post-hoc explanations of model predictions (18). Regulatory frameworks such as the EU AI Act, which entered into force in 2024, establish transparency requirements that will progressively apply to high-risk AI applications in critical infrastructure, potentially including food production systems.

9.3 Data Ownership, Privacy, and Market Power

Agricultural data generated by precision farming systems—GPS machinery tracks, yield monitor records, soil sensor time series, and satellite-derived field analytics—possess significant commercial value. Asymmetric data relationships, in which agri-tech corporations aggregate farmer-generated data at scale while offering limited reciprocal value transparency, raise legitimate concerns regarding data sovereignty and the distribution of economic rents (19). Tzachor *et al.* argue that responsible AI in agriculture requires systemic attention to these power dynamics, and propose co-design methodologies that centre farmer agency in technology governance (19).

9.4 A Framework for Responsible AI Governance in Agriculture

Drawing on the preceding analysis, we propose a five-pillar governance framework for responsible deployment of AI in sustainable agricultural systems:

- Pillar 1 — Inclusive Data Infrastructure: Public investment in open, geographically representative annotated agricultural datasets, particularly in low- and middle-income country contexts, to reduce algorithmic bias and improve model generalisability (20).
- Pillar 2 — Transparency by Design: Mandatory explainability requirements for AI systems used in consequential agricultural decisions, aligned with emerging global regulatory standards (18).
- Pillar 3 — Farmer Data Sovereignty: Legislative protection for farmer-generated data, including interoperability standards that prevent vendor lock-in and enable competitive data marketplaces (19).
- Pillar 4 — Adaptive Environmental Monitoring: Integration of AI agricultural systems into national environmental monitoring frameworks, enabling real-time tracking of sustainability outcomes and detection of rebound effects (14).
- Pillar 5 — Equitable Capacity Building: Structured digital literacy programmes linked to AI agricultural tool rollout, ensuring that productivity and environmental benefits are accessible to smallholder and resource-constrained farm operators (20).

Conclusion

Artificial intelligence and machine learning represent genuinely transformative capabilities for sustainable agriculture, offering technically robust pathways to simultaneously increase food production efficiency and reduce the environmental footprint of farming systems. The evidence synthesised in this chapter consistently indicates that ML-driven precision management can achieve 15–45% reductions in water use, up to 90% reductions in pesticide application, and 15–

25% reductions in post-harvest food waste—impacts that, if realised at scale, would make significant contributions to multiple Sustainable Development Goals simultaneously (15).

However, the technology-centric optimism that characterises much industry commentary requires grounding in empirical realism. Performance gains documented in controlled trials and early-adopter settings are not automatically replicable across the heterogeneous social, institutional, and agroecological contexts of global agriculture. The structural data divide identified by Mehrabi *et al.* (20) poses a fundamental challenge to equitable technology diffusion, risking a scenario in which AI-enabled productivity gains accrue disproportionately to large-scale, capitalised farming operations in high-income countries while smallholder systems in climate-vulnerable regions—where agricultural transformation is most urgently needed—remain underserved.

The governance agenda for AI in agriculture is therefore as consequential as the technical agenda. Without deliberate policy intervention to address data equity, algorithmic accountability, and digital infrastructure gaps, the promise of AI for sustainable agriculture risk being captured by incumbent interests rather than distributed as a public good. Future research should prioritise long-term field-scale trials of integrated AI systems under representative conditions, participatory design methodologies that embed farmer knowledge in model development, and systematic meta-analyses that move beyond individual case reporting toward population-average effect estimation (19).

The next decade will be critical: decisions made now about who controls agricultural data, which systems receive investment, and what standards govern AI deployment will determine whether the fourth agricultural revolution delivers on its sustainability promise or deepens existing inequalities in the global food system.

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ROLE OF NON-THERMAL TECHNOLOGIES IN FOOD PRESERVATION

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Abstract

Non-thermal food preservation technologies have emerged as critical alternatives to conventional thermal processing in the modern food industry. These methods achieve microbial inactivation and enzyme deactivation through physical or chemical mechanisms that operate at or near ambient temperatures, thereby maintaining the nutritional integrity, sensory attributes, and bioactive compound profiles of food products. This review provides a comprehensive examination of the major non-thermal technologies including High Hydrostatic Pressure (HHP), Pulsed Electric Fields (PEF), Ultraviolet (UV) radiation, Cold Plasma (CP), Power Ultrasound (US), Pulsed Light (PL), and Ozone (O₃) treatment, addressing their mechanisms of action, commercial applications, nutritional implications, and regulatory frameworks. Special attention is given to hurdle technology combinations, current challenges related to scale-up and cost, consumer acceptance, and future research directions. The findings confirm that non-thermal technologies represent a scientifically mature and commercially viable pathway toward safe, clean-label, and nutritionally superior food products.

Keywords: Non-Thermal Food Processing, High Hydrostatic Pressure, Pulsed Electric Fields, Cold Plasma, Ultrasonication, Food Safety, Hurdle Technology, Bioactive Compounds.

1. Introduction

The preservation of food is one of the oldest and most vital priorities of human society. Throughout history, cultures have depended on tried and true methods like salting, smoking, sun-drying and fermenting to make perishable goods last longer and to safeguard against the often lethal effects of food-borne bacteria. These early techniques were gradually replaced, or supplemented, by scientifically based thermal technologies, especially in the 19th and 20th centuries. In the 1860s, the French chemist Louis Pasteur (1822-1895) discovered that the controlled application of heat could kill spoilage-causing microbes in wine, beer and other liquids. By the mid-20th century, pasteurization and sterilization (or “retort” processing) at scale were ubiquitous throughout the global food supply chain and dramatically reduced the incidence of diseases caused by pathogens such as *Salmonella enterica*, *Listeria monocytogenes* and *Clostridium botulinum* (Huang *et al.*, 2020). Heat treatment, particularly at temperatures exceeding 72°C for pasteurization or above 121°C for sterilization, initiates a cascade of

thermally driven chemical reactions that degrade heat-sensitive vitamins, denature functional proteins, break down volatile flavour compounds, alter pigments, and destroy bioactive phytochemicals such as polyphenols, carotenoids, and glucosinolates (Barba *et al.*, 2017). The Maillard reaction, a non-enzymatic browning process driven by heat, simultaneously generates desirable flavor molecules and potentially harmful acrylamide in certain food matrices. For a modern consumer who increasingly seeks products that are minimally processed, nutritionally dense, additive-free, and labelled as natural or clean-label, these thermal degradation phenomena represent a significant and growing concern.

The global food industry has responded to this paradigm shift with substantial investment in the research, development, and commercialization of non-thermal preservation technologies. These methods achieve microbial inactivation and food safety objectives through mechanical, electromagnetic, chemical, or plasma-based mechanisms that do not require the sustained application of elevated temperatures. The commercial market for non-thermal food processing equipment and services was valued at approximately USD 2.3 billion in 2022 and is forecast to expand at a compound annual growth rate (CAGR) of over 14% through 2030, driven by rising consumer awareness, favourable regulatory developments, and the growing global trade in minimally processed ready-to-eat products (MarketsandMarkets, 2023). This growth trajectory positions non-thermal technologies as a central pillar of twenty-first century food manufacturing strategy.

The scientific foundations of modern non-thermal processing were established through a series of landmark contributions beginning in the early 1990s. Early work demonstrated that hydrostatic pressures in excess of 100 MPa could achieve log reductions in pathogenic bacterial populations comparable to those attained by thermal pasteurization (Balasubramaniam *et al.*, 2015). Concurrently, research into high-voltage Pulsed Electric Fields revealed that transient transmembrane potential differences induced by rapid electrical discharges could irreversibly disrupt the phospholipid bilayer of microbial cell membranes, a phenomenon termed electroporation, rendering bacterial, yeast, and mould cells nonviable without elevating product temperature above 40°C (Jaeger *et al.*, 2016). Subsequent decades witnessed the rapid diversification of the non-thermal technology landscape, with Cold Plasma, Pulsed Light, and Power Ultrasound emerging as scientifically validated approaches with distinct mechanistic profiles and complementary application niches. A particularly important driver of non-thermal technology adoption has been the convergence of food safety regulation and public health policy. High-profile foodborne illness outbreaks, including *Listeria* contamination in ready-to-eat deli meats and *Salmonella* in fresh produce, have imposed enormous economic and reputational costs on food manufacturers worldwide, motivating the adoption of technologies capable of delivering post-packaging pathogen inactivation or robust surface decontamination (Huang *et al.*, 2020).

Regulatory agencies, including the U.S. Food and Drug Administration (FDA), the European Food Safety Authority (EFSA), and Codex Alimentarius, have progressively clarified and expanded the approved applications of non-thermal technologies, providing manufacturers with a more predictable regulatory pathway for technology adoption (EFSA, 2022).

The nutritional and bioactive advantages of non-thermal processing are now extensively documented in peer-reviewed literature. Ascorbic acid, tocopherols, folate, carotenoids, polyphenols, and flavonoids, all of which are partially or wholly degraded by conventional thermal processing, are preserved to significantly greater extents by HHP, PEF, and Cold Plasma treatments (Barba *et al.*, 2017; Timmermans *et al.*, 2019). This nutritional superiority not only translates into enhanced consumer health outcomes but also enables manufacturers to substantiate health claims and premium positioning in competitive markets. Furthermore, non-thermal technologies generally consume significantly less thermal energy than equivalent pasteurization or sterilization operations, contributing to improved environmental sustainability profiles (Jaeger *et al.*, 2016). Despite these compelling advantages, the widespread industrial adoption of non-thermal technologies continues to be moderated by a series of practical challenges. Capital equipment costs for HHP remain substantial, typically ranging from USD 500,000 to USD 2.5 million per processing unit. PEF and Cold Plasma systems require highly specialized engineering expertise for electrode design, dielectric barrier configuration, and plasma chemistry optimization. Consumer familiarity with and acceptance of non-thermal technologies varies considerably across demographic groups and cultural contexts, with terminology such as ‘plasma-treated food’ generating apprehension among segments unfamiliar with the scientific basis of the technology (Knorr *et al.*, 2020). Overcoming these barriers requires sustained interdisciplinary collaboration among food scientists, process engineers, regulatory specialists, behavioral economists, and communication professionals.

This article provides a systematic and integrated review of the principal non-thermal food preservation technologies currently documented in the peer-reviewed literature, synthesising evidence on their mechanisms of action, efficacy against specific foodborne pathogens and spoilage organisms, effects on nutritional quality parameters, commercial applications, and regulatory status. The review further addresses the strategic deployment of these technologies within hurdle technology frameworks, discusses the challenges and opportunities associated with scale-up and commercialization, and identifies priority directions for future research. By consolidating current knowledge from recent high-impact publications, this review aims to serve as a comprehensive reference for food scientists, technologists, and industry practitioners engaged in advancing the frontiers of non-thermal food preservation.

2. Fundamental Principles of Non-Thermal Food Preservation

The unifying principle underlying all non-thermal preservation technologies is the achievement of microbiological safety and stability objectives without exposing the food matrix to temperatures above approximately 45°C for extended durations (Huang *et al.*, 2020). This temperature threshold is significant because most heat-sensitive vitamins, flavour compounds, and pigments retain their molecular integrity below this level. Non-thermal methods instead exploit a diversity of physical and chemical forces, such as hydrostatic pressure, electromagnetic radiation, high-voltage electric fields, acoustic cavitation, plasma chemistry, and reactive oxygen species, to achieve the same endpoints of microbial inactivation and enzyme deactivation that thermal processing accomplishes through protein denaturation and membrane disruption driven by heat.

Microbial inactivation kinetics in non-thermal processing frequently deviate from the classical first-order (log-linear) model that underpins thermal process design. Shoulder effects representing a lag phase before inactivation accelerates, and tailing phenomena reflecting the persistence of a resistant sub-population, are commonly observed across HHP, PEF, and ultrasound treatments (Gomez-Lopez *et al.*, 2019). These non-linearities necessitate the use of advanced inactivation models such as the Weibull distribution, biphasic models, and the modified Gompertz equation to accurately characterize non-thermal inactivation curves and underpin robust process validation. Correct modelling is essential for regulatory submission and for ensuring that validated processes consistently achieve the required log reductions in target pathogens across the full range of anticipated process variability. The selectivity of non-thermal processes is a key mechanistic advantage. Physical forces that disrupt microbial cell membranes, which are structurally distinct from the covalent molecular bonds within food constituents, can inactivate pathogens while leaving the chemical structures responsible for nutritional value and sensory quality largely intact. However, this selectivity is not absolute and is profoundly influenced by food matrix composition, including pH, water activity, ionic strength, lipid content, and the presence of protective solutes (Barba *et al.*, 2017). Understanding and controlling these matrix interactions is central to the design of effective and reproducible non-thermal processes.

3. Major Non-Thermal Technologies

3.1 High Hydrostatic Pressure (HHP) Processing

High Hydrostatic Pressure processing subjects food sealed within flexible packaging to isostatic pressures typically ranging from 100 to 800 MPa for durations of seconds to several minutes. Pursuant to Le Chatelier's principle, applied pressure favours any molecular transition accompanied by a net decrease in volume in microbial cells; this manifests as disruption of cell membranes, denaturation of membrane-bound enzymes critical to energy metabolism, and

collapse of ribosomal structures required for protein synthesis (Balasubramaniam *et al.*, 2015). HHP is the most commercially mature non-thermal technology globally, with applications in guacamole, fresh fruit juices, deli meats, oysters, sliced ham, and dairy products. It effectively inactivates vegetative bacteria, yeasts, and moulds, including *L. monocytogenes*, *Salmonella*, and *E. coli* O157:H7. Commercially, HHP-processed products are marketed in over 60 countries (Huang *et al.*, 2020). Bacterial endospores exhibit significant pressure resistance; spore inactivation generally requires pressure-assisted thermal processing combining moderate heat with high pressure. The primary commercial constraint remains the batch nature of current systems and high capital costs (Balasubramaniam *et al.*, 2015).

