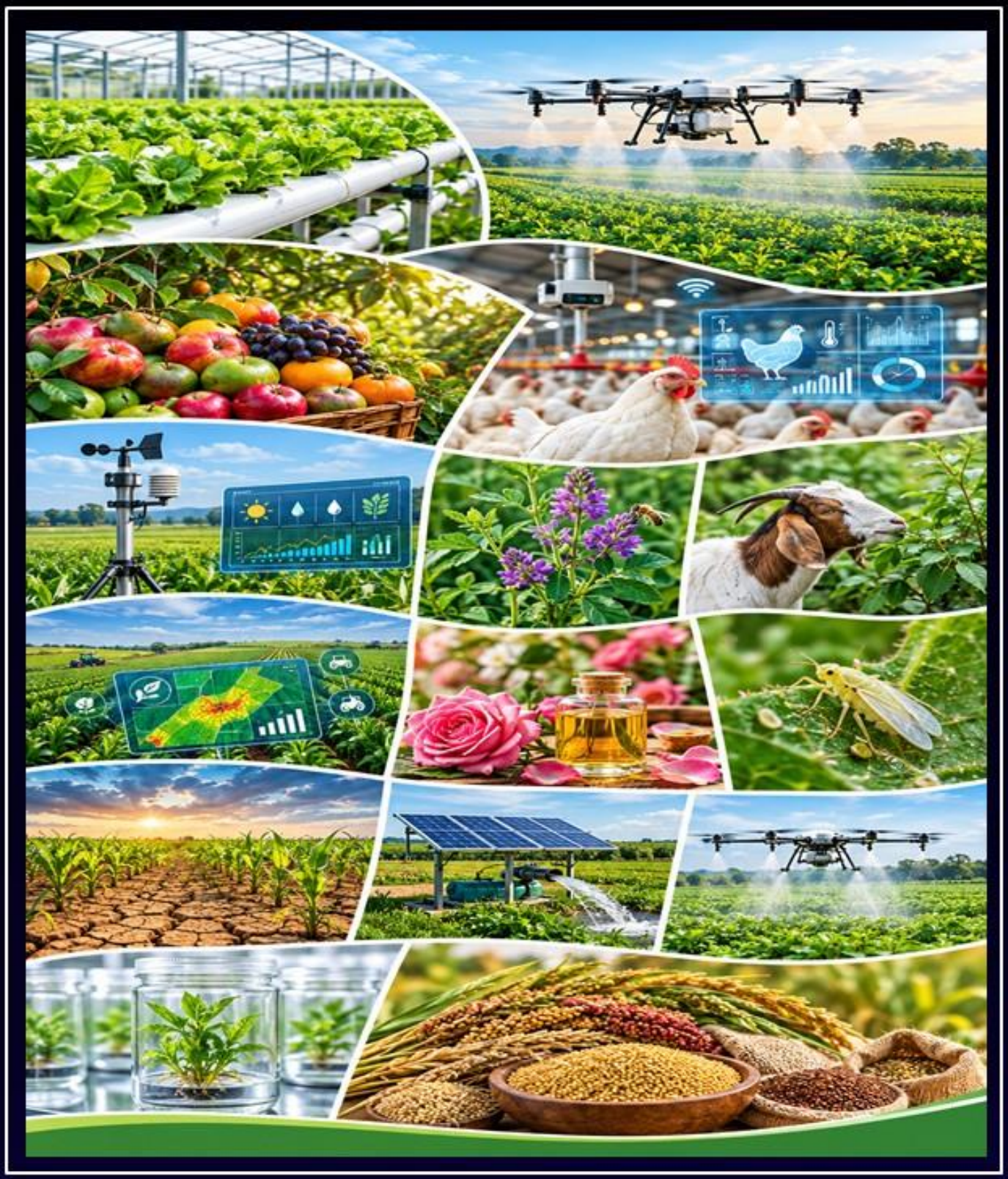
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VOL. 6 ISSUE 3 JULY- SEPTEMBER, 2026

# CONTENTS


| S. No. | | Page No |
|---|---|---|
| 1. | *HYDROPONICS: THE FUTURE OF SOIL-FREE FARMING*<br>Santhoshkumar A, Parkavi S, and Suruthika M | 1-9 |
| 2. | *FROM SKY TO SOIL: HOW DRONES AND WEATHER FORECASTING ARE TRANSFORMING INDIAN AGRICULTURE*<br>Sachin S Chinchorkar | 10-16 |
| 3. | *UNDERUTILIZED FRUITS OF THE WESTERN GHATS: BIODIVERSITY, NUTRITIONAL POTENTIAL, AND DEVELOPMENT OPPORTUNITIES*<br>Amrutha P | 17-25 |
| 4. | *ROLE OF ARTIFICIAL INTELLIGENCE IN POULTRY DISEASE DIAGNOSIS*<br>Asok Kumar M, Megha Sharma, Anshuk Sharma, and Sushmita Nautiyal | 26-31 |
| 5. | *COMPUTER MODELS IN AGRICULTURAL METEOROLOGY: A MODERN TOOL FOR CLIMATE-SMART FARMING*<br>Sachin S Chinchorkar | 32-35 |
| 6. | *SESBANIA ACULEATA: A GREEN GOLD FOR SUSTAINABLE AGRICULTURE*<br>Kamsali Sukeswara Achari, Tejaswini Chandrakar and Sanjeev Kumar | 36-42 |
| 7. | *MORINGA: A MIRACLE FEED FOR GOAT KIDS*<br>Ramesh Chandra and Srashti Dixit | 43-50 |
| 8. | *ARTIFICIAL INTELLIGENCE APPLICATIONS IN AGRICULTURE: TRANSFORMING FARMING FROM EXPERIENCE-BASED TO DATA-DRIVEN DECISION MAKING*<br>Sachin S Chinchorkar | 51-55 |

www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 3 JULY- SEPTEMBER, 2026


| | | |
|---|---|---|
| **9.** | *FRAGRANCE ENGINEERING IN FLOWERS: MOLECULAR MECHANISMS, TOOLS & FUTURE PROSPECTS*<br>Rayapu Sai Theja | 56-62 |
| **10.** | *MEALYBUGS: A POLYPHAGOUS PEST OF FIELD AND HORTICULTURE CROPS*<br>Tejpal Tetarwal and Rishika Choudhary | 63-69 |
| **11.** | *CLIMATE CHANGE AND CROP PRODUCTION: IMPACTS, RISKS, ADAPTATION STRATEGIES AND PATHWAYS FOR CLIMATE-RESILIENT AGRICULTURE*<br>Sachin S Chinchorkar | 70-74 |
| **12.** | *GREEN TECHNOLOGIES FOR SUSTAINABLE FOOD PRODUCTION*<br>K. Hazeera Bee and T. Jyothi | 75-82 |
| **13.** | *APPLICATION OF DRONE TECHNOLOGY IN PLANT PROTECTION*<br>Mohit Meena and Supriya Mondal | 83-91 |
| **14.** | *IN VITRO MUTAGENESIS IN CHRYSANTHEMUM: PROTOCOLS, STABILIZATION, AND PROSPECTS FOR CLIMATE RESILIENCE*<br>Chintakayala Srinu, Rayapu Sai Theja, and Ronanki Srinidhi | 92-96 |
| **15.** | *COMPUTER MODELS FOR AGRICULTURE: APPLICATIONS, ADVANCES AND FUTURE PROSPECTS*<br>Sachin S Chinchorkar | 97-102 |
| **16.** | *MILLETS: THE FUTURE SMART FOOD*<br>P. Bhuvaneswari and S. Hemalatha | 103-106 |
| **17.** | *MECHANIZATION TECHNOLOGIES FOR EFFICIENT AND SUSTAINABLE CHICKPEA SOWING*<br>Achugatla Kesav Kumar, A. Malliswara Reddy and V. Jayalakshmi | 107-119 |

Agri JOURNAL WORLD
www.journalworlds.com
AGRI JOURNAL WORLD
VOL. 6 ISSUE 3 JULY-SEPTEMBER, 2026

# HYDROPONICS: THE FUTURE OF SOIL-FREE FARMING

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## ABSTRACT

*Hydroponics is a soilless cultivation technology in which plants grow using nutrient solutions, with or without inert growing media. Growing concerns about water scarcity, limited arable land, urbanization and climate change have increased interest in this production system. Hydroponics enables precise nutrient management, efficient water use and intensive crop production, particularly for leafy vegetables, herbs and selected fruiting crops. However, its adoption is constrained by initial investment, energy requirements and technical complexity. This article examines the principles, major systems, advantages, limitations, crop suitability and future prospects of hydroponics in sustainable agriculture.*

**KEYWORDS:** Controlled-environment agriculture, Hydroponics, Soilless cultivation, Sustainable agriculture, Urban farming, Water-use efficiency

## INTRODUCTION

Agriculture faces increasing pressure to produce sufficient food while conserving natural resources and minimizing environmental impacts. Population growth, urbanization, declining soil quality, water scarcity and climate variability are creating challenges for conventional agricultural production systems. The Food and Agriculture Organization (FAO, 2017) emphasizes the need to transform food and agricultural systems to improve food security while promoting sustainable resource management.

Hydroponics is a soilless cultivation technique in which plants obtain essential mineral nutrients from a water-based nutrient solution. Depending on the system, plant roots may be directly exposed to the solution or supported by inert growing media. This approach enables growers to manage water and nutrient supply more precisely than in many conventional production systems (Savvas, 2003).

The term hydroponics combines the Greek words hydro, meaning water, and ponos, meaning labour. William F. Gericke helped popularize the technique during the 1930s by demonstrating that plants could be cultivated commercially without soil (Gericke, 1940).

Hydroponics is now used in greenhouses, vertical farms, rooftop gardens and other controlled-environment production facilities. It is particularly suitable for leafy vegetables, herbs and selected high-value crops where consistent quality, intensive production and efficient resource management are important. Nevertheless, its environmental and economic benefits depend on system design, crop selection, energy sources and management practices (Barbosa et al., 2015; Savvas & Gruda, 2018).

This article examines the basic principles, major production systems, benefits, limitations, suitable crops and future prospects of hydroponics as a component of sustainable agricultural development.

## PRINCIPLES OF HYDROPONIC CULTIVATION

Hydroponics is based on the principle that plants require water, essential mineral nutrients, oxygen, light and suitable environmental conditions for growth, but do not necessarily require soil. Soil primarily provides physical support and can supply or retain water and nutrients. In hydroponic systems, these functions are managed through nutrient solutions, root-supporting materials and appropriate equipment.

The nutrient solution contains essential elements such as nitrogen, phosphorus, potassium, calcium, magnesium and sulphur, together with micronutrients including iron, manganese, zinc, copper, boron and molybdenum. Their concentrations and proportions must be adjusted according to crop requirements, growth stage, water quality and environmental conditions.

Root-zone oxygen is equally important because roots require oxygen for respiration and nutrient uptake. Consequently, hydroponic systems must provide adequate aeration or maintain suitable moisture and air spaces around the roots. The pH and electrical conductivity (EC) of the nutrient solution are also monitored to maintain nutrient availability and an appropriate concentration of dissolved salts.

Plants may be grown directly in nutrient solutions or supported by materials such as coco coir, perlite, vermiculite, expanded clay pellets and rockwool (Resh, 2022). These materials provide physical support but generally do not replace the need for a properly formulated nutrient solution.

Effective hydroponic cultivation therefore depends on maintaining a balance among nutrient availability, water supply, oxygen, root-zone conditions, light and temperature. Poor management of any of these factors can reduce plant growth and productivity.

## MAJOR TYPES OF HYDROPONIC SYSTEMS

Hydroponic systems differ in the way nutrient solutions are supplied to plant roots, the degree of recirculation and the equipment required. The main systems are described below.

***1. Wick System***

The wick system is a passive hydroponic technique in which nutrient solution moves from a reservoir to the growing medium through absorbent wicks by capillary action. It requires little equipment and is relatively inexpensive to establish.

This system is suitable for small-scale cultivation, demonstrations and beginner-level applications. However, nutrient delivery may be insufficient for large plants or crops with high water and nutrient requirements.

***2. Deep Water Culture (DWC)***

In deep water culture, plant roots remain immersed in a nutrient solution, while an aeration system supplies oxygen to support root respiration. Plants are commonly held in net pots positioned above the reservoir.

DWC can support rapid growth in leafy vegetables when nutrient concentrations, water temperature and oxygen availability are appropriately managed. However, root-zone problems may develop rapidly if aeration fails or the solution becomes contaminated.

***3. Nutrient Film Technique (NFT)***

The nutrient film technique involves the continuous or near-continuous circulation of a shallow film of nutrient solution through slightly sloping channels. Plant roots partially contact the flowing solution while remaining exposed to air within the root zone.

NFT is widely used for lettuce and other leafy vegetables because it allows efficient nutrient delivery and recirculation. However, uninterrupted flow is important because roots can dry quickly when pumps fail or channels become blocked.

***4. Drip Hydroponic System***

In drip hydroponics, nutrient solution is delivered to individual plants through emitters or drip lines. Plants are commonly grown in substrates such as coco coir, perlite or rockwool, and the excess solution may be collected and recirculated or allowed to drain.

Drip systems are suitable for crops such as tomatoes, cucumbers, bell peppers and strawberries. They allow precise control of irrigation frequency and nutrient delivery, although emitters require maintenance to prevent clogging and uneven application.

***5. Ebb-and-Flow System***

The ebb-and-flow system, also known as flood-and-drain, periodically floods a growing tray with nutrient solution before allowing the solution to drain back into a reservoir. The cycle supplies water and nutrients while enabling air to re-enter the growing medium during drainage.

This system can accommodate a range of plants and substrates. Its performance depends on appropriate flooding frequency, drainage, root-zone aeration and control of nutrient-solution quality.

The selection of a hydroponic system should be based on crop requirements, available space, investment capacity, technical expertise, energy reliability and the intended scale of production.

## Advantages of Hydroponic Farming

Hydroponics offers several potential agronomic, economic and environmental advantages when the system is appropriately designed and managed.

*1. Efficient Water Use*

Recirculating hydroponic systems can reduce water consumption by limiting drainage losses and enabling unused nutrient solution to be reused. In a comparative study of lettuce production, Barbosa et al. (2015) reported substantially lower water requirements per unit of produce under hydroponic greenhouse cultivation than under conventional field production. However, actual savings vary with climate, system design, crop management and the production system used for comparison.

*2. Precise Nutrient Management*

Hydroponics allows growers to adjust nutrient concentrations and irrigation schedules according to crop requirements. This precision can improve nutrient-use efficiency and reduce nutrient losses when drainage and recirculation are properly managed.

Nevertheless, nutrient imbalances, excessive solution concentrations and inappropriate disposal of spent solutions can still cause environmental problems.

*3. Intensive Crop Production*

Hydroponics can support high productivity per unit area, particularly when crops are grown at appropriate densities under favourable environmental conditions. Vertical arrangements may further increase production area within a limited footprint.

However, higher yields are not guaranteed and depend on crop selection, light availability, temperature, nutrient management and effective operation of the production system.

*4. Year-Round Cultivation*

Greenhouses and other controlled-environment facilities can reduce the influence of adverse weather and extend production beyond normal field-growing seasons. This can improve the consistency of supply and market availability.

The extent of seasonal independence depends on the degree of environmental control, local climate and the availability and cost of heating, cooling and supplementary lighting.

*5. Reduced Soil-Related Problems*

Because hydroponic crops are grown without field soil, they avoid many soil-associated weeds, nematodes and soil-borne diseases. This can reduce the need for certain soil-management operations and improve production hygiene.

However, hydroponics does not eliminate plant diseases or insect pests. Root pathogens can spread through recirculating nutrient solutions, and above-ground pests may still affect crops. Sanitation, monitoring and integrated pest management remain essential.

*6. Potential for Urban and Space-Limited Agriculture*

Hydroponics can be established in greenhouses, rooftops and suitable indoor facilities, bringing food production closer to urban consumers. Such systems may be useful where access to productive land is limited.

Nevertheless, structural safety, access to sunlight, water quality, energy availability, local regulations and market demand must be considered before installation.

## Challenges and Limitations of Hydroponics

Despite its advantages, hydroponics presents technical, economic and environmental challenges that influence its adoption and long-term viability.

*1. High Initial Investment:* Commercial hydroponic production may require greenhouses, growing channels, reservoirs, pumps, filtration systems, sensors, irrigation equipment and environmental-control infrastructure. The initial investment can be substantial, particularly for automated and indoor vertical farms. The financial feasibility of a system depends on its scale, crop value, infrastructure costs, access to markets and expected returns.

*2. Technical Knowledge and Nutrient Management:* Successful hydroponic production requires knowledge of plant nutrition, irrigation scheduling, water quality, pH, EC, root-zone oxygen and crop-specific requirements. Errors in nutrient formulation or environmental management can quickly affect plant growth and product quality. Training, routine monitoring and access to technical support are therefore important for both small-scale and commercial growers.