3.2 Pulsed Electric Field (PEF) Processing

PEF technology applies microsecond to millisecond duration pulses of high-intensity electric fields (10-80 kV/cm) to food positioned between two electrodes. The primary antimicrobial mechanism is electroporation: when the electric field-induced transmembrane potential exceeds approximately 1 V, irreversible pore formation in the phospholipid bilayer causes loss of membrane integrity and cell death (Jaeger *et al.*, 2016). PEF is ideally suited for pumpable liquid and semi-liquid food matrices, including fruit juices, milk, liquid eggs, soups, and smoothies. Recent studies confirm that PEF-processed juices retain statistically significantly higher ascorbic acid, flavonoid, and carotenoid concentrations compared to thermally pasteurized counterparts, while achieving equivalent 5-log pathogen reductions (Timmermans *et al.*, 2019). PEF also enhances the extraction efficiency of bioactive compounds and oils from plant cells, broadening its commercial relevance beyond pasteurization.

3.3 Ultraviolet (UV) Radiation

Ultraviolet-C radiation (200-280 nm) is an established, cost-effective non-thermal decontamination technology widely applied to fresh produce surfaces, fruit juice thin-film systems, meat surfaces, and food contact surfaces. The antimicrobial mechanism involves photochemical absorption by microbial DNA, predominantly forming cyclobutene pyrimidine dimers that block DNA replication and transcription, leading to cell death (Keyser *et al.*, 2008). UV-C is effective against a broad pathogen spectrum, including *Salmonella*, *E. coli* O157:H7, *L. monocytogenes*, and *Cryptosporidium parvum*, the latter being chlorination-resistant. A significant limitation is the low penetration depth of UV radiation in turbid or opaque food matrices, restricting its primary utility to surface decontamination and thin, transparent liquid films processed in specialized thin-film reactors. The FDA approved UV-C for apple juice and cider treatment in 2000, and subsequent guidance has extended its recognized applications.

3.4 Cold Plasma Technology

Cold plasma, also termed non-thermal plasma, is generated by partial ionization of atmospheric gases, including air, nitrogen, argon, or helium, using electrical discharges such as dielectric

barrier discharges or plasma jets. The resulting plasma contains a complex, synergistic mixture of reactive oxygen species (superoxide, hydrogen peroxide, hydroxyl radicals, ozone), reactive nitrogen species (nitric oxide, nitrogen dioxide), UV photons, charged particles, and electrical fields, all of which contribute to potent antimicrobial activity through simultaneous attack on DNA, proteins, lipids, and the cell wall (Misra *et al.*, 2019). Cold plasma has demonstrated robust inactivation of *Salmonella*, *E. coli* O157:H7, *L. monocytogenes*, and *Staphylococcus aureus*, and is uniquely effective on dry solid matrices such as spices, seeds, grains, and powders that are not amenable to liquid-phase non-thermal treatments. Recent research has also documented CP efficacy in mycotoxin degradation and biofilm disruption, representing important food safety applications (Misra *et al.*, 2019).

3.5 Power Ultrasound

Power ultrasound at frequencies above 20 kHz induces acoustic cavitation in liquid food matrices the formation, oscillation, and violent collapse of microbubbles generating localised transient temperatures exceeding 5,000 K, pressures above 50 MPa, intense microstreaming, and highly reactive hydroxyl radicals. These extreme local conditions physically disrupt microbial cell walls and membranes, inactivating bacteria, yeasts, and moulds. Alone, ultrasound typically requires extended treatment times for meaningful microbial reductions; however, synergistic combinations with mild heat (thermosonication), elevated pressure (manosonication), or antimicrobial compounds substantially enhance inactivation efficacy while preserving nutritional quality (Chemat *et al.*, 2017). Thermosonication at 55-60°C achieves pasteurization-equivalent microbial reductions at temperatures substantially below conventional pasteurization thresholds. Beyond microbial inactivation, power ultrasound enables emulsification, crystallization control, enhanced extraction of bioactive compounds, and improved mass transfer in brining, marination, and convective drying processes.

3.6 Pulsed Light (PL) Technology

Pulsed Light delivers intense, broad-spectrum light pulses spanning 200-1100 nm at peak power densities up to 34,000 W/cm² via xenon flash lamps. The broad spectral emission, inclusive of the germicidal UV-C band, combined with the extremely high peak irradiance, produces photochemical and photothermal effects on microbial cells more potent than those achievable by continuous UV-C at equivalent total doses. PL is FDA-approved for food and food contact surface treatments and has demonstrated consistent efficacy against *E. coli* O157:H7, *Salmonella*, *L. monocytogenes*, *Aspergillus* species, and human norovirus surrogates (Gomez-Lopez *et al.*, 2019). Limitations include restricted penetration depth and potential surface temperature elevation at high fluence levels that may affect heat-sensitive food components.

3.7 Ozone Treatment

Ozone (O₃) is a powerful oxidising agent generated on-site by corona discharge and applicable as gaseous ozone or ozonated water. With a standard reduction potential of +2.07 V, substantially exceeding that of chlorine (+1.36 V), ozone rapidly inactivates microorganisms through oxidation of sulfhydryl enzyme groups, unsaturated membrane fatty acids, and nucleic acid bases. Ozone decomposes spontaneously to oxygen, leaving no chemical residues on treated food surfaces. The FDA affirmed ozone as Generally Recognised as Safe (GRAS) for direct food contact applications in 2001 (FDA, 2001). Commercially, ozone is applied in produce washing, spice treatment, grain storage, and processing surface sanitation. Elevated ozone concentrations can cause oxidative deterioration of pigments, ascorbic acid, and lipid-rich foods, necessitating careful dose optimisation and integration within broader hurdle frameworks (Brodowska *et al.*, 2018).

4. Hurdle Technology: Combining Non-Thermal and Mild Thermal Approaches

The concept of hurdle technology, developed by Leistner and progressively refined over subsequent decades, holds that the intelligent sequential or simultaneous application of multiple preservation factors, each at sub-lethal individual levels, can achieve synergistic or additive microbial inactivation exceeding the combined individual effects, while minimising the impact of any single treatment on food quality (Leistner, 2000). Each preservation factor constitutes a hurdle that microorganisms must surmount; when multiple hurdles are applied simultaneously, the cumulative physiological stress overwhelms microbial homeostatic mechanisms and drives populations below detectable levels. Non-thermal technologies are ideally positioned as components within hurdle frameworks because their distinct mechanisms of action are complementary and act on different cellular targets. Well-documented hurdle combinations include HHP with antimicrobial bacteriocins such as nisin for enhanced inactivation of pressure-resistant spores of *Clostridium botulinum* and *Bacillus cereus* (Balasubramaniam *et al.*, 2015); PEF combined with mild heat at 50-55°C for synergistic enzyme inactivation and pathogen reduction in fruit juices without compromising ascorbic acid content (Timmermans *et al.*, 2019); Cold Plasma combined with modified atmosphere packaging for extended shelf life of fresh-cut produce (Misra *et al.*, 2019); and UV-C combined with aqueous chlorine washing for produce decontamination exceeding the efficacy of either individual treatment (Keyser *et al.*, 2008). The practical design of hurdle combinations requires systematic process optimisation using response surface methodology, accounting for complex interactions between hurdle factors and their differential effects on target pathogens versus food quality markers.

5. Effects on Nutritional Quality and Bioactive Compounds

One of the most compelling and extensively documented advantages of non-thermal processing is the superior retention of nutritional quality and bioactive compounds relative to conventional

thermal processing. Ascorbic acid serves as a particularly sensitive quality indicator due to its established thermal lability. Meta-analytic evidence consistently demonstrates that HHP-processed fruit juices retain 90-99% of initial ascorbic acid, compared to 60-80% retention following thermal pasteurization at 85°C for 30 seconds (Barba *et al.*, 2017). PEF-processed beverages similarly exhibit significantly higher vitamin C concentrations than thermally treated equivalents. Carotenoids, including beta-carotene and lycopene, fat-soluble antioxidants associated with reduced cardiovascular disease and cancer risk, are retained to greater extents in PEF and HHP-processed matrices (Timmermans *et al.*, 2019).

Phenolic compounds and flavonoids, constituting the largest class of plant-based antioxidants, respond to non-thermal processing in a matrix-dependent and technology-specific manner. Multiple studies report not only preservation but actual enhancement of total polyphenol content and antioxidant capacity in HHP- and PEF-processed plant foods, attributable to disruption of cell wall structures and protein-phenol complexes that release previously bound phenolics into extractable forms (Barba *et al.*, 2017). Cold plasma treatment has been shown to increase the bioavailability of phenolic compounds from berry matrices through similar cell-disruption mechanisms, while also modifying phenolic profiles through oxidative reactions at high plasma doses (Misra *et al.*, 2019).

The impact of non-thermal technologies on enzymes and structural proteins is technologically significant. HHP above 300 MPa induces partial unfolding of globular proteins that can be exploited advantageously, for instance, improving cheese texture, enhancing rennet coagulation in dairy processing, and increasing the emulsifying capacity of protein ingredients. However, polyphenol oxidase and peroxidase enzymes responsible for enzymatic browning and off-flavour development exhibit considerable pressure resistance, typically requiring pressures above 600 MPa or a combination with mild heat for complete inactivation (Balasubramaniam *et al.*, 2015). This residual enzyme activity must be considered in the design of HHP-processed fresh juice and produce products.

6. Regulatory Status and Consumer Acceptance

The regulatory landscape governing non-thermal food processing technologies differs substantially across jurisdictions, creating complexity for globally operating food manufacturers. In the United States, the FDA and USDA regulate non-thermal technologies through existing frameworks that encompass food additives, processing aids, irradiation, and GRAS affirmation procedures. HHP is regulated as a processing technology requiring no specific pre-market approval for the pressure treatment per se, facilitating its widespread commercial adoption. Pulsed Light was approved by the FDA for use on food surfaces in 1996 under 21 CFR Part 179.41, and ozone was affirmed as GRAS for direct food contact applications in 2001 (FDA, 2001). The European Food Safety Authority (EFSA) has been progressively developing safety

assessment frameworks for novel non-thermal technologies, including Cold Plasma and Pulsed Light, with scientific opinions published following systematic evidence reviews (EFSA, 2022). Consumer acceptance is a critical determinant of commercial success for non-thermal technologies, and evidence from consumer research reveals a nuanced picture shaped by product type, processing terminology, communication strategy, and cultural context. Survey-based studies conducted in European and North American markets indicate broadly positive consumer attitudes toward HHP-processed products framed as natural, fresh, and minimally processed, with particular receptiveness among health-conscious and younger consumer segments (Knorr *et al.*, 2020). In contrast, the terminology associated with Cold Plasma and Pulsed Electric Fields tends to generate uncertainty or apprehension among consumers unfamiliar with the underlying science, reflecting the influence of 'naturalness' heuristics and technology neophobia on food acceptance behaviour. These findings underscore the importance of evidence-based consumer communication, transparent labelling strategies, and investment in public science education as prerequisites for realising the market potential of emerging non-thermal technologies.

7. Challenges and Future Research Directions

Despite substantial scientific and commercial progress, several systemic challenges continue to moderate the broader industrial adoption of non-thermal food preservation technologies. The high capital and operational costs of HHP equipment, typically USD 500,000 to USD 2.5 million per processing unit, with associated operational costs, remain a significant barrier for small and medium-sized food enterprises, limiting the technology's accessibility and thus its impact on global food security. The batch nature of current commercial HHP systems constrains throughput and imposes process discontinuities incompatible with high-speed continuous production lines standard in commodity food manufacturing. PEF systems require sophisticated engineering for electrode material selection, pulse generator design, and chamber geometry optimisation, and their restriction to pumpable food matrices limits their applicability across the full breadth of the food product spectrum (Jaeger *et al.*, 2016). Cold Plasma scale-up faces fundamental challenges in achieving uniform reactive species distribution across complex three-dimensional food geometries and large-volume batch operations (Misra *et al.*, 2019).

Process validation and regulatory approval of novel non-thermal technologies demand substantial investment in surrogate organism identification, microbial challenge study design, inactivation model development, and longitudinal shelf-life evaluation, all conducted under conditions representative of worst-case commercial processing scenarios. The absence of internationally harmonised validation protocols and mutual recognition frameworks between regulatory jurisdictions creates duplicative validation burdens for manufacturers seeking global market access (EFSA, 2022). Addressing these regulatory barriers will require proactive engagement between the food processing industry, academic researchers, and regulatory

authorities in the development of standardised guidance documents and internationally accepted process validation methodologies.

Future research directions of highest priority include the development of continuous-flow HHP systems to overcome throughput constraints; application of computational fluid dynamics and finite element modeling to optimize electric field distribution in PEF chambers and plasma species transport in Cold Plasma reactors; integration of real-time machine learning-based process monitoring systems capable of adaptive control of treatment intensity; systematic investigation of combined non-thermal hurdle strategies in complex real food matrices; and life cycle assessment studies to rigorously quantify the environmental footprint advantages of non-thermal relative to thermal processing across entire product life cycles (Knorr *et al.*, 2020; Misra *et al.*, 2019). The convergence of non-thermal processing with nanotechnology, including nano-encapsulated natural antimicrobials activated by PEF or ultrasound stimuli, and with active and intelligent packaging systems, represents a particularly fertile area for translational research with significant commercial potential (Brodowska *et al.*, 2018).

Conclusion

Non-thermal food preservation technologies collectively represent one of the most consequential paradigm shifts in food processing since the industrial adoption of thermal pasteurization in the twentieth century. High Hydrostatic Pressure, Pulsed Electric Fields, Ultraviolet radiation, Cold Plasma, Power Ultrasound, Pulsed Light, and Ozone treatment constitute a complementary and technologically diverse toolkit capable of achieving robust microbial inactivation and food safety objectives while preserving the nutritional integrity, sensory quality, and bioactive compound profiles that modern consumers demand. The scientific evidence reviewed herein confirms that non-thermal technologies can meet or exceed regulatory pathogen reduction standards across a wide range of food matrices and target organisms, while delivering measurable advantages in vitamin retention, polyphenol bioavailability, and flavour preservation relative to conventional thermal processing. When strategically deployed within hurdle technology frameworks, the efficacy of individual non-thermal treatments is synergistically amplified, enabling formulation of minimally processed, clean-label products that satisfy both safety and quality requirements. Significant challenges remain in the domains of equipment cost reduction, continuous processing engineering, process validation standardisation, regulatory harmonisation, and consumer communication. However, the convergence of non-thermal processing with artificial intelligence, nanotechnology, active packaging, and advanced sustainability assessment methodologies positions this field for continued rapid advancement. Sustained interdisciplinary collaboration among food scientists, process engineers, microbiologists, regulatory specialists, and consumer researchers will be indispensable in translating laboratory-scale innovations into

widely deployed industrial applications, ultimately contributing to enhanced global food security, reduced food waste, and improved public health outcomes.