*3. Dependence on Electricity and Equipment:* Pumps, aerators, sensors and environmental-control equipment may require a reliable electricity supply. Power interruptions or mechanical failures can disrupt water and oxygen delivery, particularly in systems where roots depend on continuous circulation.

Backup power, equipment maintenance and failure-response plans can reduce these risks but may increase operating costs.

*4. Energy Consumption and Environmental Footprint:* Hydroponics may reduce land and water requirements while increasing energy demand, especially in indoor facilities that rely on artificial lighting, heating, cooling and dehumidification. Barbosa et al. (2015) demonstrated that the energy requirements of hydroponic lettuce production can be substantially higher than those of conventional production, even when water use and land productivity are favourable. The environmental performance of hydroponics therefore depends on the energy source, system efficiency, climate, crop yield, infrastructure and transport requirements.

*5. Nutrient-Solution Management:* Recirculating systems require regular monitoring to prevent nutrient imbalances, salt accumulation and the spread of root pathogens. Discharging nutrient-rich water without appropriate treatment can contribute to water pollution.

Effective filtration, sanitation, nutrient replenishment and responsible management of spent solutions are essential for reducing environmental risks.

*6. Economic Viability and Market Access:* Hydroponics is often more commercially attractive for crops that command suitable prices and have reliable market demand. High production costs, price fluctuations, packaging requirements and competition from conventional growers may limit profitability. Crop selection and investment decisions should therefore be based on local market assessments and realistic financial projections rather than expected yields alone.

## CROPS SUITABLE FOR HYDROPONIC CULTIVATION

Hydroponics can support a variety of horticultural crops, although suitability depends on the system, cultivar, environmental conditions and production objectives.

**Table 1. Major crops suitable for hydroponic cultivation and their characteristics**

| Crop category | Examples | Key considerations |
|---|---|---|
| Leafy vegetables | Lettuce, spinach and other leafy greens | Short production cycles and suitability for NFT and DWC |
| Culinary herbs | Basil, mint and coriander | Suitable for small-scale and commercial production; quality depends on light and nutrient management |
| Fruiting vegetables | Tomato, bell pepper and cucumber | Require adequate root support, trellising, irrigation control and crop management |
| Small fruits | Strawberry | Requires careful management of root-zone moisture, nutrient supply and temperature |
| Microgreens | Radish, broccoli and other edible seedlings | Short production cycles and high emphasis on hygiene and seed quality |

Leafy vegetables and culinary herbs are particularly suitable for many hydroponic systems because they have relatively short production cycles and can be cultivated at high densities. Fruiting crops can also perform well, but often require more complex nutrient management, structural support and environmental control.

Microgreens are commonly produced in shallow substrates or other specialized growing arrangements. Their production methods vary, so not all microgreen systems should be classified as conventional recirculating hydroponics.

Crop selection should consider the local climate, market demand, production costs, available technical skills and the suitability of the proposed hydroponic system.

## FUTURE PROSPECTS OF HYDROPONICS

Hydroponics is likely to remain an important component of intensive horticulture and controlled-environment agriculture. Advances in digital technologies, automation and resource-efficient system design may improve production consistency and reduce management demands.

*1. Sensor-Based Monitoring and Automation:* Sensors can continuously monitor pH, EC, temperature, humidity, light intensity and other production parameters. Automated irrigation and nutrient-dosing systems can use these measurements to improve precision and reduce routine labour.

However, sensors require calibration and maintenance, and automated systems must be designed to detect and respond to equipment failures.

*2. Artificial Intelligence and the Internet of Things:* Artificial intelligence (AI) and the Internet of Things (IoT) may support hydroponic management through real-time data collection, crop monitoring, predictive analysis and automated control. These technologies can help identify abnormal conditions and improve the timing of irrigation, nutrient delivery and environmental adjustments.

Their practical value depends on data quality, system affordability, technical support and the ability to translate digital recommendations into reliable crop-management decisions.

*3. Integration with Renewable Energy:* Solar power and other renewable energy sources may reduce dependence on conventional electricity and improve the environmental performance of hydroponic facilities. Energy-efficient pumps, optimized lighting and improved greenhouse designs can also reduce operating costs.

The feasibility of renewable-energy integration depends on local climatic conditions, system size, energy-storage requirements and the reliability of the power supply.

*4. Urban Agriculture and Vertical Farming:* Integrating hydroponics with vertical farming can increase production within a limited urban footprint. Locating production closer to consumers may reduce some transport requirements and improve access to fresh produce.

Nevertheless, vertical farms can have high capital and energy costs. Their overall sustainability must be evaluated using production efficiency, energy sources, water use, infrastructure requirements, food quality and life-cycle environmental impacts.

*5. Research, Training and Policy Support:* Further research is needed to improve nutrient-use efficiency, develop cost-effective system designs, manage root diseases, recycle nutrients safely and identify suitable crops and cultivars. Training programmes, demonstrations and technical advisory services can help growers adopt hydroponic systems more effectively.

Public and private investment should prioritize technologies that are technically reliable, economically viable and environmentally appropriate for local production conditions.

## CONCLUSION

Hydroponics is a promising soilless cultivation technology that enables intensive crop production with precise control over water and nutrient supply. It offers particular advantages for leafy vegetables, herbs and selected high-value crops, especially where land is limited or water-use efficiency is a priority. However, high initial costs, energy requirements, technical complexity and nutrient-solution management remain important constraints. Hydroponics should therefore be viewed as a complementary component of sustainable agriculture rather than a universal replacement for soil-based farming. Its long-term contribution will depend on efficient system design, responsible resource management, economic feasibility and continued technological development.

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# FROM SKY TO SOIL: HOW DRONES AND WEATHER FORECASTING ARE TRANSFORMING INDIAN AGRICULTURE

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## ABSTRACT

*Indian agriculture is entering a technological era where drones, satellites, artificial intelligence (AI), remote sensing, and advanced weather forecasting support precision farming. Drones detect crop stress, pests, diseases, weeds, and nutrient deficiencies while enabling targeted input application. AI-driven, localized weather forecasts help farmers make informed decisions about sowing, irrigation, fertilization, spraying, and harvesting. Integrating drone observations with weather intelligence can improve resource-use efficiency and strengthen climate resilience. However, affordability, technical training, connectivity, regulation, and data management remain key challenges for widespread adoption.*

**KEYWORDS:** Agricultural drones, artificial intelligence, climate-smart agriculture, crop monitoring, precision agriculture, remote sensing, weather forecasting

## INTRODUCTION

Agriculture has always depended on the sky. Farmers watch clouds, temperature, rainfall and winds before deciding when to sow, irrigate, spray or harvest. Today, technology is making this traditional relationship between weather and farming far more precise.

A new agricultural ecosystem is emerging in India in which drones provide a bird's-eye view of the crop while weather forecasting provides a forward-looking view of the atmosphere. When these two sources of information are combined with satellite data, sensors, AI and farm-level observations, agriculture can become more predictive rather than reactive.

India is already moving in this direction. The Government of India is using drones, satellites, remote sensing, GIS, AI and IoT for technology-driven crop monitoring. The FASAL system, for example, uses satellite and agro-meteorological information for pre-harvest crop forecasting.

## DRONES: THE FARMER'S EYE IN THE SKY

An agricultural drone is much more than a flying camera. Equipped with RGB, multispectral, thermal or other sensors, it can collect detailed information about crop and soil conditions. A drone flying over a field can reveal differences that may not be visible from the ground. Healthy plants reflect light differently from stressed plants. By analysing these differences, vegetation indices such as NDVI can help identify areas affected by water stress, nutrient deficiency or poor growth. Recent research shows that UAV-based remote sensing combined with machine learning and deep learning is becoming increasingly important for crop monitoring and disease detection. UAV imagery can provide high spatial and temporal resolution, allowing farmers and agricultural experts to examine specific portions of a field rather than treating the entire field uniformly.

## FROM DETECTION TO ACTION

The real value of drones begins when information is converted into action.

For example, suppose a drone identifies a patch of crop showing signs of disease. Instead of spraying the entire field, farmers may be able to target the affected area. Similarly, drone-based mapping can identify areas requiring additional irrigation or nutrient management.

Drones can also be used for spraying fertilizers, pesticides and other agricultural inputs. India's Ministry of Agriculture has developed operational guidelines and schemes to promote agricultural drone use, including assistance for kisan drones and custom hiring centres.