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BIODIVERSITY-DRIVEN INNOVATIONS IN REFORESTATION AND SUSTAINABLE AGRICULTURE

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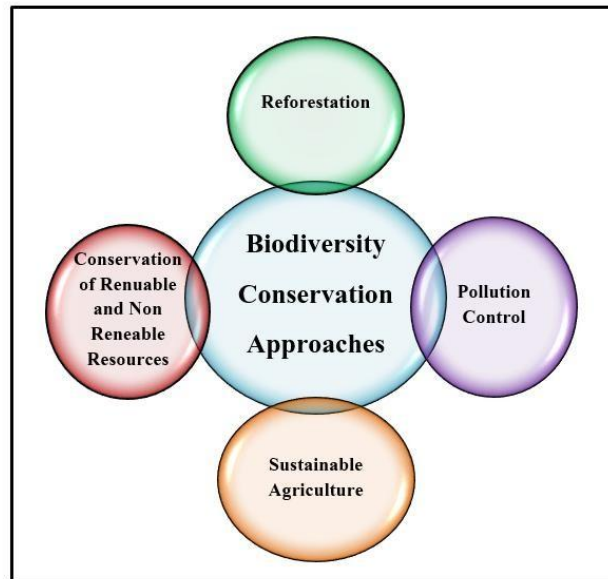
Abstract

The term "biodiversity" refers to the variety of life on Earth, which includes all living things (from micro to macroorganisms, animals, plant species, and ecosystems) as well as the biological processes that sustain them. It includes environmental variety, taxonomic variation, and genetic diversity. The diversity offers fundamental necessities like oxygen-rich air, fresh water, food, nutrition, and regulation of the climate with healthy atmosphere, which is the vital part of all lives on earth. However, due to human activities like deforestation, habitat loss for construction and agriculture, commercialization, improper use of renewable and nonrenewable natural resources, and rising pollution of the land, air, and water that contributes to climate change, it is rapidly declining. Everyone is concerned about the increasing negative effects on biodiversity brought about by social expectations. In order to preserve biodiversity and ensure sustainable future security, it is necessary to educate society about the application of creative strategies such as the appropriate use of both renewable and non-renewable energy sources, pollution control, reforestation techniques, and sustainable farming.

Keywords: Biodiversity, Reforestation, Renewable and Non-Renewable Energy Sources, Pollution And Sustainable Agriculture.

Introduction

The diversity in gene level, species level and ecological level has positive impact on the environment but due to some natural calamities and more inappropriate human activities the drastic changes occur within this, which affected the balance of ecosystem. The primary and most effective defence mechanism has always been our biological makeup. Biodiversity is our most powerful protector, as proved by the potential of natural approaches for disaster prevention and global warming recovery. Several biodiversity hotspots in the globe are well maintained and stable for environmental protection due to the absence of human influence. However, combined with the preferences and necessities of a rising population leads to biodiversity loss. As consequence, innovative approaches are required to meet societal needs while simultaneously preserving ecological balance and conservation biodiversity, which are briefly described further.



Reforestation

Reforestation the process of restoring tree cover to deforested or degraded lands, is a critical pillar of biodiversity conservation and climate change mitigation. However, traditional reforestation efforts have often focused on monoculture plantations of fast-growing, commercially valuable species, which fail to restore complex ecosystem functions and support native wildlife (Holl & Brancalion, 2020). Innovative approaches are now shifting the standard from simply planting trees to engineering robust, biodiverse forests that accelerate ecological recovery and provide sustainable benefits.

- 1. Drone Seeding and Precision Forestry:** Aerial drone technology is revolutionizing largescale reforestation in inaccessible or vast degraded areas. Drones equipped with mapping sensors first conduct topographic and soil analyses to identify optimal planting sites. They then fire specially designed seedpods, containing pre-germinated native seeds coated in nutrientrich gel, into the soil. This method, employed by companies like Dendra Systems and nonprofits like Worldview International Foundation, can plant hundreds of thousands of seeds per day at a fraction of the cost and time of manual planting (Brovelli & Sun, 2020). The precision of drone mapping ensures seeds are distributed in ecologically appropriate patterns, mimicking natural dispersal and enhancing plant establishment rates.
- 2. The Miyawaki Method:** Creating Mini-Forests: Pioneered by Japanese botanist Akira Miyawaki, this technique creates dense, native, and rapidly growing forests on small plots of land in urban or suburban areas. The method involves planting a high diversity of native seedlings (typically 20-30 species) very close together in prepared soil. This intense competition for sunlight drives vertical growth up to ten times faster than conventional plantations, resulting in a multi-layered, self-sustaining forest within 20-30 years (Miyawaki, 2004). These "mini-forests" rapidly enhance local biodiversity, providing habitat

for insects, birds, and small mammals, while also cooling urban heat islands and sequestering carbon efficiently.

3. **Assisted Natural Regeneration (ANR):** ANR is a cost-effective, low-tech innovation that forces the natural seed bank and rootstock already present in degraded lands. Instead of planting new trees, ANR involves removing barriers to natural growth, such as invasive grasses, preventing fire, and protecting emerging seedlings from grazing. Studies in the Philippines and Brazil have shown that ANR can restore forest structure and biodiversity at a fraction of the cost of active planting, while ensuring that the regenerated forest is perfectly adapted to local conditions (Chazdon & Guariguata, 2016). This strategy empowers local communities as agents of the regeneration process.
4. **Native Seed Encapsulation in Composite Block:** Large parts of North Africa have gradually shifted from forested landscapes to desert due to long-term human pressure and changing climate, a process that severely degrades soil and prevents natural forest recovery. In regions such as Djelfa in central Algeria, conventional reforestation efforts often fail because young seedlings cannot survive prolonged drought and the absence of soil organic matter. To overcome these limitations, researchers proposed an innovative approach in which each planted seedling is supported by its own localized water and nutrient reserve, reducing dependence on irrigation and increasing survival under arid conditions (Liiv *et al.*, 2024). This method uses a biodegradable, moisture-encapsulating composite placed deep in the soil, forming a protected reservoir that sustains seedlings until their roots reach deeper moisture layers. Trials conducted under dry conditions demonstrated markedly improved growth and biomass production in drought-resistant tree species compared to conventional planting. By creating small, fertile micro-sites that gradually, enhance surrounding soil quality, the technique shows strong potential for large-scale desert restoration and urban greening in water-limited environments (Liiv *et al.*, 2024).

Impact on Biodiversity

These innovative strategies directly address biodiversity loss by prioritizing native species composition and structural complexity. Diverse plantings create heterogeneous habitats that support a wider range of pollinators, birds, and soil organisms. For instance, a Miyawaki forest in Utrecht, Netherlands, recorded a 60% increase in local bird species within three years (Troubleyn *et al.*, 2021). Furthermore, by restoring ecological corridors through strategic reforestation, these innovations help reconnect fragmented habitats, allowing for genetic flow and species migration essential for long-term population viability.

In conclusion, moving beyond monoculture plantations to embrace technologically enhanced and ecologically principled reforestation is vital. These innovative strategies—drone seeding, the Miyawaki method, and ANR—offer scalable, efficient, and ecologically robust pathways to not

only increase tree cover but to authentically restore biodiverse forest ecosystems, securing their critical services for a sustainable future.

Conclusion

The use of such Innovative approaches can help to restore the biodiversity. The Reforestation by various means, Conservation of Renewable and Non-Renewable Energy sources by implementing healthy practices, Pollution Control through CO₂ capture and utilization of stored CO₂, Sustainable Agricultural methodologies helps to reduces global warming and boosts ecosystem function. Therefore, it is concluded that by using the new technologies, innovations relevant to sustainable system of various sectors can deliver environmental benefits, restoration of biodiversity and can be a healthy pursuit to a better life.

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VALORIZATION OF FRUIT AND VEGETABLE PROCESSING WASTE: SUSTAINABLE STRATEGIES FOR BIOACTIVE RECOVERY AND VALUE-ADDED PRODUCT DEVELOPMENT

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Abstract

The fruit and vegetable processing industry generates enormous quantities of by-products, including peels, seeds, pomace, cores, stems, and pulp residues, that are conventionally discarded through landfilling or incineration despite retaining substantial nutritional, functional, and economic value. Current estimates indicate that fruit and vegetable losses and waste account for the highest proportion among all food categories along the global supply chain, giving rise to significant environmental, economic, and food security concerns. This chapter reviews the composition and generation of fruit and vegetable processing waste and evaluates the principal valorization pathways through which this waste stream can be converted into value-added products. Emphasis is placed on the recovery of bioactive compounds such as polyphenols, carotenoids, and dietary fibre; the extraction and application of pectin; the development of active and biodegradable packaging materials; and the generation of bioenergy through anaerobic digestion. Green and emerging extraction technologies, circular economy and biorefinery frameworks, and the principal technological and regulatory barriers to commercial-scale adoption are also examined. The chapter concludes that systematic valorization of fruit and vegetable processing waste offers a scientifically robust and commercially promising pathway toward reducing the environmental footprint of the food industry while generating novel, sustainable, and economically viable product streams.

Keywords: Fruit and Vegetable Waste, Valorization, Bioactive Compounds, Pectin, Circular Economy, Biorefinery, Anaerobic Digestion, Sustainable Food Processing.

1. Introduction

Fruits and vegetables occupy a central position in global agri-food systems, valued both for their direct nutritional contribution and for their role as raw material for an extensive range of processed products, including juices, purees, jams, pickles, dehydrated snacks, and canned goods. However, the cultivation, handling, processing, and distribution of these commodities generate substantial quantities of organic residues at every stage of the supply chain. Losses and

waste associated with fruits and vegetables are consistently reported to be the highest among all food categories, with global estimates indicating that a large proportion of total fruit and vegetable production, in some assessments approaching half of all output, is lost or wasted between the field and the consumer's plate. The Food and Agriculture Organization of the United Nations has repeatedly identified fruits and vegetables as the food group most susceptible to loss because of their high moisture content, delicate tissue structure, and continued physiological activity after harvest, all of which accelerate spoilage relative to more durable commodities such as cereals.

Within the processing sector specifically, residues such as peels, seeds, pomace, rinds, cores, stems, and pulp remnants are generated as an unavoidable consequence of juicing, canning, freezing, and drying operations, frequently constituting between one-quarter and one-half of the raw material mass depending on the commodity and processing method. Conventional disposal of these residues, whether through open dumping, landfilling, or incineration, imposes considerable environmental burdens, including methane emissions from anaerobic decomposition, leachate-related water contamination, and the loss of embedded nutritional and economic value that could otherwise be recovered. At the same time, the perishable nature of these residues, combined with logistical and infrastructural constraints in many producing regions, has historically limited the extent to which fruit and vegetable processing waste has been systematically valorized rather than discarded.

In recent years, however, a substantial body of scientific literature has established that fruit and vegetable processing residues are not merely a disposal burden but a concentrated reservoir of nutritionally and functionally valuable compounds. Peels, seeds, and pomace fractions have been repeatedly shown to contain equal or even higher concentrations of polyphenols, carotenoids, dietary fibre, and other bioactive constituents than the corresponding edible portions of the fruit, reflecting the protective and structural roles these compounds play in the outer tissues of plants. This recognition, combined with growing regulatory and consumer pressure to minimise food loss and waste in line with the United Nations Sustainable Development Goals, has driven a rapid expansion of research into technologies capable of extracting, stabilising, and commercially deploying these residual compounds. The concept of a circular bioeconomy, in which agricultural and food-processing residues are systematically reintegrated into productive value chains rather than treated as terminal waste, has emerged as the dominant organising framework for this body of research.

This chapter provides a structured review of the composition of fruit and vegetable processing waste and the principal strategies through which it can be valorized, encompassing the recovery of high-value bioactive compounds, the extraction of functional biopolymers such as pectin, the development of active and biodegradable packaging materials, and the generation of renewable

energy through anaerobic digestion. The chapter further considers the extraction technologies that underpin these valorization pathways, the integration of these approaches within circular economy and biorefinery frameworks, and the technological, economic, and regulatory challenges that continue to constrain large-scale industrial adoption.

2. Composition and Generation of Fruit and Vegetable Processing Waste

Fruit and vegetable processing waste is highly heterogeneous in composition, reflecting the diversity of raw materials, processing operations, and product streams from which it originates. Broadly, this waste stream can be classified into peel and rind fractions, seed and kernel fractions, pomace and pulp residues remaining after juice or puree extraction, and vegetative residues such as stems, leaves, and husks. Each fraction differs markedly in its proximate composition, moisture content, and concentration of bioactive constituents. Citrus peels, for example, are particularly rich in pectin, essential oils, and flavonoids such as hesperidin and naringin, whereas pomace from grape and apple processing is a concentrated source of polyphenols, including anthocyanins and procyanidins, alongside substantial dietary fibre content. Tomato processing residues are notable for their lycopene and carotenoid content, while onion and garlic peels contain high concentrations of quercetin and organosulfur compounds with documented antioxidant and antimicrobial activity.

The scale of waste generation within the fruit and vegetable processing sector is considerable. Industry-level estimates indicate that processing operations such as juicing and canning can generate residue streams equivalent to a substantial proportion of the initial raw material mass, with peel and pomace fractions alone accounting for a significant share of total output in commodities such as citrus, apple, mango, and pineapple. The seasonal and geographically concentrated nature of fruit and vegetable processing further complicates waste management, as large volumes of residue are generated within short harvest windows, straining the capacity of conventional disposal infrastructure and increasing the urgency of developing rapid, cost-effective valorization pathways that can be deployed close to the point of generation.