The Government's Namo Drone Didi initiative is another important development. Under the programme, women Self-Help Groups are being supported to provide drone-based agricultural services to farmers. The scheme aims to create a new rural service model in which farmers can hire drone services rather than having to purchase expensive equipment themselves.

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## WEATHER FORECASTING: FROM "WHAT HAPPENED?" TO "WHAT WILL HAPPEN?"

Knowing the present condition of a crop is only half the solution. Farmers also need to know what is likely to happen during the next few days. Rainfall, temperature, humidity, wind speed and solar radiation strongly influence crop growth and agricultural operations. A pesticide application immediately before heavy rain may be ineffective. Irrigating just before significant rainfall can waste water. Similarly, high winds can make drone spraying unsafe or reduce application efficiency. This is why weather forecasting is becoming an essential component of precision agriculture. The India Meteorological Department (IMD) has a long history of providing weather information for agriculture through its agricultural meteorology services. Today, these services include crop-specific advisories, weather forecasts and farmer-oriented dissemination systems. IMD's Gramin Krishi Mausam Sewa has been delivering agrometeorological advisories through multiple channels, including mobile-based services. In 2026, India introduced advanced AI-enabled forecasting products designed to provide more localized weather information. These developments include high-resolution rainfall forecasting and localized monsoon forecasting systems.

## WHEN THE DRONE MEETS THE FORECAST?

The real revolution will come from integrating drone data with weather forecasts. Imagine a farmer growing cotton. A drone survey identifies early signs of water stress in one section of the field. The weather forecast predicts little rainfall during the next five days. The farmer can therefore prioritize irrigation in the affected area. Now consider another situation. A drone detects conditions associated with a potential pest or disease problem, while the weather forecast predicts high humidity and rainfall. Such weather conditions may increase the risk of disease development. An agricultural advisory system could alert the farmer to monitor the crop more closely and recommend an appropriate management strategy.

This creates a simple technological chain:

**Drone observation → Weather forecast → AI analysis → Farm advisory → Farmer action**

Such integration could make agricultural decisions timelier and more site-specific.

## WEATHER FORECASTING AND CROP YIELD PREDICTION

Weather data are also becoming increasingly useful for estimating crop yields. Recent research published in MAUSAM has demonstrated the application of statistical, neural-network and hybrid models for weather-based crop yield forecasting. Such models can use rainfall, temperature and other weather variables to estimate yields before harvest, supporting agricultural planning and decision-making. Research in Gujarat has also explored the integration of meteorological information and machine learning for sugarcane yield prediction, showing the growing importance of combining weather science with AI in crop forecasting.

In the future, yield prediction systems may combine three major data streams:

1. *Weather data* – rainfall, temperature, humidity and wind.
2. *Remote sensing data* – satellite and drone observations.
3. *Field data* – soil moisture, crop stage, pest incidence and farmer observations.

The result could be a continuously updated digital picture of the farm.

## BENEFITS FOR INDIAN FARMERS

The integration of drones and weather forecasting can offer several benefits:

1. *Better input management:* Fertilizers, pesticides and irrigation can be applied according to crop and field requirements.
2. *Early detection:* Drone imagery can identify crop stress, weeds, pests and diseases before they become widespread. Recent reviews highlight the growing use of UAVs and AI for targeted disease, weed and pest management.
3. *Water conservation:* Combining crop-stress information with rainfall forecasts can improve irrigation decisions.
4. *Reduced labour requirements:* Drone spraying can reduce the need for manual operations, particularly in large or difficult-to-access fields.

5. *Climate resilience:* Localized weather information can help farmers adjust sowing, irrigation and crop-protection decisions according to expected weather.
6. *Better decision-making:* Instead of relying only on visual observations or generalized forecasts, farmers can receive field-specific information.

## CHALLENGES ON THE ROAD AHEAD

Technology alone cannot transform agriculture. Several challenges need attention.

The initial cost of drones, sensors, software and trained operators can be high. Small and marginal farmers may therefore benefit more from custom hiring centres, cooperatives and drone service providers than from individual ownership.

Training is equally important. A drone may collect thousands of images, but these images are useful only when correctly interpreted. Farmers and extension workers need training in understanding maps, crop indices and advisories.

Weather itself can also restrict drone operations. Strong winds, rain and poor visibility can interfere with flights and affect image quality and spraying performance.

Data privacy, cybersecurity, regulatory compliance, battery limitations and connectivity are additional concerns. Research on Indian agricultural drones has also identified cost, training, infrastructure and regulatory barriers as important issues for large-scale adoption.

## THE FUTURE: SMART FIELDS, NOT JUST SMART MACHINES

The next step is not simply to put more drones in the sky. The objective should be to build an intelligent agricultural decision-support system. In the future, a farmer may receive a simple message such as:

“Rain is unlikely for the next five days. Drone imagery indicates moderate water stress in the eastern part of your field. Irrigate the affected area and avoid unnecessary irrigation elsewhere.”

Such a system would combine the expertise of meteorologists, agronomists, remote-sensing scientists, drone operators and AI developers. India is already developing this ecosystem. ICAR's precision-agriculture initiatives involve sensors, remote sensing from ground, drone and satellite platforms, AI and ICT for crop and soil monitoring. The integration of technology is therefore moving agriculture from uniform management to site-specific management, and from reaction to prediction.

## CONCLUSION

The future of Indian agriculture will increasingly depend on the intelligent use of information. Drones can tell us what is happening in the field, while weather forecasting can tell us what may happen next. When these two technologies are connected through AI, remote sensing, sensors and agricultural expertise, farmers can make faster and more precise decisions. The transformation is not about replacing farmers with machines. It is about giving farmers better information at the right time. From the sky to the soil, the emerging message is clear that the farm of the future will not simply be mechanized—it will be informed, connected and climate-smart.

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# UNDERUTILIZED FRUITS OF THE WESTERN GHATS: BIODIVERSITY, NUTRITIONAL POTENTIAL, AND DEVELOPMENT OPPORTUNITIES

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## ABSTRACT

*The Western Ghats of India harbour diverse wild and underutilized fruit species with considerable nutritional, ecological and socioeconomic value. Fruits such as kokum (Garcinia indica), lasora (Cordia dichotoma), karanda (Carissa spinarum) and chironji (Buchanania cochinchinensis) offer opportunities for dietary diversification, value addition and rural livelihood development. However, habitat degradation, unsustainable harvesting, limited domestication and weak market linkages constrain their utilization. Integrating in situ conservation, cultivation, nutritional research and community-based processing could enhance biodiversity conservation, nutritional security and sustainable livelihoods in the region.*

**KEYWORDS:** Biodiversity conservation, Indigenous fruits, Nutritional security, Rural livelihoods, Value addition, Western Ghats

## INTRODUCTION

The Western Ghats, extending approximately 1,600 km along India's western coast, represent one of the world's major centres of biological diversity and are recognized as a global biodiversity hotspot. Their varied topography, rainfall patterns and climatic conditions support diverse forest ecosystems and numerous plant species, including taxa of considerable nutritional, medicinal and economic importance. Among these resources, wild and underutilized fruits constitute an important but insufficiently developed component of regional plant diversity.

Species such as *Garcinia indica* (kokum), *Syzygium jambos* (rose apple), *Buchanania cochinchinensis* (chironji), *Carissa spinarum* and *Cordia dichotoma* have traditional uses as foods, ingredients in processed products and, in some communities, components of traditional medicine. Depending on the species and growing conditions, their fruits may provide vitamins, minerals, dietary fibre, oils and other bioactive compounds. Many are adapted to local environments and may offer opportunities for diversified production, agroforestry and climate-resilient livelihood systems.

Despite their potential, many underutilized fruits remain neglected in mainstream agricultural research, commercial horticulture and formal food markets. Habitat degradation, changes in land use, unsustainable harvesting, limited planting material, inadequate post-harvest infrastructure and insufficient market development can restrict their conservation and utilization. Furthermore, a lack of standardized information on their nutritional composition, cultivation requirements, safety and processing characteristics limits their wider adoption.

Promoting these species requires an integrated approach that combines biodiversity conservation with scientific evaluation, sustainable harvesting, domestication and community participation. This article examines the nutritional and ecological importance of selected underutilized fruits of the Western Ghats and discusses opportunities for their conservation, value addition and sustainable commercialization.