3. Recovery of Bioactive Compounds from Processing Waste

The recovery of bioactive compounds represents one of the most extensively researched and commercially promising valorization pathways for fruit and vegetable processing waste. Peel, seed, and pomace fractions are established sources of phenolic compounds, carotenoids, flavonoids, and dietary fibre, all of which retain substantial antioxidant, antimicrobial, and health-promoting properties following extraction. Comprehensive reviews of this literature confirm that fruit and vegetable waste streams frequently contain higher concentrations of these compounds than the corresponding edible tissue, a consequence of the concentration of protective phytochemicals in outer peel and seed layers as a defence against oxidative stress and microbial attack (Sagar *et al.*, 2018). These recovered compounds have demonstrated application

as natural antioxidants and antimicrobial agents in food preservation, as functional ingredients in nutraceutical and dietary supplement formulations, and as active components in cosmetic and pharmaceutical products.

Dietary fibre recovered from fruit and vegetable processing residues has attracted particular research interest owing to its favourable technological and physiological properties. Peel, pomace, and pulp fractions are typically rich in both soluble and insoluble fibre, and their incorporation into bakery, dairy, and meat products has been shown to improve water- and oil-holding capacity, enhance textural stability, and increase the total dietary fibre content of the fortified product without materially altering sensory acceptability (Hussain *et al.*, 2020). Beyond their conventional role as fibre sources, several fibre-rich fruit and vegetable waste fractions have demonstrated prebiotic potential, selectively stimulating the growth of beneficial gut microbiota populations and thereby offering a pathway toward the development of functional foods targeting digestive health.

Specific waste fractions have been the subject of detailed characterisation studies establishing their suitability for targeted bioactive recovery. Onion peel, for instance, has been documented as a particularly concentrated source of the flavonol quercetin and its glycosides, exhibiting pronounced antioxidant, anti-inflammatory, and antimicrobial activity that supports its application as a functional ingredient and natural preservative (Kumar *et al.*, 2022). Comparable case studies exist for citrus, pomegranate, mango, and grape processing residues, collectively demonstrating that the bioactive potential of fruit and vegetable waste is not restricted to a small number of commodities but is a broadly generalisable characteristic of horticultural processing residues across diverse botanical families.

4. Extraction Technologies for Waste Valorization

The efficient and economically viable recovery of bioactive compounds from fruit and vegetable processing waste is critically dependent on the extraction technology employed. Conventional solvent extraction methods, while widely used, are frequently characterised by extended processing times, substantial solvent consumption, and thermal degradation of heat-sensitive compounds, prompting a sustained shift toward green and emerging extraction technologies. Ultrasound-assisted extraction exploits acoustic cavitation to disrupt plant cell walls and enhance mass transfer, substantially reducing extraction time and solvent requirements relative to conventional maceration while improving yields of phenolic and flavonoid compounds. Microwave-assisted extraction similarly accelerates cell disruption through rapid, volumetric dielectric heating, and has been widely applied to the recovery of pectin, essential oils, and polyphenols from citrus and other fruit processing residues.

Enzyme-assisted extraction, employing cellulolytic, pectinolytic, or hemicellulolytic enzyme preparations to degrade structural plant cell wall polysaccharides, offers a further green

alternative capable of operating under mild temperature and pH conditions favourable to the preservation of thermolabile bioactive compounds. Supercritical fluid extraction using carbon dioxide as a non-toxic, readily removable solvent has likewise gained prominence for the recovery of lipophilic compounds such as carotenoids and essential oils, offering the additional advantage of a solvent-residue-free extract suitable for food and pharmaceutical applications. Comparative reviews of these emerging technologies consistently report that green extraction methods achieve comparable or superior extraction yields relative to conventional solvent-based approaches while substantially reducing processing time, energy consumption, and environmental impact, positioning them as the preferred technological pathway for industrial-scale valorization of fruit and vegetable processing waste (Rodriguez Garcia & Raghavan, 2022).

5. Pectin Extraction and Functional Applications

Pectin, a structural heteropolysaccharide abundant in the cell walls of citrus peel, apple pomace, and a range of other fruit processing residues, represents one of the most commercially mature value-added products derived from fruit and vegetable waste valorization. Conventionally extracted using hot acid hydrolysis, pectin recovery has increasingly incorporated green extraction methods, including ultrasound- and microwave-assisted techniques, which improve extraction yield and reduce processing time while offering greater control over the degree of esterification and molecular weight distribution that determine pectin's gelling and thickening functionality (Mao *et al.*, 2019). Recovered pectin retains extensive application across the food industry as a gelling and stabilising agent in jams, confectionery, and dairy products, and its established biocompatibility and biodegradability have additionally positioned it as a candidate biopolymer for pharmaceutical drug delivery systems and edible packaging films.

The structural characteristics of pectin extracted from fruit and vegetable waste vary considerably depending on the source material, extraction method, and processing conditions, necessitating careful optimisation to achieve the specific gelling, viscosity, and stability properties required for a given industrial application. Nonetheless, the well-established market demand for pectin as a food additive, combined with the wide availability of citrus and apple processing residues as low-cost feedstock, has made pectin recovery one of the most economically attractive and technologically mature pathways for fruit and vegetable waste valorization at commercial scale.

6. Active and Biodegradable Packaging Materials

The development of active and biodegradable packaging materials from fruit and vegetable processing waste has emerged as a rapidly expanding valorization pathway, driven by mounting regulatory and consumer pressure to reduce reliance on petroleum-derived plastic packaging. Biopolymers extracted from fruit and vegetable residues, including pectin, cellulose, and starch, have been formulated into edible films and coatings that extend the shelf life of fresh and

minimally processed produce by functioning as a barrier to moisture loss and gas exchange while simultaneously offering biodegradability at the end of their functional life. The incorporation of polyphenol- and anthocyanin-rich extracts derived from fruit and vegetable waste into these packaging matrices has further enabled the development of active and intelligent packaging systems, in which the incorporated bioactive compounds impart antioxidant and antimicrobial functionality to the packaging material while simultaneously acting as visual pH- or freshness-indicators capable of signalling spoilage through a colour change (Mohd Basri *et al.*, 2021).

Beyond film and coating applications, fruit and vegetable waste fractions have also been investigated as reinforcing fillers in biocomposite materials, where their fibrous structure contributes to improved mechanical strength and thermal stability relative to unreinforced biopolymer matrices. Collectively, these applications position fruit and vegetable processing waste as a viable and sustainable feedstock for the packaging industry, offering a pathway to simultaneously reduce food waste, plastic packaging demand, and the associated environmental burden of both waste streams.

7. Bioenergy Generation through Anaerobic Digestion

Where the direct recovery of bioactive compounds or biopolymers is not economically viable, particularly for highly degraded, mixed, or contaminated waste streams, anaerobic digestion offers an effective pathway for converting fruit and vegetable processing residues into biogas, a renewable energy source composed primarily of methane and carbon dioxide. The high moisture content, favourable carbon-to-nitrogen ratio, and readily biodegradable carbohydrate fraction characteristic of fruit and vegetable waste make it a highly suitable substrate for anaerobic digestion, with reported biogas yields varying considerably depending on the specific waste composition, digester configuration, and operating parameters such as retention time, organic loading rate, and pH (Bouallagui *et al.*, 2009).

Co-digestion of fruit and vegetable waste with complementary substrates, including animal manure or lignocellulosic residues, has been repeatedly shown to improve process stability and biogas yield relative to mono-digestion, by correcting nutrient imbalances and buffering the rapid acidification that can otherwise destabilise digesters fed exclusively with readily fermentable fruit and vegetable substrates. The digestate remaining after anaerobic digestion additionally retains value as a nutrient-rich organic fertilizer, further enhancing the overall resource efficiency of this valorization pathway. Given the seasonal and often geographically dispersed nature of fruit and vegetable processing operations, anaerobic digestion offers particular utility as a decentralised, on-site waste management solution capable of converting otherwise unmanageable waste volumes into usable renewable energy with comparatively modest capital investment relative to advanced bioactive extraction infrastructure.

8. Circular Economy and Integrated Biorefinery Approaches

The various valorization pathways for fruit and vegetable processing waste, spanning bioactive compound recovery, pectin extraction, packaging material development, and bioenergy generation, are increasingly conceptualised not as competing alternatives but as complementary stages within an integrated biorefinery framework. Under this approach, a single waste stream is sequentially processed to recover the highest-value fractions first, typically bioactive compounds and functional biopolymers, with the residual biomass subsequently directed toward lower-value but still productive applications such as animal feed, composting, or anaerobic digestion, thereby maximising the total resource recovery achieved from a given quantity of waste (Sarker *et al.*, 2024).

This biorefinery model aligns closely with the broader principles of the circular bioeconomy, which seeks to minimise waste generation across agricultural and food-processing value chains while maximising the productive reuse of unavoidable residues. Systematic reviews of fruit and vegetable waste valorization consistently identify conventional utilisation pathways, including composting and animal feed formulation, alongside emerging high-value applications such as targeted bioactive extraction and biopolymer recovery, as complementary rather than mutually exclusive components of a comprehensive waste management strategy (Ganesh *et al.*, 2021). The successful implementation of integrated biorefinery approaches at commercial scale nonetheless requires substantial investment in process engineering, logistics coordination, and market development to ensure that the diverse product streams generated can be reliably matched to corresponding downstream demand.

9. Challenges and Barriers to Commercial Adoption

Despite the substantial scientific evidence supporting the technical feasibility of fruit and vegetable waste valorization, several persistent challenges continue to constrain widespread commercial adoption. The seasonal and geographically dispersed nature of fruit and vegetable processing generates highly variable waste volumes and compositions, complicating the design of valorization infrastructure sized for consistent year-round operation. The perishable nature of fresh waste streams necessitates rapid processing or preservation immediately following generation to prevent microbial spoilage and the associated degradation of target bioactive compounds, imposing logistical constraints that are particularly acute in regions lacking cold chain infrastructure.

Economic viability remains a further significant barrier, particularly for high-value bioactive extraction pathways that require substantial capital investment in extraction, purification, and stabilisation equipment. The regulatory pathway for novel food ingredients and packaging materials derived from waste streams also varies considerably across jurisdictions, and in many regions remains insufficiently developed to provide manufacturers with a predictable and

streamlined route to market approval. Consumer perception presents an additional consideration, as ingredients explicitly derived from waste streams may encounter scepticism or reduced acceptance among certain consumer segments despite their demonstrated safety and functional equivalence to conventionally sourced ingredients, underscoring the importance of transparent communication regarding the safety, quality, and sustainability benefits of waste-derived products.

Conclusion

Fruit and vegetable processing waste, long regarded primarily as a disposal burden, is increasingly recognised as a concentrated and commercially valuable reservoir of bioactive compounds, functional biopolymers, and renewable energy potential. The valorization pathways reviewed in this chapter, encompassing bioactive compound recovery, pectin extraction, active and biodegradable packaging development, and anaerobic digestion for bioenergy generation, collectively demonstrate that fruit and vegetable waste can be systematically converted into a diverse portfolio of value-added products across the food, packaging, pharmaceutical, and energy sectors. The integration of these pathways within circular economy and biorefinery frameworks offers a particularly promising strategy for maximising total resource recovery from a given waste stream, aligning food industry practice with broader sustainability and environmental objectives. Realising the full commercial potential of fruit and vegetable waste valorization will nonetheless require continued investment in process optimisation, supply chain logistics, regulatory harmonisation, and consumer communication, underscoring the need for sustained interdisciplinary collaboration among food scientists, process engineers, policymakers, and industry stakeholders in translating this substantial body of scientific evidence into widely deployed commercial practice.

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EDIBLE COATINGS: PRINCIPLES, MATERIALS, APPLICATIONS, AND EMERGING TRENDS

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Abstract

Edible coatings are thin, consumable layers applied directly onto the surface of food products to extend shelf life, preserve quality, and, increasingly, to deliver bioactive and antimicrobial compounds. Formulated from polysaccharides, proteins, lipids, or their composites, these coatings act as semi-permeable barriers that regulate moisture loss, gas exchange, and microbial contamination, thereby slowing senescence in fresh produce and reducing oxidative and microbial spoilage in a wide range of foods. This chapter presents a comprehensive overview of edible coatings, tracing their historical evolution from simple wax applications to today's multifunctional, nanostructured systems. It examines the conceptual basis and classification of coatings, the film-forming materials, plasticizers, and bioactive additives used in their formulation, and the principal methods of preparation and application. The mechanisms by which coatings protect food, the functional properties they confer, and the factors that govern their performance are discussed, along with their specific applications in fruits and vegetables. The advantages and limitations of edible coatings are critically evaluated, and recent advances in nanotechnology-enabled, active, and smart coatings are reviewed. The chapter concludes with a discussion of future perspectives, emphasizing the role of edible coatings in sustainable food packaging and postharvest loss reduction.

Keywords: Edible Coatings, Film-Forming Materials, Postharvest Preservation, Active Packaging, Nanotechnology, Fruits and Vegetables.

1. Introduction

Post-harvest losses of fresh produce remain one of the most persistent challenges in global food security, with estimates suggesting that up to half of all harvested fruits and vegetables are lost between farm and fork, largely due to moisture loss, microbial spoilage, and physiological deterioration (Ali *et al.*, 2025). Conventional synthetic packaging materials, while effective barriers, are increasingly scrutinized for their environmental footprint and limited biodegradability. Against this backdrop, edible coatings have emerged as a sustainable, food-

compatible alternative capable of simultaneously extending shelf life and reducing dependence on petroleum-based plastics.

An edible coating is generally defined as a thin layer of edible material, typically less than 0.3 mm thick, formed directly on the surface of a food product from a solution, emulsion, or dispersion of biopolymers (Martins *et al.*, 2024). Unlike edible films, which are pre-formed as standalone sheets and subsequently wrapped around or placed between food components, coatings are applied in situ, most commonly by dipping, spraying, or brushing (Martins *et al.*, 2024). Because they are consumed along with the food, edible coatings must be formulated exclusively from food-grade, non-toxic, and organoleptically neutral materials. This chapter synthesizes current scientific understanding of edible coatings, integrating classical concepts with recent developments in bioactive, nanostructured, and smart coating systems, with particular emphasis on their application to fruits and vegetables.