## IMPORTANCE OF WILD AND UNDERUTILIZED FRUITS

1. **Nutritional and dietary importance:** Wild and underutilized fruits can supplement diets dominated by staple cereals and other energy-rich foods. Depending on the species, they provide micronutrients, dietary fibre, natural sugars, organic acids and phytochemicals. Some fruits and kernels may also contribute useful quantities of oils and proteins. Their nutritional composition, however, varies with genotype, maturity, growing environment, processing and storage conditions. The inclusion of locally available fruits in household diets can improve dietary diversity, particularly in remote rural and forest-dependent communities where access to a wide range of fresh produce may be seasonal or limited. Encouraging their consumption alongside established horticultural crops may also help preserve traditional food practices and local knowledge.
2. **Livelihood and economic importance:** Wild fruits provide supplementary food and income to some forest-dependent households. They may be sold fresh in local markets or processed into pickles, jams, juices, syrups and other products. For example, *Cordia dichotoma* fruits are traditionally used in pickles, while fruits of *Carissa spinarum* can be processed into jams and other preserved products. Kernels of *Buchanania cochinchinensis* are commercially valued as chironji, and kokum (*Garcinia indica*) is used in regional food preparations and processed products. Developing appropriate harvesting, grading, processing and marketing systems could increase the value retained by local collectors and small-scale producers. Such initiatives should ensure fair returns to communities and avoid encouraging excessive extraction from wild populations.
3. **Ecological importance:** Wild fruit-bearing trees and shrubs contribute to forest biodiversity and provide food and habitat for wildlife. When incorporated into suitable agroforestry systems, they may diversify farm production, provide shade, contribute organic matter and support beneficial organisms.

Their roots and canopy can also contribute to soil protection and microclimate regulation, although the magnitude of these benefits depends on species characteristics and management. Where ecologically appropriate, integrating native fruit species into farm boundaries, home gardens and degraded agricultural landscapes can support landscape diversification. Restoration efforts should prioritize locally native species and suitable planting sites rather than introducing species indiscriminately into natural habitats.

4. **Nutraceutical and food-processing potential:** Several underutilized fruits contain phenolic compounds, carotenoids, vitamin C and other constituents of interest to food scientists. These characteristics provide opportunities for developing fruit-based beverages, concentrates, powders, natural ingredients and other value-added products. Nevertheless, the presence of bioactive compounds does not by itself establish a health benefit. Nutritional composition, bioavailability, processing stability, antinutritional factors and food safety must be evaluated before specific health claims are made. Scientific validation and appropriate regulatory compliance are therefore essential for developing credible nutraceutical products.

## SELECTED UNDERUTILIZED FRUIT SPECIES OF THE WESTERN GHATS

The following species illustrate the diversity of wild and underutilized fruits associated with the Western Ghats and adjoining landscapes. Their distribution, local names, seasonal availability and reported uses can vary among locations. Species-specific nutritional figures and medicinal claims should be confirmed using primary research before being used in commercial or scientific communications.

1. ***Elaeagnus kologa*** — **Kolungai:** *Elaeagnus kologa* is reported from parts of the Nilgiri region and is associated with local wild-fruit use. Its edible fruits may provide opportunities for dietary diversification and local marketing. However, information on its nutritional composition, reproductive biology, propagation and cultivation remains limited compared with that available for established fruit crops. Where wild populations face pressure from harvesting or habitat change, conservation should begin with verification of species identity, population status and habitat requirements. Propagation trials, seed-germination studies and evaluation of suitable cultivation methods could help determine whether the species is a candidate for home gardens or other appropriate cultivation systems.
2. ***Cordia dichotoma*** — **Lasora or Lasoda:** *Cordia dichotoma* is a small to medium-sized tree found in several parts of India, including suitable habitats within the broader Western Ghats region. Its fleshy fruits are consumed at different stages of maturity and are widely used in traditional pickling. The fruits contain polysaccharides and other constituents of interest for food and phytochemical research.

The species also has a history of use in traditional medicinal preparations, including formulations associated with cough remedies. These traditional applications should be distinguished from clinically demonstrated therapeutic effects. Its potential for home gardens, farm boundaries and small-scale processing makes it relevant to livelihood diversification. Research on fruit quality, processing methods, shelf life and standardized planting material could improve its commercial prospects.

3. ***Canthium parviflorum*** — **Locally known as Kaduk or Karanda in some areas:** *Canthium parviflorum* is a shrub associated with dry and other seasonally suitable habitats. Its small fruits are reported as edible in some local food traditions, and ethnobotanical accounts describe its use in traditional remedies. The species may have potential for documenting indigenous food knowledge and investigating plant-derived bioactive compounds. However, claims that its fruits are among the richest sources of β-carotene, or that they contain a particular concentration of this compound, require confirmation from a traceable analytical study. Any reported value should specify the analytical method and whether the result is expressed on a fresh-weight or dry-weight basis. Further research could examine fruit acceptability, nutritional composition, propagation and the sustainability of harvesting. Local names and reported uses should be documented with reference to the specific communities and locations in which they occur.
4. ***Carissa spinarum*** — **Karanda or Cherumully**: *Carissa spinarum* is a thorny shrub found in various habitats across South Asia and other regions. Its fruits are consumed locally in some areas and may be suitable for preparing preserves, jams, syrups and other processed foods. The nutritional and phytochemical composition of the fruits merits further investigation, particularly regarding vitamin C, minerals and phenolic compounds. However, the composition of *C. spinarum* should not be inferred directly from studies of related species, including *Carissa carandas*, because different species may vary substantially in their chemical characteristics. The shrub may be useful in selected farm-boundary or agroforestry systems, subject to local ecological suitability and management requirements. Research on fruit quality, consumer acceptance, processing performance and safe utilization could help establish its potential as a supplementary fruit crop.
5. ***Buchanania cochinchinensis*** **— Chironji:** *Buchanania cochinchinensis*, commonly known as chironji, is a deciduous tree valued for its edible kernels. The kernels are used in food preparations and are commercially important in some regional markets. They contain substantial amounts of oil and protein, although reported concentrations vary according to the source material and analytical basis. The species offers opportunities for combining forest-resource management with the development of higher-value food products. However, commercial harvesting should be balanced

with natural regeneration and the long-term maintenance of wild populations. Harvesting practices that damage trees or reduce regeneration can undermine future supplies. Potential development activities include improving seed collection, nursery propagation, planting-material availability, kernel processing and storage. Community-based enterprises could also explore quality grading and traceable sourcing to improve market returns.

6. ***Elaeocarpus tectorius* — Bikki Palzam:** *Elaeocarpus tectorius* is a tree reported from tropical forest habitats in parts of South and Southeast Asia. Its fruits are used as food by wildlife and, in some locations, by local communities. The species may therefore be relevant to both forest ecology and the documentation of traditional food resources. Claims concerning exceptionally high carotenoid concentrations or specific medicinal effects require confirmation from reliable species-specific studies. In particular, numerical values for carotenoids should be checked carefully to distinguish total carotenoids from individual compounds and to establish the correct reporting units. Conservation and research priorities include documenting its distribution, assessing the status of wild populations, understanding fruiting and regeneration patterns, and evaluating propagation methods. Any future utilization should be based on verified identification, sustainable collection and evidence of food safety.
7. **Other fruit resources:** Other species associated with wild-fruit use in the Western Ghats and surrounding regions include *Flacourtia indica* (governor's plum), *Diospyros* species, *Garcinia* species and selected wild *Prunus* species. Their distribution and suitability for consumption or cultivation must be assessed individually rather than assumed from the characteristics of related species. Collectively, these resources may contribute to seasonal dietary diversity, local food traditions and livelihood opportunities. However, their successful development depends on reliable identification, sustainable harvesting, adequate nutritional data and appropriate post-harvest handling.

## 4. CONSERVATION AND DEVELOPMENT STRATEGIES

The conservation and sustainable utilization of underutilized fruits require coordinated action across ecological, agricultural, nutritional and socioeconomic domains. The following strategies address the principal constraints identified above.

1. *In situ conservation and habitat restoration*: Protecting wild populations within their natural habitats is essential for maintaining genetic diversity and ecological relationships. Conservation measures should include habitat protection, monitoring of population regeneration and the identification of areas where harvesting pressure is excessive. Where appropriate, native fruit-bearing species can be

incorporated into restoration projects and farm boundaries. Such interventions should be based on verified distribution records and local ecological conditions. Species should not be introduced into natural habitats outside their native ranges simply because they have commercial potential.

2. *Domestication and cultivation:* Domestication can reduce dependence on wild collection while providing farmers with additional production options. Priority species should be selected according to local suitability, consumer demand, nutritional potential, ease of propagation and conservation status. Research and extension programs should support the development of quality planting material, nursery techniques, propagation protocols and suitable cultivation practices. Home gardens, mixed agroforestry systems and farm boundaries may provide opportunities for selected species, depending on their growth requirements and compatibility with existing land uses. Farmer Producer Organizations and community groups could help coordinate planting-material production, cultivation demonstrations and collective marketing. Domestication should complement, rather than replace, the protection of genetically diverse wild populations.
3. *Value addition and post-harvest management:* Seasonality and perishability can limit the market value of wild fruits. Small-scale processing facilities could help address these constraints through the production of juices, jams, pickles, dried products, concentrates and other locally appropriate foods. For example, kokum can be developed into suitable processed food products, while chironji kernels can be graded and processed for food markets. The choice of product should be based on the properties of the raw material, local demand and the technical and economic feasibility of processing. Training in hygienic processing, packaging, storage and quality control is essential. Community processing units should also have access to appropriate equipment, reliable raw-material supplies and information on food-safety requirements.
4. *Market linkages and equitable benefit sharing:* Weak market connections, inconsistent product quality and limited transport infrastructure can restrict income opportunities for fruit collectors and small producers. Producer cooperatives, transparent purchasing arrangements and partnerships with food processors may improve market access. Improved grading, packaging, traceability and information about product origin could help establish niche markets for selected fruits. However, claims about premium prices, export potential or growing consumer demand should be supported by market assessments rather than assumed. Policies supporting local enterprises, sustainable harvesting and small-scale processing can strengthen value chains. Benefit-sharing arrangements should recognize the contributions of indigenous and local communities, particularly where traditional knowledge and locally conserved genetic resources support product development.

5. *Research, propagation and quality assessment:* Research is needed to identify promising species and genotypes, improve propagation, characterize fruit composition and establish suitable post-harvest practices. Priority areas include:
    - Taxonomic identification and documentation of distribution.
    - Assessment of wild population status and regeneration.
    - Evaluation of fruit yield, quality and seasonal availability.
    - Analysis of nutritional composition, antinutritional factors and food safety.
    - Development of propagation, nursery and cultivation protocols.
    - Assessment of processing performance, shelf life and consumer acceptance.
    - Economic analysis of cultivation, collection and value-added products.
    - Nutritional and medicinal claims should be supported by appropriate analytical and experimental evidence. Studies should distinguish preliminary laboratory findings from evidence of benefits in humans.
6. *Documentation of indigenous knowledge:* Local and indigenous communities hold valuable knowledge about fruit collection, preparation, storage and traditional uses. Documenting this knowledge can support biodiversity conservation and the preservation of regional food cultures. Such documentation should be conducted with community participation, informed consent and appropriate recognition of knowledge holders. Where traditional knowledge contributes to commercial development, benefit-sharing and relevant legal requirements should be addressed. Extension programs can help communicate safe preparation methods, promote suitable traditional recipes and encourage sustainable harvesting. Knowledge documentation should complement scientific evaluation rather than substitute for nutritional, safety or clinical evidence.

## 5. CHALLENGES AND FUTURE OPPORTUNITIES

Despite their potential, underutilized fruits face several interconnected challenges. These include habitat loss, uncertain availability of planting material, inadequate information on cultivation requirements, limited nutritional characterization, short shelf life and weak market infrastructure. In some cases, overharvesting may threaten natural regeneration, while low and irregular production can make commercial processing difficult.

Future initiatives should prioritize species for which conservation needs, nutritional value and livelihood opportunities can be demonstrated. Participatory research involving local communities, agricultural

universities, forestry institutions, food scientists and rural enterprises can help establish practical development models.

Climate-resilient production systems and diversified agroforestry may provide suitable settings for selected species, but claims of drought tolerance or climate resilience should be supported by species-specific evidence. Similarly, the development of nutraceutical products and export markets should follow scientific validation, food-safety assessment and realistic economic analysis.

Monitoring should assess not only income and product sales but also changes in wild populations, regeneration, harvesting pressure and the distribution of benefits among stakeholders. This would help ensure that commercial development contributes to long-term conservation rather than increasing pressure on vulnerable resources.

## 6. CONCLUSION

Underutilized fruits of the Western Ghats represent valuable biological resources with potential contributions to dietary diversity, rural livelihoods, agroforestry and biodiversity conservation. Species such as *Cordia dichotoma*, *Carissa spinarum* and *Buchanania cochinchinensis* illustrate opportunities for linking traditional food use with scientific research and value addition. Nevertheless, their potential should not be overstated without reliable evidence on nutritional composition, food safety, cultivation and market demand. A coordinated strategy combining in situ conservation, domestication, sustainable harvesting, post-harvest processing and equitable market development is essential. Research institutions, government agencies, local communities and private enterprises should work together to improve species identification, develop suitable planting material, validate nutritional claims and strengthen community-based value chains. With evidence-based management and appropriate safeguards, underutilized fruits can contribute to the conservation of the Western Ghats' biological heritage while supporting more diverse and sustainable rural livelihoods.

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# ROLE OF ARTIFICIAL INTELLIGENCE IN POULTRY DISEASE DIAGNOSIS

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## ABSTRACT

*Rapid and accurate poultry disease diagnosis is essential for protecting flock health, productivity, and biosecurity. Conventional methods rely on clinical examination, laboratory testing, and expert interpretation. Artificial intelligence (AI), including machine learning, deep learning, computer vision, and sensor-based analytics, offers promising tools for poultry health surveillance. By analysing images, movement, vocalisations, temperature, and environmental data, AI can identify potential disease indicators. However, reliable adoption requires high-quality datasets, independent validation, data security, affordability, and veterinary oversight. AI should complement, not replace, veterinary diagnosis and confirmatory laboratory testing.*

**KEYWORDS:** Artificial intelligence, Computer vision, Deep learning, Early diagnosis, Machine learning, Poultry disease, Precision poultry farming

## INTRODUCTION

Poultry production supports food security, employment and rural livelihoods, but infectious and non-infectious diseases can rapidly reduce flock performance. The Food and Agriculture Organization of the United Nations emphasises that rapid recognition of poultry disease and adequate diagnostic capacity are essential because poultry pathogens can cross production and geographic boundaries, while some are also relevant to public health (Food and Agriculture Organization of the United Nations [FAO], 2022). In practice, diagnosis may require clinical history, post-mortem examination, microbiology, serology or molecular tests. These approaches remain indispensable, but they may require time, skilled personnel and laboratory access.

## WHAT CAN AI "SEE" IN A POULTRY FLOCK?

AI learns relationships within large datasets and can detect patterns that may be difficult to quantify consistently by eye. In poultry, the input may be an image, video, sound recording, thermal image, sensor measurement or combination of these data. Computer-vision models can evaluate posture, gait, feather condition, lesions, body conformation and droppings. Sensor-based systems can monitor temperature, humidity, activity, water and feed consumption, while audio analysis can identify changes in flock vocalisation. Recent reviews describe AI applications involving movement, vocalisation, body temperature and excreta, together with thermal imaging and video tracking (Kalita et al., 2025).

## DEEP LEARNING FOR EARLY DISEASE DETECTION

Deep learning is particularly useful for image-based diagnosis because it can learn relevant visual features directly from examples. A notable poultry study developed models for distinguishing healthy birds from coccidiosis, Salmonella and Newcastle disease using faecal images. After fine-tuning, reported test accuracies reached 95.01% for VGG16, 95.45% for InceptionV3, 98.02% for MobileNetV2 and 98.24% for Xception; the authors also highlighted the suitability of lightweight models for mobile deployment (Machuve et al., 2022). These results are encouraging, but accuracy obtained from a particular dataset should not be interpreted as equivalent to field diagnostic accuracy. Model performance can fall when images come from different breeds, lighting conditions, camera devices, farms or disease stages.

## FROM IMAGE TO ACTION: HOW AI CAN SUPPORT THE VETERINARIAN

AI can be most valuable when it functions as an early-warning layer in the diagnostic chain. A camera or mobile phone may capture a suspicious image; an algorithm can assign a probability score; and the result can trigger closer flock observation or collection of appropriate diagnostic samples. The veterinarian then integrates the AI output with flock history, clinical examination, pathology and laboratory findings. This approach is especially important for diseases with overlapping clinical signs. For Newcastle disease, for example, laboratory confirmation can involve virus isolation, serology or real-time reverse-transcription polymerase chain reaction (RT-PCR) (Zhao et al., 2022). AI may therefore help identify which birds or flocks require attention, while confirmatory tests establish the diagnosis (Figure 1).