2. Historical Development of Edible Coatings

The practice of coating foods to extend their usability predates modern food science by centuries. Waxing of citrus fruits to retard moisture loss is documented as early as the twelfth and thirteenth centuries in China, where fruits were dipped in wax to create a glossy, protective layer. Later, larding techniques in the sixteenth century used fat layers to protect meat from spoilage during storage. Commercial wax coatings for fresh produce were introduced in the 1930s in the United States, marking the beginning of systematic industrial application of edible coatings to fruits and vegetables. Modern reviews note that early wax-based coatings applied to fruit surfaces represent the direct precursor of contemporary edible coating technology (Martins *et al.*, 2024).

Through the mid-twentieth century, the development of composite films based on gelatin, starch, and other hydrocolloids expanded the functional scope of edible coatings beyond simple gloss and moisture retention. Kester and Fennema's seminal review in the 1980s consolidated the scientific basis of edible films and coatings, systematically classifying materials and clarifying the mechanisms by which they influence moisture and gas transfer (Kester & Fennema, 1986). The 1990s and 2000s saw the incorporation of antimicrobial and antioxidant agents into coating matrices, an approach later termed "active" edible coatings (Rojas-Graü *et al.*, 2009). Since the 2010s, research has moved toward nanotechnology-enabled and stimuli-responsive ("smart") coatings, reflecting a broader shift toward multifunctional, intelligent food preservation systems (Garcia, 2022).

3. Concept and Principles

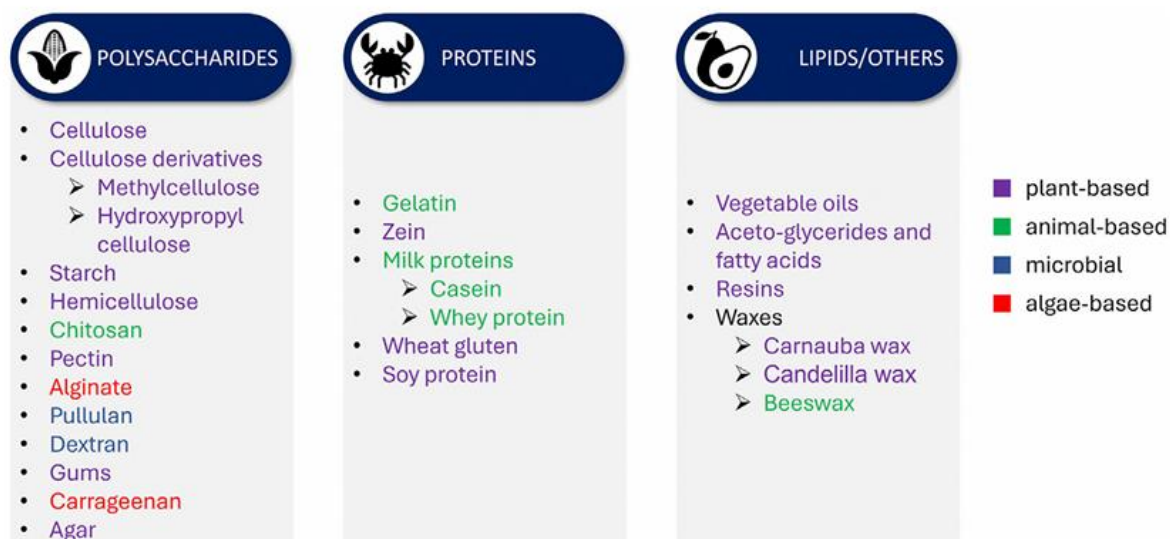
At its core, an edible coating functions as a semi-permeable barrier interposed between the food surface and its surrounding environment. The underlying principle is the modification of the internal atmosphere immediately surrounding the product, analogous to modified atmosphere

packaging, but achieved through a thin, adherent, edible layer rather than an external package. By selectively restricting the diffusion of water vapor, oxygen, carbon dioxide, and volatile compounds, coatings reduce respiration rate, transpiration, and enzymatic browning, and can also serve as carriers for functional additives such as antimicrobials, antioxidants, colorants, and nutrients (Falguera *et al.*, 2011). For a coating to be effective, its formulation must achieve a balance between several often competing properties: adequate barrier performance, sufficient mechanical strength and flexibility to withstand handling, transparency and gloss for consumer appeal, and, above all, safety and sensory neutrality, since the coating is ingested along with the food. The film-forming solution must also exhibit good adhesion and wettability on the target food surface, which depends on the surface tension of the coating solution relative to the surface energy of the food (Falguera *et al.*, 2011).

4. Classification of Edible Coatings

Edible coatings are most commonly classified according to the chemical nature of their primary film-forming component into three broad categories: hydrocolloid-based, lipid-based, and composite coatings.

- **Hydrocolloid-based coatings** include polysaccharides (starch, cellulose derivatives, chitosan, alginate, pectin, carrageenan, and gums) and proteins (whey, casein, gelatin, soy protein, zein, and wheat gluten). These coatings generally form transparent, mechanically strong films with good barrier properties against oxygen and carbon dioxide but relatively poor resistance to water vapor transmission due to their hydrophilic nature (Falguera *et al.*, 2011).
- **Lipid-based coatings** are formulated from waxes (carnauba, beeswax, candelilla), acylglycerols, and fatty acids. Owing to their hydrophobic character, lipid coatings provide excellent moisture barrier properties but are typically brittle, opaque, and mechanically weaker than hydrocolloid films (Martins *et al.*, 2024).
- **Proteins based coatings** offer strong mechanical strength and gas barrier properties. They come from sources like animal proteins (e.g., casein, whey, gelatin) and plant proteins (e.g., soy, zein, wheat gluten). Their physicochemical properties, such as moisture retention, tensile strength, and vapor permeability, impact their effectiveness in edible films (Mathura *et al.*, 2025).
- **Composite (or bilayer/emulsion) coatings** combine hydrocolloids and lipids to exploit the complementary strengths of both material classes, achieving improved water vapor barrier properties while retaining the structural integrity conferred by the polymer matrix (Díaz-Montes & Castro-Muñoz, 2021).



Classification of edible coatings (Mathura *et al.*, 2025)

A further distinction can be made between passive coatings, which function primarily as physical barriers, and active or intelligent coatings, which incorporate functional agents or sensing elements to interact dynamically with the food or its environment (Garcia, 2022).

5. Film-Forming Materials

The choice of film-forming material determines the physicochemical and functional properties of the resulting coating. Polysaccharides such as chitosan, alginate, pectin, cellulose derivatives (carboxymethyl cellulose, methylcellulose, hydroxypropyl methylcellulose), and starch are widely used because of their abundance, biodegradability, and inherent film-forming capacity arising from their largely linear molecular structure. Chitosan, derived from crustacean exoskeletons, has attracted particular attention due to its intrinsic antimicrobial activity in addition to its filmogenic properties, and has become the most extensively studied base compound in recent bio-based coating research (Martins *et al.*, 2024). Proteins, including whey protein isolate, casein, gelatin, zein, and soy protein, form films through denaturation and cross-linking of polypeptide chains, typically induced by heat, pH adjustment, or the presence of plasticizers. Protein-based coatings generally offer excellent gas barrier properties, although their mechanical performance is sensitive to environmental humidity (Martins *et al.*, 2024). Lipids, such as beeswax, carnauba wax, candelilla wax, and various fatty acids and acylglycerols, are valued primarily for their hydrophobicity and consequent effectiveness as moisture barriers. Lipids are seldom used alone, since they lack the cohesive, self-supporting matrix formed by polysaccharides and proteins, and are more commonly incorporated into composite or emulsion-based systems (Díaz-Montes & Castro-Muñoz, 2021). Composite materials, combining two or more of the above classes, are increasingly favored because they allow formulators to tailor barrier, mechanical, and optical properties to the specific requirements of a given food product.

6. Plasticizers and Additives

Pure biopolymer films are frequently brittle and prone to cracking, which limits their practical application. Plasticizers, low-molecular-weight, hydrophilic compounds such as glycerol, sorbitol, and polyethylene glycol, are incorporated into film-forming formulations to reduce intermolecular forces between polymer chains, thereby increasing free volume and imparting flexibility, extensibility, and reduced brittleness to the resulting coating (Falguera *et al.*, 2011).

However, plasticizers also increase the free volume available for the diffusion of small molecules, which typically raises water vapor and gas permeability and can reduce the tensile strength of the film, illustrating the trade-off that formulators must manage between flexibility and barrier performance. Beyond plasticizers, coating formulations may incorporate surfactants and emulsifiers to stabilize lipid-hydrocolloid emulsions and improve wettability on the food surface, as well as cross-linking agents, such as calcium chloride for alginate- and pectin-based systems, which modify film thickness, moisture content, and mechanical rigidity through ionic gelation (Ali *et al.*, 2025).

7. Bioactive Compounds in Edible Coatings

A defining feature of contemporary edible coating research is the incorporation of bioactive compounds that confer functional benefits beyond passive barrier protection. Commonly incorporated bioactives include:

- **Antimicrobial agents:** essential oils (clove, cinnamon, oregano, rosemary), organic acids, bacteriocins, and, more recently, probiotic microorganisms, which inhibit the growth of spoilage and pathogenic microorganisms on food surfaces (Oliveira *et al.*, 2021).
- **Antioxidants:** ascorbic acid, tocopherols, and plant polyphenols, which delay lipid oxidation and enzymatic browning.
- **Nutraceuticals and vitamins,** added to enhance the nutritional value of the coated product.
- **Probiotics,** embedded within hydrocolloid or lipid matrices, which represent an innovative bioprotection strategy for fresh and minimally processed produce, delivering beneficial metabolites with inhibitory effects against surface-contaminating microorganisms while the encapsulating matrix protects the microbial cells during storage (Oliveira *et al.*, 2021).

The efficacy of bioactive-loaded coatings depends strongly on the compatibility between the active compound and the polymer matrix, the loading concentration, and the release kinetics of the compound from the film during storage.

8. Preparation and Application Methods

Preparation of edible coatings generally begins with the formation of a film-forming solution, emulsion, or dispersion, achieved by dissolving or dispersing the chosen biopolymers in an aqueous or hydroalcoholic medium, followed by the addition of plasticizers, bioactive compounds, and, where relevant, cross-linking agents. Homogenization, and in some cases mild heating, is used to ensure uniform distribution of components and to promote polymer solubilization or protein denaturation. Several methods are used to apply the resulting formulation to the food surface:

- Dipping, in which the product is immersed briefly in the coating solution, is the most widely used method for fruits and vegetables due to its simplicity and uniform coverage, particularly for irregularly shaped produce.
- Spraying, which atomizes the coating solution onto the food surface, allows more precise control of coating thickness and is well suited to continuous, high-throughput processing lines.
- Brushing, generally reserved for small-scale or artisanal applications.
- Panning, used mainly for confectionery and nuts, in which the coating is applied while the product is tumbled in a rotating drum.
- More advanced techniques, including electrospraying, electrospinning, and layer-by-layer assembly, have recently been introduced to achieve finer control over coating microstructure and to enable more sophisticated release kinetics for encapsulated bioactive compounds (Ali *et al.*, 2025).

Following application, coatings are typically dried under ambient or mildly heated conditions to remove residual solvent and promote film formation through polymer chain entanglement, cross-linking, or crystallization.

9. Mechanism of Action

Edible coatings protect food through several interrelated mechanisms. First, they act as semi-permeable barriers that restrict the transfer of water vapor, oxygen, and carbon dioxide between the food and its environment, thereby reducing moisture loss, retarding respiration, and creating a modified internal atmosphere that slows ripening and senescence in climacteric fruits (Falguera *et al.*, 2011). Second, coatings provide a physical barrier against microbial ingress and mechanical damage, reducing opportunities for spoilage organisms to colonize the food surface. Third, when loaded with antimicrobial or antioxidant agents, coatings function as active delivery vehicles, releasing these compounds gradually at the food surface, where microbial or oxidative activity is concentrated, thereby achieving a targeted, sustained protective effect that would not be possible with agents added directly to the bulk food. Fourth, certain coatings reduce ethylene accumulation or its perception at the tissue surface, indirectly delaying ripening-associated

softening and colour change. The relative contribution of each mechanism depends on the barrier properties, thickness, and composition of the coating, as well as the physiological characteristics of the coated product.

10. Functional Properties

The performance of an edible coating is assessed through several key functional properties. Water vapor permeability determines the coating's effectiveness in controlling moisture loss and is strongly influenced by the hydrophilic or hydrophobic nature of the film-forming material. Gas permeability (oxygen and carbon dioxide) governs the modification of internal atmosphere and, consequently, respiration rate and ripening behavior. Mechanical properties, including tensile strength, elongation at break, and elastic modulus, determine the coating's ability to withstand handling stresses without cracking or detaching. Optical properties, namely transparency, gloss, and color, influence consumer acceptance, since coatings are expected to enhance rather than detract from the visual appeal of the product. Solubility and water resistance affect the coating's structural integrity under conditions of high humidity or direct contact with water. Finally, when bioactive compounds are incorporated, antimicrobial and antioxidant activity become critical functional attributes, generally assessed through zone-of-inhibition assays, microbial count reduction, and measures of lipid oxidation or browning inhibition over the storage period (Ali *et al.*, 2025).

11. Factors Affecting Performance

The performance of edible coatings is governed by an interplay of formulation and environmental factors. The type and concentration of the film-forming polymer dictate the intrinsic barrier and mechanical characteristics of the coating, while the type and concentration of plasticizer modulate flexibility at the expense of barrier performance. Coating thickness, determined by the concentration of the film-forming solution and the application method, directly affects barrier efficiency, with thicker coatings generally providing greater protection but at increased risk of altering sensory characteristics such as taste and mouthfeel. Storage conditions, particularly temperature and relative humidity, influence both the physical stability of the coating and the physiological response of the coated produce; coatings that perform well under refrigerated conditions may behave quite differently at ambient temperature. The surface characteristics of the food product, including its natural wax layer, surface roughness, and moisture content, affect the adhesion and uniformity of the applied coating. Finally, interactions between the coating and the food matrix, including compatibility between plasticizers, bioactive compounds, and the food surface, can influence the release rate of active agents and the overall efficacy of the coating over time (Ali *et al.*, 2025).