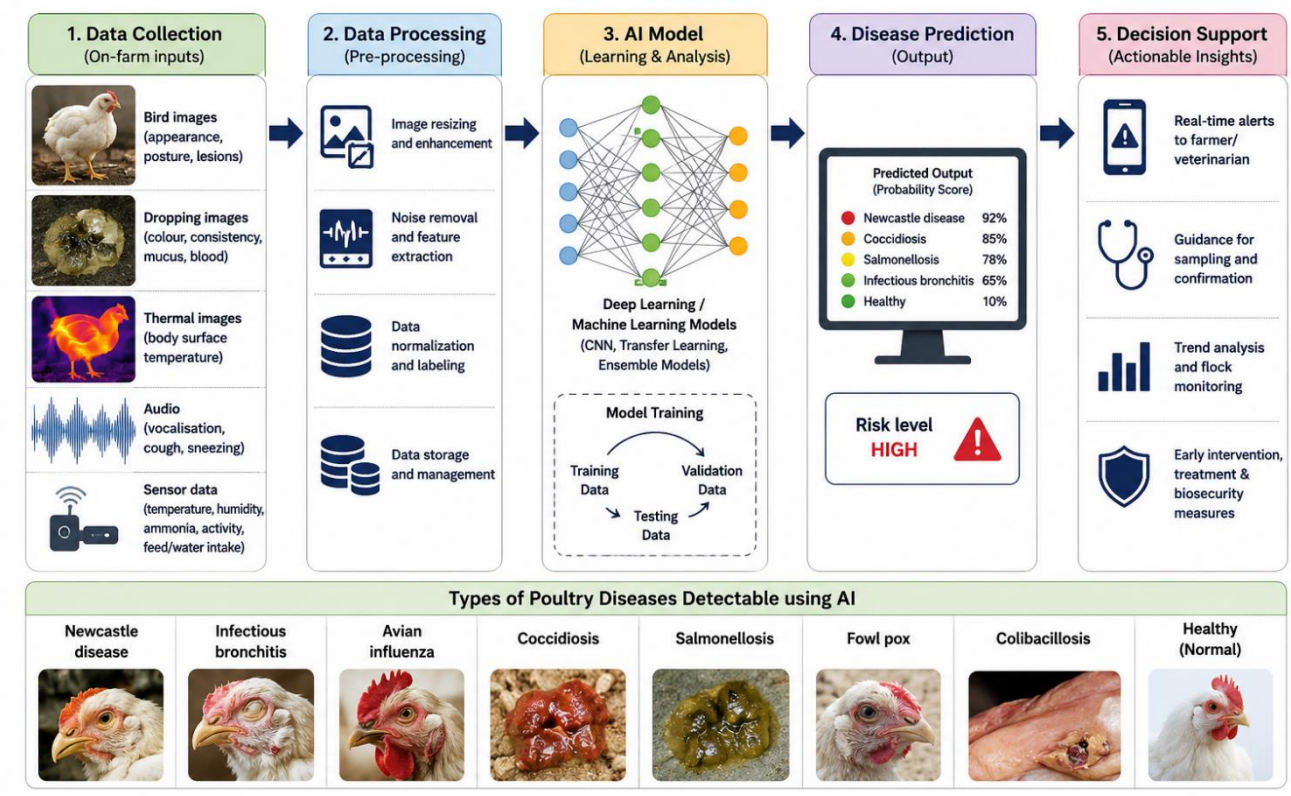



**Figure 1. AI-based framework for poultry disease diagnosis**

## MULTIMODAL AI: THE NEXT STEP

Future systems are likely to combine several information streams rather than rely on a single photograph. For example, an AI platform could combine bird activity, sound, feed and water intake, environmental conditions, thermal images and clinical photographs. This is known as multimodal or sensor-fusion AI. Recent work on AI and machine learning in poultry farming identifies disease detection, behaviour analysis, environmental control, automation and productivity optimisation as interconnected application areas (Figure 2). Edge-AI, in which computation occurs close to the farm rather than entirely in the cloud, can reduce latency and dependence on continuous internet connectivity (Natsir et al., 2025).

## BENEFITS FOR POULTRY HEALTH MANAGEMENT

Early warning is the greatest potential benefit. A system that identifies an abnormal pattern before mortality becomes obvious may allow farmers and veterinarians to investigate sooner. AI can also support continuous surveillance, reduce repetitive manual observations and create digital records for flock-level comparison. In large farms, automated monitoring can help prioritise personnel attention. In resource-limited settings, smartphone-based tools may extend basic screening capability where veterinary services

and laboratory facilities are not immediately accessible. Importantly, AI can support biosecurity by flagging unusual changes that justify isolation, sampling and further investigation.

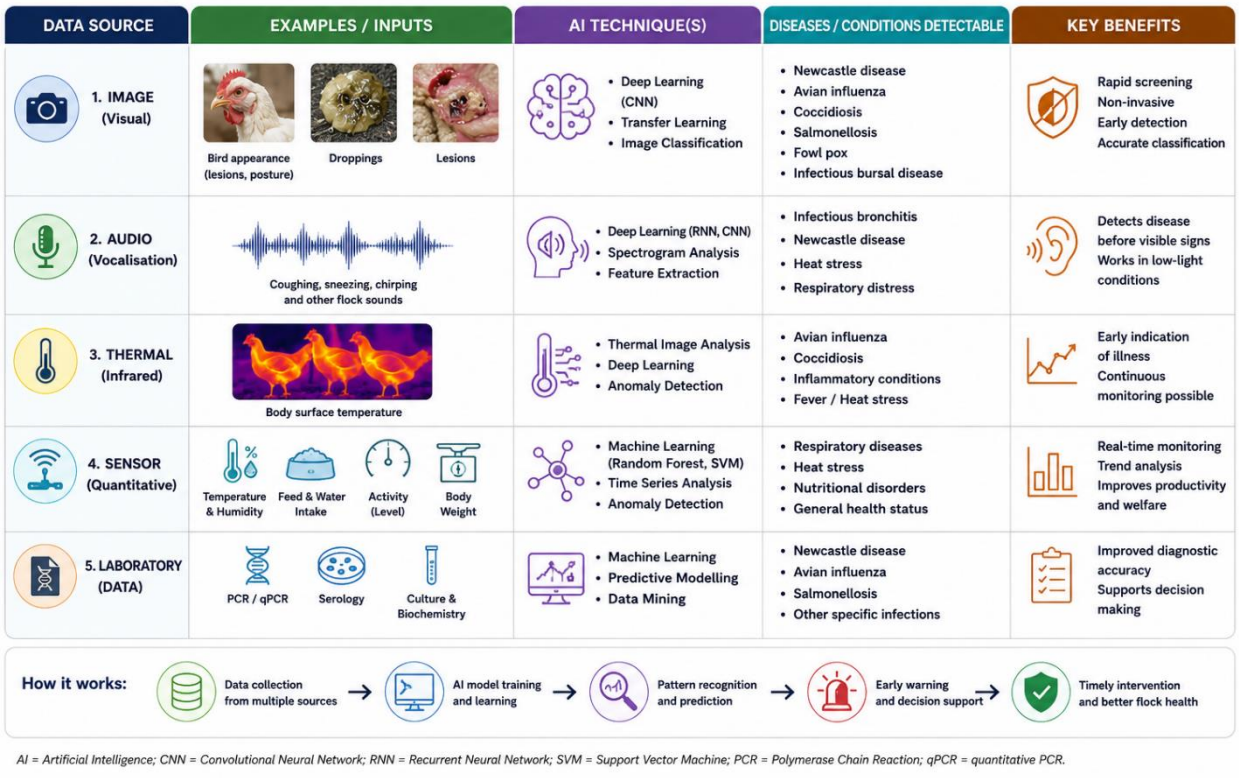



**Figure 2. AI Techniques and Data Sources used in poultry disease diagnosis**

## LIMITATIONS AND RESPONSIBLE USE

AI is not automatically reliable simply because a model reports a high accuracy. The quality and representativeness of training data are critical. Bias may arise if datasets contain too few breeds, production systems, geographical regions or disease presentations. Similar-looking conditions may also confuse an image classifier. A further concern is the distinction between association and causation: an AI model may recognise a visual pattern associated with disease without identifying the pathogen itself. Therefore, AI predictions should not be used alone to make high-consequence decisions such as declaring a flock free of a regulated disease.