12. Applications in Fruits and Vegetables

Edible coatings have found their most extensive application in the postharvest handling of fresh and minimally processed fruits and vegetables, where they help mitigate weight loss, delay ripening and softening, control browning, and inhibit microbial spoilage. Wax-based coatings have long been used commercially on citrus fruits, apples, and cucumbers to restore gloss and reduce moisture loss following washing (Ali *et al.*, 2025). Chitosan coatings have demonstrated efficacy in delaying ripening and reducing decay incidence in mangoes, strawberries, and tomatoes, attributable both to their gas barrier properties and their intrinsic antifungal activity. Alginate- and pectin-based coatings, often cross-linked with calcium salts, have been applied to fresh-cut fruit to reduce enzymatic browning and maintain firmness. Composite coatings combining hydroxypropyl methylcellulose with lipids have shown reduced water vapor permeability compared to lipid-free films while retaining acceptable transparency (Ali *et al.*, 2025).

Studies comparing different coating formulations on the same commodity illustrate the importance of matching coating chemistry to the specific physiology of the produce; for example, differences in the water-barrier limitations of hydrophilic coatings versus the more effective moisture control of wax-based coatings can lead to markedly different outcomes for weight loss and soluble solids retention across fruit types (Ali *et al.*, 2025). Beyond whole and fresh-cut produce, edible coatings loaded with probiotic cultures have also been explored as a bioprotective strategy for minimally processed vegetables, offering antimicrobial protection through the metabolic activity of the embedded microorganisms (Oliveira *et al.*, 2021).

13. Advantages and Limitations

Edible coatings offer several notable advantages. They are biodegradable and, being consumed with the food, generate no packaging waste. They can be tailored to carry functional bioactive compounds, adding value beyond simple physical protection. They are compatible with a wide range of fresh and processed foods and can often be applied using existing post-harvest handling infrastructure, such as dip tanks or spray lines used for waxing. Because they reduce moisture loss and respiration, they can meaningfully extend shelf life and reduce post-harvest losses, contributing directly to food security and sustainability goals (Ali *et al.*, 2025).

However, important limitations remain. Most hydrocolloid-based coatings offer relatively poor water vapor barrier properties compared to synthetic plastics, limiting their effectiveness for highly perishable, high-moisture produce unless combined with lipids or other barrier-enhancing strategies. Coating performance can be inconsistent across different cultivars or growing conditions, complicating standardization for commercial use. Sensory attributes, including taste, aftertaste, and mouthfeel, may be altered, particularly at higher coating thicknesses or bioactive loadings, potentially reducing consumer acceptance. Regulatory and labeling requirements for

coatings containing novel materials, particularly nanomaterials, remain unclear or inconsistent across jurisdictions, creating a barrier to commercialization (Ali *et al.*, 2025). Finally, the cost of specialty film-forming materials and bioactive compounds can be prohibitive relative to conventional packaging, particularly for low-margin commodity crops.

14. Recent Advances (Nanotechnology, Active, and Smart Coatings)

Recent research has substantially expanded the functional scope of edible coatings through the integration of nanotechnology, active packaging concepts, and stimuli-responsive design.

Nanotechnology-enabled coatings incorporate nanoemulsions, nanoparticles, or nanocomposites into the film-forming matrix to enhance barrier, mechanical, and optical properties while maintaining transparency and sensory acceptability. Nanoscale delivery systems can improve the dispersion and controlled release of hydrophobic bioactive compounds that would otherwise be difficult to incorporate into hydrophilic biopolymer matrices, and green-synthesized nanomaterials are increasingly favored to address consumer and regulatory concerns about nanomaterial safety. Metal and metal oxide nanoparticles, such as zinc oxide and copper oxide, have demonstrated potent antimicrobial activity in coating formulations applied to fruit surfaces, although questions remain regarding their long-term safety and migration behavior (Garcia, 2022).

Active edible coatings extend beyond passive barrier functions by incorporating antimicrobial, antioxidant, or controlled-release systems directly into the coating matrix. Advanced manufacturing techniques, including electrospraying, electrospinning, and layer-by-layer assembly, are being explored to engineer coating microstructures that provide more precise control over the release kinetics of embedded bioactive agents, moving active coatings from simple biopolymer layers toward genuinely multifunctional preservation systems (Garcia, 2022). Smart (intelligent) coatings incorporate sensing elements capable of responding to, or reporting on, changes in the internal or external environment, such as pH shifts associated with spoilage, providing real-time information on product freshness. While much of this innovation has originated in the broader active and intelligent packaging literature, its principles are increasingly being translated into edible coating formulations for fresh produce, reflecting a convergence between food packaging science and coating technology (Garcia, 2022). Collectively, these advances are reframing edible coatings from simple physical barriers into multifunctional platforms capable of simultaneously extending shelf life, delivering functional compounds, and communicating product quality.

15. Future Perspectives

The future development of edible coatings will likely be shaped by several converging trends. Greater emphasis will be placed on sourcing film-forming materials from agro-industrial by-products and food processing waste streams, aligning coating development with circular

bioeconomy principles and reducing the environmental footprint of coating production (Martins *et al.*, 2024). Continued advances in nanotechnology and encapsulation are expected to improve the stability, bioavailability, and controlled release of bioactive compounds, while green synthesis methods will help address consumer and regulatory concerns about nanomaterial safety. The integration of sensing and indicator technologies into edible coatings may enable genuinely intelligent produce that communicates its own freshness status to consumers and supply chain operators. At the same time, the field faces the ongoing challenge of translating promising laboratory-scale formulations into cost-effective, scalable industrial processes, and of establishing clear, harmonized regulatory frameworks for novel coating materials, particularly those incorporating nanomaterials or non-traditional bioactive agents. Consumer acceptance, encompassing sensory quality, perceived naturalness, and transparency about coating composition, will remain a decisive factor in the commercial success of next-generation edible coatings.

Conclusions

Edible coatings represent a versatile and increasingly sophisticated tool for extending the shelf life and enhancing the quality and safety of fresh and processed foods, particularly fruits and vegetables. Rooted in centuries-old wax-coating practices, the field has evolved into a rigorous scientific discipline encompassing polysaccharide, protein, and lipid-based film-forming materials, engineered plasticizer and additive systems, and, most recently, nanostructured, active, and smart coating technologies. By functioning as selective barriers to moisture and gas exchange and as delivery vehicles for antimicrobial, antioxidant, and nutraceutical compounds, edible coatings address multiple post-harvest challenges simultaneously. Realizing their full potential will require continued interdisciplinary research spanning food chemistry, materials science, and regulatory policy, aimed at improving barrier performance, ensuring safety, and achieving cost-effective, scalable commercial application. As pressure mounts to reduce both food waste and reliance on synthetic plastic packaging, edible coatings are well positioned to play an expanding role in sustainable food systems.

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NANOTECHNOLOGY IN SUSTAINABLE AGRICULTURE: EMERGING APPLICATIONS, CHALLENGES AND FUTURE PERSPECTIVES

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Abstract

Sustainable agriculture is essential for ensuring global food security while conserving natural resources and minimizing environmental degradation. Conventional farming practices, characterized by the extensive use of chemical fertilizers, pesticides, and irrigation, have increased agricultural productivity but have also contributed to soil degradation, water pollution, biodiversity loss and greenhouse gas emissions. These challenges have accelerated the search for innovative technologies that enhance productivity while promoting environmental sustainability. Nanotechnology has emerged as a promising interdisciplinary approach by offering advanced solutions for precision farming, efficient resource utilization and sustainable crop production. The unique physicochemical properties of engineered nanomaterials, including their high surface area, enhanced reactivity and controlled-release capabilities, improve nutrient delivery, crop protection, and water-use efficiency. Nano-enabled technologies such as nanofertilizers, nanopesticides, nanobiosensors, smart irrigation systems and soil remediation materials have demonstrated significant potential to improve crop productivity, enhance soil health, optimize water management and reduce the environmental footprint of agriculture. Furthermore, integration with precision agriculture and digital farming technologies facilitates real-time monitoring and site-specific resource management. Despite these advantages, concerns regarding environmental persistence, ecotoxicity, food safety, regulatory frameworks and large-scale commercialization remain significant challenges. This chapter reviews the principles, applications, benefits, environmental implications and future prospects of nanotechnology in sustainable agriculture, emphasizing the need for responsible innovation, comprehensive risk assessment and interdisciplinary research to support resilient agricultural systems and long-term global food security.

Keywords: Nanotechnology, Sustainable Agriculture, Nanofertilizers, Nanopesticides, Precision Agriculture, Nanobiosensors, Soil Remediation, Water Management, Climate-Smart Agriculture, Food Security.

1. Introduction

Agriculture forms the foundation of global food security, rural livelihoods, and economic development. However, rapid population growth, climate change, declining soil fertility, water scarcity, biodiversity loss, and increasing environmental pollution have created unprecedented challenges for sustainable agricultural production. According to the Food and Agriculture Organization, food production must increase substantially by 2050 to meet the nutritional demands of a growing population while ensuring efficient use of land, water, and other natural resources. Conventional agricultural practices have significantly enhanced crop productivity over the past few decades through the extensive use of synthetic fertilizers, pesticides, irrigation, and mechanization. Nevertheless, excessive dependence on these inputs has resulted in nutrient imbalance, soil degradation, groundwater contamination, greenhouse gas emissions, pesticide resistance, and adverse effects on non-target organisms, thereby threatening long-term agricultural sustainability (Liu and Lal, 2015; Kah *et al.*, 2018).

The need to produce more food using fewer resources has accelerated the search for innovative technologies capable of improving agricultural efficiency while minimizing environmental impacts. Among these, nanotechnology has emerged as one of the most promising scientific advances for sustainable agriculture. Nanotechnology involves the manipulation and application of materials with dimensions between 1 and 100 nanometers. At this scale, materials exhibit unique physicochemical properties, including high surface area, enhanced catalytic activity, improved adsorption capacity, and controlled-release behavior, making them highly effective for agricultural applications (Roco, 2003; Bayda *et al.*, 2020).

The application of nanotechnology has led to the development of several nano-enabled agricultural products, including nanofertilizers, nanopesticides, nanobiosensors, nanoherbicides, and smart delivery systems. These technologies improve nutrient use efficiency, reduce agrochemical losses, enhance crop protection, support precision farming, and promote efficient utilization of water and soil resources (Dimkpa and Bindraban, 2018). Nanobiosensors integrated with Artificial Intelligence (AI), Geographic Information Systems (GIS), and the Internet of Things (IoT) further enable real-time monitoring of crop health, soil fertility, irrigation requirements, and pest incidence, allowing farmers to adopt site-specific management practices and optimize agricultural inputs (Khot *et al.*, 2012).

Nanotechnology also offers promising solutions for environmental management through wastewater purification, heavy metal remediation, restoration of contaminated soils, and development of biodegradable nano-based formulations. Recent advances in green nanotechnology, involving the synthesis of nanoparticles using plant extracts, microorganisms, algae, and agricultural residues, have further improved the environmental compatibility of nano-enabled products by reducing the use of hazardous chemicals and promoting sustainable manufacturing processes (Iravani, 2011).

Despite these significant advantages, concerns regarding nanoparticle toxicity, environmental persistence, bioaccumulation, food safety, and occupational exposure continue to attract scientific attention. Comprehensive risk assessment, standardized safety protocols, and effective regulatory frameworks are therefore essential to ensure the responsible and sustainable application of nanotechnology in agriculture (Servin *et al.*, 2015).

This chapter critically reviews recent advances in agricultural nanotechnology, highlighting its applications in nutrient management, crop protection, precision agriculture, water conservation, and soil remediation. It also discusses environmental and human health concerns, regulatory developments, current challenges, and future research directions, emphasizing the role of nanotechnology in building resilient and sustainable agricultural systems capable of addressing future food security challenges.

2. Fundamentals of Nanotechnology and Agricultural Nanomaterials

Nanotechnology is a multidisciplinary field that involves the manipulation, design, and application of materials at the nanoscale, typically ranging from 1 to 100 nanometers (nm). Materials at this scale exhibit unique physicochemical properties, including a high surface area-to-volume ratio, enhanced catalytic activity, superior adsorption capacity, and distinct optical, electrical, and magnetic characteristics that differ considerably from their bulk counterparts. These properties have enabled the development of innovative technologies across medicine, electronics, environmental science, and agriculture, making nanotechnology one of the most rapidly advancing scientific disciplines of the twenty-first century (Roco, 2003; Bayda *et al.*, 2020).

The concept of nanotechnology was first proposed by physicist Richard Feynman in his visionary lecture "There's Plenty of Room at the Bottom" in 1959, where he highlighted the possibility of manipulating matter at the atomic level. Since then, remarkable advances in nanoscience have facilitated the synthesis of engineered nanomaterials with tailored physical and chemical properties for specific applications. In agriculture, nanotechnology has emerged as a promising tool to improve crop productivity while minimizing environmental impacts through efficient resource utilization and precision farming (Khot *et al.*, 2012; Prasad *et al.*, 2017).

Agricultural nanomaterials can be broadly categorized into carbon-based nanomaterials, metallic nanoparticles, metal oxide nanoparticles, polymeric nanoparticles, and nanocomposites. Carbon-based nanomaterials, including carbon nanotubes (CNTs), graphene, and graphene oxide, possess exceptional mechanical strength, electrical conductivity, and adsorption capacity, making them suitable for biosensors, water purification, and controlled delivery systems. Metallic nanoparticles such as silver (Ag), gold (Au), copper (Cu), and iron (Fe) exhibit remarkable antimicrobial properties and have been extensively investigated for crop protection and disease management. Among these, silver nanoparticles have demonstrated effective antibacterial and antifungal activity against several economically important phytopathogens (Kah

et al., 2018). Metal oxide nanoparticles, including zinc oxide (ZnO), titanium dioxide (TiO₂), iron oxide (Fe₃O₄), and silicon dioxide (SiO₂), represent another important class of agricultural nanomaterials. These nanoparticles are widely used in nanofertilizers, photocatalytic degradation of pollutants, environmental remediation, and stress tolerance enhancement. Zinc oxide nanoparticles, for instance, improve zinc availability to crops, while titanium dioxide nanoparticles enhance photosynthetic efficiency and facilitate degradation of organic pollutants under light irradiation (Liu & Lal, 2015; Duhan *et al.*, 2017).

Biodegradable polymeric nanoparticles synthesized from natural polymers such as chitosan, alginate, starch, cellulose, and poly(lactic-co-glycolic acid) (PLGA) have gained considerable attention because of their environmental compatibility. These nanocarriers enable controlled release of fertilizers, pesticides, herbicides, and plant growth regulators, thereby improving input efficiency while minimizing environmental contamination. Similarly, nanocomposites combine two or more nanomaterials to improve mechanical strength, nutrient retention, moisture conservation, and controlled-release properties, making them valuable in sustainable agricultural practices (Fraceto *et al.*, 2016; Dimkpa and Bindraban, 2018).

Nanoparticles can be synthesized through physical, chemical, and biological (green) methods. While physical and chemical methods provide precise control over particle size and morphology, they often require expensive equipment and hazardous chemicals. In contrast, green synthesis employs plant extracts, bacteria, fungi, algae, or agricultural wastes as reducing and stabilizing agents, offering an environmentally friendly and cost-effective alternative. Green-synthesized nanoparticles generally exhibit lower toxicity, improved biocompatibility, and reduced environmental impacts, making them particularly suitable for agricultural applications (Iravani, 2011; Ahmed *et al.*, 2016).

Following synthesis, nanoparticles are characterized using advanced analytical techniques such as Transmission Electron Microscopy (TEM), Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Dynamic Light Scattering (DLS), Fourier Transform Infrared Spectroscopy (FTIR), and Zeta Potential Analysis. These techniques provide information regarding particle size, morphology, crystallinity, elemental composition, and surface charge, ensuring the quality, stability, and reproducibility of nano-enabled agricultural products before field application (Kah *et al.*, 2018).

3. Applications of Nanotechnology in Sustainable Agriculture

Nanotechnology has emerged as a transformative technology for modern agriculture by enabling precise, efficient, and environmentally sustainable management of agricultural resources. Unlike conventional agricultural practices that rely heavily on chemical fertilizers and pesticides, nano-enabled technologies improve nutrient utilization, enhance crop protection, conserve water resources, and restore degraded soils while minimizing adverse environmental impacts. The integration of engineered nanomaterials into agricultural systems has significantly contributed to

the development of precision agriculture, climate-resilient farming, and sustainable crop production (Kah *et al.*, 2018; Prasad *et al.*, 2017).

3.1 Nanofertilizers

Nutrient management remains one of the most critical components of sustainable agriculture. Conventional fertilizers often exhibit low nutrient use efficiency because substantial quantities of applied nitrogen, phosphorus, and potassium are lost through volatilization, runoff, leaching, and soil fixation. Such losses not only reduce crop productivity but also contribute to eutrophication, groundwater contamination, and greenhouse gas emissions (Liu and Lal, 2015).

Nanofertilizers have emerged as an effective alternative by delivering nutrients in a controlled and site-specific manner. These fertilizers are developed either by synthesizing nutrients into nanoparticles or by encapsulating conventional fertilizers within nanocarriers such as chitosan, silica, nanoclays, or biodegradable polymers. Their small particle size and high surface area facilitate enhanced interaction with plant roots and leaves, improving nutrient uptake and translocation. Controlled nutrient release ensures synchronization between nutrient availability and crop demand, thereby increasing nutrient use efficiency while minimizing environmental losses (Dimkpa and Bindraban, 2018; Raliya *et al.*, 2018).

Several studies have demonstrated that zinc oxide, iron oxide, and nano-hydroxyapatite fertilizers significantly improve seed germination, chlorophyll synthesis, root development, photosynthetic efficiency, and crop yield compared with conventional fertilizers. Nano-enabled nutrient delivery systems also reduce fertilizer application frequency and contribute to sustainable nutrient management, particularly under intensive agricultural systems (Duhan *et al.*, 2017).

3.2 Nanopesticides

Crop losses caused by insects, pathogens, and weeds continue to threaten global food production. Although conventional pesticides remain indispensable for crop protection, their indiscriminate use has resulted in pesticide resistance, environmental contamination, and adverse effects on non-target organisms. Nanotechnology offers an alternative approach through the development of nanopesticides, which provide controlled, targeted, and sustained delivery of active ingredients (Khot *et al.*, 2012).

Nanopesticides are generally formulated by encapsulating pesticides within biodegradable nanocarriers or by utilizing nanoparticles possessing intrinsic antimicrobial activity. Chitosan nanoparticles, polymeric nanocapsules, silica nanoparticles, and liposomes enhance pesticide stability while reducing photodegradation and volatilization. Metallic nanoparticles such as silver, copper, and zinc oxide also exhibit broad-spectrum antimicrobial properties against bacterial and fungal pathogens. Consequently, nanopesticides require lower application rates, reduce pesticide residues, and improve compatibility with Integrated Pest Management (IPM) strategies (Kah *et al.*, 2018; Chhipa, 2019).

In addition to disease management, nano-formulations are being investigated for controlled herbicide delivery, reducing herbicide resistance and minimizing contamination of soil and aquatic ecosystems. Continued research is focusing on biodegradable nanocarriers that further enhance environmental safety.

3.3 Nanobiosensors and Precision Agriculture

Precision agriculture aims to optimize agricultural inputs through site-specific crop management. Nanobiosensors have become indispensable tools for this purpose because of their exceptional sensitivity, rapid response, and ability to detect biological and chemical changes at very low concentrations. These sensors integrate nanomaterials with biological recognition molecules to monitor soil nutrients, plant pathogens, pesticide residues, moisture status, and crop physiological responses in real time (Gogos *et al.*, 2012; Rai *et al.*, 2012).

Modern precision farming integrates nanobiosensors with AI, IoT, remote sensing, drones, and GIS. Continuous monitoring enables automated irrigation scheduling, variable-rate fertilizer application, disease forecasting, and pest surveillance, thereby reducing unnecessary agricultural inputs while improving crop productivity. Such digital agriculture technologies are expected to become increasingly important under climate change scenarios where timely decision-making is critical for maintaining agricultural sustainability (Wolfert *et al.*, 2017).

3.4 Nano-enabled Water Management and Soil Remediation

Water scarcity is one of the most pressing challenges confronting global agriculture. Nano-enabled technologies contribute to efficient water management through moisture-retaining nano-hydrogels, smart irrigation systems, nanofiltration membranes, and advanced water purification technologies. Nano-hydrogels increase soil water-holding capacity by absorbing large quantities of water and gradually releasing it during periods of moisture deficit. Soil moisture nanosensors further improve irrigation efficiency by continuously monitoring water availability and supporting automated irrigation systems (Duhan *et al.*, 2017).

Nanotechnology also plays an important role in restoring degraded agricultural soils. Nanomaterials such as nano zero-valent iron (nZVI), titanium dioxide, graphene oxide, and carbon nanotubes have demonstrated remarkable ability to adsorb, immobilize, or degrade heavy metals, pesticides, petroleum hydrocarbons, and other persistent pollutants. Their high adsorption capacity and catalytic activity accelerate remediation while improving soil quality and supporting sustainable land management (Mukhopadhyay, 2014; Servin *et al.*, 2015).

The adoption of green-synthesized nanoparticles produced using plant extracts, fungi, bacteria, and agricultural wastes further enhances environmental sustainability by reducing chemical consumption and improving biodegradability. Integration of nanotechnology with biological remediation approaches is expected to play a major role in restoring contaminated agricultural ecosystems and promoting circular bioeconomy practices.

4. Environmental and Human Health Risks of Nanotechnology in Agriculture

The rapid advancement of nanotechnology has revolutionized sustainable agriculture by improving nutrient management, crop protection, water conservation, and environmental remediation. Despite these significant benefits, the widespread application of engineered nanomaterials (ENMs) has raised concerns regarding their potential environmental and human health impacts. The unique physicochemical properties of nanoparticles, including their small size, high surface area, and enhanced reactivity, influence their interactions with living organisms and ecosystems in ways that differ from conventional agricultural chemicals (Kah *et al.*, 2018; Bayda *et al.*, 2020).

Once released into agricultural environments, nanoparticles may undergo aggregation, dissolution, oxidation, adsorption, or transformation depending on soil characteristics, pH, organic matter content, and microbial activity. These processes influence their persistence, mobility, and bioavailability in soil and water systems (Cornelis *et al.*, 2014). Although many nanoparticles improve nutrient availability and plant growth at appropriate concentrations, excessive accumulation may alter soil physicochemical properties and affect ecosystem functioning.

Soil microorganisms are particularly sensitive to engineered nanomaterials because they regulate nutrient cycling, decomposition, and maintenance of soil fertility. Several studies have demonstrated that prolonged exposure to high concentrations of silver (Ag), copper oxide (CuO), and zinc oxide (ZnO) nanoparticles can suppress microbial biomass, reduce enzyme activity, and modify microbial community structure (Servin *et al.*, 2015; Dimkpa *et al.*, 2020). Such changes may influence nutrient mineralization and long-term soil productivity. However, the magnitude of these effects depends on nanoparticle concentration, exposure duration, soil properties, and crop species, highlighting the importance of appropriate dosage and formulation.

Nanoparticles may also be absorbed by plant roots and translocated to stems, leaves, fruits, and seeds. At recommended concentrations, several nanoformulations enhance nutrient uptake, photosynthetic efficiency, and tolerance to abiotic stresses. Conversely, excessive nanoparticle exposure may induce oxidative stress through the generation of reactive oxygen species (ROS), resulting in membrane damage, chlorophyll degradation, and growth inhibition (Rico *et al.*, 2011). Therefore, understanding plant–nanoparticle interactions is essential for optimizing agricultural applications while minimizing phytotoxicity.

Environmental concerns also extend to aquatic ecosystems. Nanoparticles may enter rivers, lakes, and groundwater through agricultural runoff and irrigation return flows, where they can interact with algae, aquatic plants, invertebrates, and fish. Laboratory studies have reported that certain metallic nanoparticles cause oxidative stress, reduced growth, and impaired reproduction in aquatic organisms, although environmentally relevant concentrations are generally much

lower than those used in experimental studies (Klaine *et al.*, 2008). Continuous environmental monitoring is therefore necessary to evaluate long-term ecological impacts.

Human exposure to nanoparticles may occur through inhalation during manufacturing and field application, dermal contact, or ingestion of food containing nanoparticle residues. Current evidence indicates that nanoparticle toxicity depends on particle size, surface chemistry, concentration, and duration of exposure rather than solely on chemical composition (Fadeel *et al.*, 2018). Although most commercially developed agricultural nanomaterials are considered safe when used according to recommended guidelines, comprehensive toxicological studies and long-term epidemiological investigations remain limited.

To ensure the responsible application of nanotechnology in agriculture, robust environmental risk assessment and life-cycle analysis should accompany product development and commercialization. Greater emphasis should also be placed on green nanotechnology, which employs plant extracts, microorganisms, and agricultural wastes for nanoparticle synthesis, thereby reducing toxicity and improving biodegradability (Iravani, 2011). The adoption of science-based regulatory frameworks, standardized toxicity testing, and sustainable manufacturing practices will be essential for maximizing the benefits of nanotechnology while safeguarding environmental quality and public health.

5. Regulatory Framework, Challenges and Future Perspectives

The successful adoption of nanotechnology in sustainable agriculture depends not only on technological innovation but also on the establishment of comprehensive regulatory frameworks, effective risk assessment protocols, and public acceptance. Although numerous nano-enabled agricultural products have demonstrated promising results under laboratory and field conditions, their commercialization remains constrained by uncertainties regarding environmental safety, human health, standardization, and regulatory compliance. The unique physicochemical characteristics of engineered nanomaterials distinguish them from conventional agrochemicals and require specialized evaluation procedures before large-scale agricultural use (Kah *et al.*, 2018; Fadeel *et al.*, 2018).

Several international organizations have initiated efforts to develop guidelines for the safe application of nanotechnology. The Organisation for Economic Co-operation and Development (OECD) has established standardized protocols for evaluating the physicochemical properties, environmental fate, ecotoxicity, and human health risks of engineered nanomaterials (OECD, 2023). Similarly, the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) have emphasized the importance of science-based risk assessment and responsible innovation to ensure food safety and environmental sustainability. In the European Union, nanomaterials are regulated under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) framework, whereas the United States Environmental

Protection Agency (EPA) evaluates nano-enabled pesticides under existing pesticide legislation with additional safety requirements (European Commission, 2022; USEPA, 2023).

Despite these regulatory developments, several scientific and technical challenges continue to limit the widespread adoption of agricultural nanotechnology. One of the major concerns is the lack of standardized methods for nanoparticle characterization, toxicity assessment, and environmental monitoring. The behavior of nanoparticles is strongly influenced by particle size, shape, surface chemistry, aggregation, and environmental conditions, making risk assessment considerably more complex than that of conventional chemicals (Cornelis *et al.*, 2014). Furthermore, most available studies have been conducted under laboratory conditions, whereas long-term field investigations evaluating nanoparticle persistence, transformation, and ecological impacts remain limited.

Economic considerations also influence the adoption of nano-enabled agricultural technologies. Although nanofertilizers and nanopesticides improve resource-use efficiency, their production costs remain relatively high because of sophisticated synthesis methods and quality control requirements. This may limit accessibility for smallholder farmers, particularly in developing countries where conventional agricultural inputs remain more affordable. In addition, inadequate awareness, limited technical knowledge, and insufficient extension services further restrict farmer acceptance and large-scale implementation (Prasad *et al.*, 2017).

Future research should focus on developing environmentally benign and economically viable nanomaterials that combine high agricultural efficiency with minimal ecological risk. Green synthesis approaches using plant extracts, bacteria, fungi, algae, and agricultural residues have attracted considerable attention because they reduce hazardous chemical consumption, improve biocompatibility, and support circular bioeconomy principles (Iravani, 2011; Ahmed *et al.*, 2016). Such sustainable synthesis methods are expected to play an increasingly important role in the commercialization of nano-enabled agricultural products.

Another promising direction is the integration of nanotechnology with AI, IoT, GIS, remote sensing, robotics, and unmanned aerial vehicles (UAVs) to develop intelligent farming systems. Networks of nanosensors capable of continuously monitoring soil moisture, nutrient availability, crop health, and environmental conditions can generate real-time data for AI-based decision support systems. These technologies will enable automated irrigation, site-specific fertilizer application, early disease diagnosis, and precision pest management, thereby improving resource-use efficiency while reducing environmental impacts (Wolfert *et al.*, 2017).

Continued interdisciplinary collaboration among agronomists, nanotechnologists, environmental scientists, toxicologists, policymakers, and industry stakeholders will be essential for translating laboratory-scale innovations into commercially viable agricultural technologies. Equally important are public awareness programs, farmer training, and transparent regulatory policies that promote confidence in nano-enabled agricultural products. With responsible innovation,

rigorous scientific evaluation, and harmonized international regulations, nanotechnology has the potential to become a key driver of sustainable and climate-resilient agriculture in the coming decades.

Conclusion

Nanotechnology represents one of the most promising technological innovations for achieving sustainable agriculture by enhancing crop productivity, improving nutrient use efficiency, strengthening crop protection, conserving water resources, and restoring degraded soils. Nano-enabled products such as nanofertilizers, nanopesticides, nanobiosensors, and advanced soil and water management technologies offer significant advantages over conventional agricultural practices through precise delivery systems, controlled release of agrochemicals, and real-time monitoring of crop and environmental conditions. These innovations contribute to increased agricultural productivity while reducing resource consumption and environmental pollution.

Despite these benefits, the responsible implementation of nanotechnology requires careful consideration of environmental persistence, ecotoxicity, food safety, occupational exposure, and socioeconomic factors. Continued research on long-term environmental impacts, standardized risk assessment protocols, and science-based regulatory frameworks is essential to ensure the safe commercialization of nano-enabled agricultural products. Furthermore, advances in green nanotechnology and the integration of nanotechnology with AI, IoT, and precision agriculture are expected to accelerate the development of intelligent and resource-efficient farming systems.

In conclusion, nanotechnology has the potential to transform modern agriculture by supporting sustainable food production, environmental conservation, and climate resilience. Its successful adoption will depend on interdisciplinary research, technological innovation, effective regulation, and collaboration among researchers, policymakers, industry, and farmers. With these efforts, nanotechnology can make a significant contribution toward achieving global food security and sustainable agricultural development.

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ROLE OF MOLECULAR MARKERS AND GENOMIC TOOLS IN VEGETABLE CROP IMPROVEMENT: RECENT ADVANCES AND FUTURE PROSPECTS

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Abstract

Vegetable crops are indispensable components of human nutrition, providing essential vitamins, minerals, dietary fiber, antioxidants, and other health-promoting compounds. They play a crucial role in ensuring food and nutritional security, particularly in developing countries. However, vegetable production is frequently challenged by various biotic and abiotic stresses, limited adaptability to diverse environments, and the complex inheritance of economically important traits. Although conventional breeding methods have significantly contributed to vegetable crop improvement, their efficiency is often constrained by long breeding cycles, environmental influences, and difficulties in accurately selecting superior genotypes based solely on phenotypic performance. The advent of molecular markers has revolutionized plant breeding by enabling the identification and selection of desirable genes and genomic regions at the DNA level. Molecular markers act as reliable genomic landmarks associated with specific traits and facilitate precise, rapid, and environment-independent selection. Various marker systems, including Restriction Fragment Length Polymorphism (RFLP), Random Amplified Polymorphic DNA (RAPD), Amplified Fragment Length Polymorphism (AFLP), Simple Sequence Repeats (SSR), and Single Nucleotide Polymorphisms (SNPs), have been widely employed for genetic diversity analysis, gene mapping, phylogenetic studies, heterosis assessment, cultivar identification, and marker-assisted selection (MAS). Recent advancements in next-generation sequencing (NGS), high-throughput genotyping, genome-wide association studies (GWAS), genomic selection (GS), transcriptomics, and genome editing technologies such as CRISPR-Cas systems have further accelerated the pace and precision of vegetable breeding. The integration of molecular markers with these modern genomic tools has facilitated the development of high-yielding, quality-enhanced, and stress-resilient vegetable cultivars while significantly reducing breeding time and improving selection efficiency. This review highlights the principles, classification, applications, recent advances, and future prospects of molecular markers and genomic tools in vegetable crop

improvement, emphasizing their potential to address emerging agricultural challenges and contribute to sustainable vegetable production.

Keywords: Vegetable Breeding, Molecular Markers, Genomic Tools, Genetic Diversity, Genomic Selection, Next-Generation Sequencing, CRISPR-Cas, Sustainable agriculture.

Introduction

Vegetable crops are essential components of human nutrition and play a significant role in ensuring food and nutritional security worldwide. They are rich sources of vitamins, minerals, dietary fibre, antioxidants, and other health-promoting compounds. Besides their nutritional importance, vegetables contribute substantially to agricultural diversification, rural employment, and farmers' income. However, vegetable production is frequently constrained by various biotic stresses such as pests and diseases, as well as abiotic stresses including drought, salinity, temperature extremes, and climate change. These challenges often result in reduced productivity and quality, highlighting the need for the development of improved vegetable cultivars with enhanced yield potential, superior quality, and greater stress tolerance.

Conventional breeding methods have played a crucial role in the genetic improvement of vegetable crops and have led to the development of numerous commercially successful varieties. However, these approaches are often time-consuming and largely dependent on phenotypic selection, which can be influenced by environmental conditions and genotype \times environment interactions. Furthermore, many economically important traits such as yield, quality, and stress resistance are quantitatively inherited and controlled by multiple genes, making their improvement through conventional breeding relatively difficult and less precise.

The advent of molecular marker technology has revolutionized plant breeding by enabling the identification and selection of desirable genetic variations directly at the DNA level. Molecular markers are specific DNA sequences associated with particular genomic regions and serve as reliable tools for detecting genetic polymorphism among individuals. Their application has significantly improved the accuracy and efficiency of breeding programs by facilitating genetic diversity analysis, gene mapping, cultivar identification, phylogenetic studies, heterosis assessment, and marker-assisted selection. Various molecular marker systems, including RFLP, RAPD, AFLP, SSR, and SNP markers, have been successfully utilized in vegetable crop improvement programs.

Recent advances in genomic technologies have further expanded the scope of molecular breeding. The integration of next-generation sequencing (NGS), genome-wide association studies (GWAS), genomic selection (GS), and genome editing technologies such as CRISPR-Cas systems has enabled precise identification and manipulation of genes associated with important agronomic traits. These innovations have accelerated the development of high-yielding, nutritionally enriched, and stress-resilient vegetable cultivars. Therefore, molecular markers and

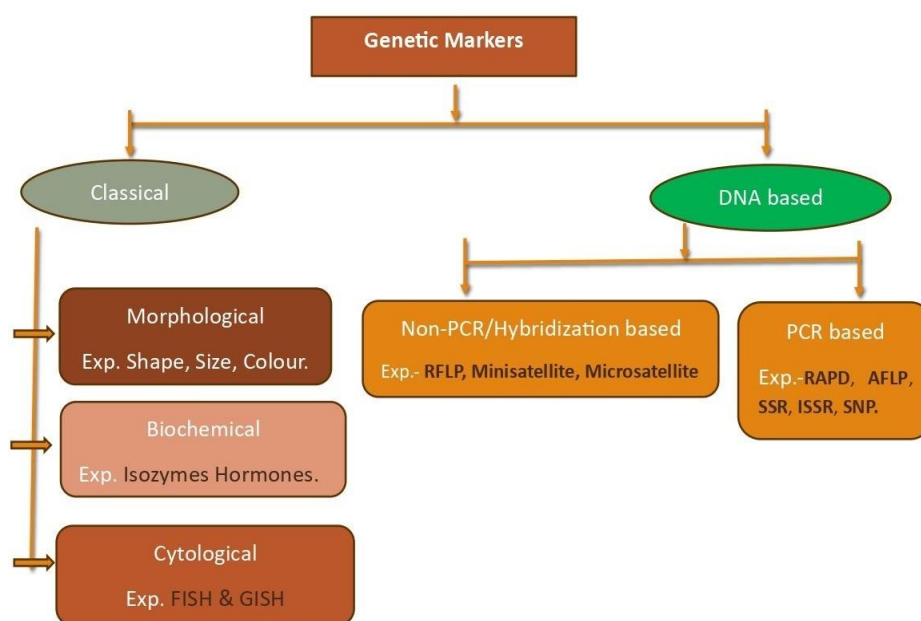
genomic tools have become indispensable components of modern vegetable breeding programs. This review discusses the principles, applications, recent advances, and future prospects of molecular markers and genomic technologies in vegetable crop improvement for sustainable agricultural development.

Applications:

- It plays a crucial role in gene mapping by identifying the position of linked genes in the chromosome which inherited together.
- It also detects any alteration in a sequence of DNA or any genetic oddity. It ascertains genes involved in genetic disorders.
- It is used to determine different characters in a DNA sequence which is used to distinguish between individuals, populations or species.

Molecular marker possesses unique genetic properties (i.e. they are heritable DNA sequences and phenotypically neutral) and identified by techniques such as southern hybridization and PCR. by integrating molecular markers into breeding programs, scientists can achieve greater accuracy in trait selection, improve genetic diversity, and develop vegetable varieties with enhanced resistance to biotic and abiotic stresses.

The use of molecular markers in vegetable breeding has gained significant attention due to their efficiency in identifying genes responsible for disease resistance, drought tolerance, early maturity, and enhanced nutritional content. Marker-assisted selection (MAS), quantitative trait loci (QTL) mapping, and genome-wide association studies (GWAS) have facilitated the rapid development of superior vegetable varieties with improved productivity and adaptability to changing environmental conditions.



Types of Molecular Markers Used in Vegetable Crop Improvement

- **Restriction Fragment Length Polymorphisms (RFLPs)** – One of the earliest molecular markers, used in genetic mapping and diversity studies.
- **Simple Sequence Repeats (SSRs)** – Highly polymorphic markers used for genome mapping and fingerprinting.
- **Single Nucleotide Polymorphisms (SNPs)** – High-throughput markers useful for MAS, GWAS, and genomic selection.
- **Amplified Fragment Length Polymorphisms (AFLPs)** – Useful for analysing genetic diversity and phylogenetic studies.
- **Random Amplified Polymorphic DNA (RAPD)** – Cost-effective markers used for genetic diversity studies and cultivar identification.
- **Diversity Arrays Technology (DArT)** – A high-throughput marker system for analysing genome-wide variation.

Applications of Molecular Markers in Vegetable Crops

1. Genetic Diversity Assessment

Molecular markers help assess genetic variation within and between vegetable species. This knowledge is crucial for germplasm conservation and breeding programs. For example, SSR and SNP markers have been used to evaluate genetic diversity in tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus*), and eggplant (*Solanum melongena*).

2. Marker-Assisted Selection (MAS)

MAS enables the selection of desirable traits at an early stage, reducing breeding cycles and improving efficiency. Examples include:

- **Disease resistance:** SNP markers have been used to develop Fusarium wilt-resistant tomato varieties.
- **Yield improvement:** QTL mapping and MAS have improved fruit size and weight in cucumber.
- **Abiotic stress tolerance:** Molecular markers help in developing drought and salt-tolerant varieties of lettuce and spinach.

3. Quantitative Trait Loci (QTL) Mapping

QTL mapping helps identify genomic regions controlling complex traits like fruit firmness, flavor, and nutritional content. For example:

- In carrot (*Daucus carota*), SNP markers have identified QTLs responsible for carotenoid accumulation.
- In pepper (*Capsicum spp.*), QTL mapping has facilitated the selection of capsaicin biosynthesis genes, controlling pungency.

4. Genome-Wide Association Studies (GWAS)

GWAS utilizes high-density SNP markers to link genetic variations with phenotypic traits. Recent studies in broccoli (*Brassica oleracea*) have identified loci controlling glucosinolate content, important for nutritional quality.

5. Genomic Selection (GS)

GS predicts breeding values of plants based on genome-wide markers. This accelerates selection and enhances breeding efficiency in crops like onion (*Allium cepa*) and cabbage (*Brassica oleracea*), where complex traits like storage life and disease resistance are targeted.

6. Hybrid Identification and Seed Purity Testing

Molecular markers help distinguish between hybrids and parental lines, ensuring seed purity. SNP markers have been widely used for hybrid purity testing in melon (*Cucumis melo*) and watermelon (*Citrullus lanatus*).

Future Prospects

The future of vegetable crop improvement will increasingly rely on the integration of molecular markers with advanced genomic and digital breeding technologies. Molecular markers are expected to become indispensable tools for accelerating the development of high-yielding, nutritionally enriched, and climate-resilient vegetable cultivars. Their integration with next-generation sequencing (NGS), genome-wide association studies (GWAS), genomic selection (GS), and genome editing technologies such as CRISPR-Cas systems will enable precise identification and manipulation of genes controlling complex agronomic traits.

The increasing availability of whole-genome sequences and high-throughput genotyping platforms will facilitate rapid gene discovery, quantitative trait loci (QTL) mapping, and marker-assisted selection for traits such as disease resistance, abiotic stress tolerance, quality, and yield. Furthermore, the application of artificial intelligence, machine learning, and bioinformatics will improve genomic data analysis and enhance breeding efficiency by enabling accurate prediction of superior genotypes.

Despite remarkable progress, challenges such as limited genomic resources for minor vegetable crops, high implementation costs, and the need for skilled personnel remain. Addressing these constraints through collaborative research, capacity building, and affordable genomic technologies will promote wider adoption of molecular marker-assisted breeding. Overall, molecular markers will continue to play a pivotal role in precision breeding, contributing to sustainable vegetable production, enhanced food and nutritional security, and the development of resilient cultivars capable of meeting future agricultural challenges.

Conclusion

Molecular markers and genomic tools have revolutionized vegetable crop improvement by enhancing selection accuracy, reducing breeding time, and facilitating the identification of genes

controlling economically important traits. Technologies such as QTL mapping, GWAS, genomic selection, next-generation sequencing, and genome editing have significantly accelerated breeding progress. In vegetable crops including onion, tomato, pepper, cucumber, and brinjal, these tools have enabled the development of high-yielding, stress-tolerant, and quality-enhanced cultivars. Future integration of genomics, phenomics, and artificial intelligence will further strengthen precision breeding and contribute to sustainable vegetable production and global food security.

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About Editor



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