AI adoption also requires attention to explainability, cybersecurity, privacy and cost. Farmers need understandable alerts, not only technical probability scores. Equipment must withstand dust, heat and farm conditions, and systems should continue functioning when connectivity is poor. Recent reviews identify infrastructure limitations, initial cost, digital literacy, dataset generalisability and the shortage of large real-world trials as important barriers (Natsir et al., 2025).

## A PRACTICAL ROADMAP FOR INDIA

For Indian poultry production, development should begin with locally representative datasets collected from commercial farms, backyard units, diagnostic laboratories and veterinary institutions. Images and sensor data should be linked, wherever possible, with laboratory-confirmed diagnoses and relevant metadata such as age, breed, vaccination status, production system and environmental conditions. Models should then be externally validated across states, seasons, breeds and camera devices. Collaboration among veterinarians, pathologists, microbiologists, epidemiologists, data scientists and poultry producers will be essential. Such a One Health-oriented approach can help ensure that AI strengthens, rather than bypasses, established diagnostic and surveillance systems.

## CONCLUSION

Artificial intelligence is moving poultry disease diagnosis from occasional observation toward continuous, data-driven health surveillance. Computer vision, deep learning, thermal imaging, audio analysis and sensor fusion can provide valuable early-warning signals and help veterinarians focus attention where it is most needed. Evidence from poultry disease image classification demonstrates that high-performing models are technically feasible, while newer edge and multimodal approaches offer opportunities for practical farm deployment. Nevertheless, AI should complement—not replace—clinical expertise, pathology and confirmatory laboratory diagnosis. The future of poultry health will depend not simply on more powerful algorithms, but on better datasets, transparent validation, affordable technologies and close collaboration between animal-health professionals and technology developers. Used responsibly, AI can become an important tool for earlier detection, better biosecurity, improved welfare and more resilient poultry production.

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# COMPUTER MODELS IN AGRICULTURAL METEOROLOGY: A MODERN TOOL FOR CLIMATE-SMART FARMING

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## ABSTRACT

*Agricultural production is strongly influenced by weather and climate variables, including temperature, rainfall, humidity, solar radiation, wind speed, and soil moisture. Agricultural meteorology employs computer models to translate these observations into actionable information for crop management and decision-making. Process-based models such as DSSAT, APSIM, WOFOST, and CERES simulate crop growth and yield. Recent advances in artificial intelligence, machine learning, remote sensing, and big data have enhanced predictive capabilities. Integrating crop-growth processes with data-driven approaches can strengthen climate resilience, optimize resource use, and improve agricultural sustainability.*

**KEYWORDS:** Agricultural meteorology, APSIM, Climate change, Computer models, Crop simulation, Decision support system, Machine learning, Weather forecasting

## INTRODUCTION

Agricultural meteorology is the science of understanding how weather and climate affect agriculture. Farmers traditionally depend on their experience to make decisions about sowing, irrigation, fertilization and harvesting. However, increasing weather variability, droughts, heat waves, intense rainfall and changing growing seasons make farm decisions more difficult. Computer models provide a scientific way to understand these complex interactions and explore different management options before they are implemented in the field.

A computer model is essentially a mathematical representation of a real agricultural system. It uses information such as daily temperature, rainfall, solar radiation, soil characteristics, crop variety, sowing date, irrigation and fertilizer application to simulate crop development and estimate outcomes. Modern crop models can therefore act as a “virtual field” in which different weather and management scenarios can be tested.

## MAJOR TYPES OF COMPUTER MODELS

1. *Statistical and empirical models:* These models establish relationships between weather variables and agricultural outcomes. For example, historical rainfall and temperature data can be related to crop yield. They are relatively simple and useful for yield forecasting, but their performance may decline when weather conditions are substantially different from the historical data.
2. *Process-based crop models:* These models represent biological and physiological processes such as photosynthesis, respiration, phenological development, biomass accumulation and water use. Well-known examples include DSSAT, APSIM, WOFOST and CERES. They can evaluate the effects of sowing date, irrigation, nitrogen management, temperature and future climate scenarios. Recent research continues to demonstrate the value of these models for crop management and climate-resilient agriculture.
3. *Weather and agro-meteorological models:* Weather prediction models provide forecasts of temperature, rainfall, wind, humidity and other variables. When linked with agricultural models, these forecasts can generate practical advisories such as whether irrigation should be postponed, whether spraying conditions are suitable, or whether heavy rainfall may affect harvesting.
4. *Artificial intelligence and machine-learning models:* Machine learning techniques such as Random Forest, XGBoost, artificial neural networks and deep learning can analyse large datasets from weather stations, satellites, sensors and crop observations. They are increasingly being used for yield prediction, drought assessment, evapotranspiration estimation and crop stress detection. However, purely data-driven models may have difficulty when they encounter environmental conditions that were not represented in their training data.
5. *Hybrid models:* One of the most promising developments is the combination of process-based crop models with artificial intelligence. Such models attempt to combine the biological understanding and interpretability of traditional crop models with the predictive ability of machine learning. Recent research on next-generation crop models identifies integration with machine learning, sensors, standardized databases and remote sensing as important directions for future agricultural modelling.

## APPLICATIONS IN AGRICULTURAL METEOROLOGY

Computer models have numerous applications in agriculture. They can estimate crop yield before harvest, identify optimum sowing windows and assess the effects of delayed sowing. They can also estimate crop water requirements and support irrigation scheduling. By combining weather forecasts with crop

information, models can provide early warnings for drought, heat stress, frost, heavy rainfall and other extreme events.

Models are also useful for climate-change impact assessment. Researchers can simulate crop performance under future temperature and rainfall scenarios and compare adaptation measures such as changing sowing dates, selecting heat-tolerant varieties, modifying irrigation or improving soil management.

Another important application is agro-advisory services. Model outputs can be converted into simple recommendations for farmers through mobile applications, websites and extension services. In India, recent agro-meteorological programmes have emphasized the development of weather-based decision systems, climate adaptation tools and farmer-oriented technologies.

## CHALLENGES AND FUTURE PROSPECTS

Despite their advantages, computer models are not perfect. Their accuracy depends on the quality of weather, soil and crop data and on appropriate calibration and validation. Different models may produce different results because they represent agricultural processes differently. Recent research has highlighted the importance of quantifying uncertainty rather than relying only on a single model prediction.

Future agricultural meteorology will increasingly use real-time weather observations, automatic weather stations, Internet of Things sensors, satellite imagery, drones, artificial intelligence and cloud computing. Multi-model and hybrid approaches are likely to provide more reliable predictions than relying on one modelling technique. Greater integration of farmer knowledge with model-based information will also be important for developing practical and locally relevant advisories.

## CONCLUSION

Computer models have become an important component of modern agricultural meteorology. They provide a scientific framework for linking weather, soil, crop and management factors and converting complex data into useful agricultural information. From conventional crop simulation models to artificial intelligence and hybrid modelling systems, technological development is making agricultural predictions increasingly detailed and timely. However, successful application requires high-quality data, proper calibration, validation and communication of uncertainty. The future lies in integrating process-based models, machine learning, remote sensing and real-time weather information into farmer-friendly decision-support systems. Such computer-based approaches can contribute significantly to climate-smart agriculture, efficient use of water and fertilizers, reduction of weather-related risks, and sustainable food production.

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# *SESBANIA ACULEATA*: A GREEN GOLD FOR SUSTAINABLE AGRICULTURE

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## ABSTRACT

*Dhaincha (Sesbania aculeata) is a fast-growing leguminous crop with considerable potential to promote sustainable and resource-efficient agriculture. Beyond its traditional use as green manure, it contributes to biological nitrogen fixation, biomass production, nutrient recycling and soil organic matter enrichment. Its multiple applications include green manuring, brown manuring, cover cropping, mulching and weed suppression. Its tolerance to saline conditions makes it valuable for selected salt-affected soils, while young biomass can supplement green fodder for livestock. These diverse benefits make Dhaincha a "Green Gold" for improving soil health, farm resilience and long-term agricultural sustainability.*

**KEYWORDS:** Biological nitrogen fixation, Dhaincha, Green manuring, Soil health, Sustainable agriculture

## INTRODUCTION

Modern agriculture has substantially increased crop yields; however, intensive cropping, rising fertilizer costs, declining soil fertility and environmental concerns continue to pose significant challenges. These issues have renewed interest in sustainable nutrient management practices, particularly green manuring (Rani et al., 2022). Among green manure crops, Dhaincha (Sesbania aculeata) is a versatile option because of its rapid biomass production, ability to fix atmospheric nitrogen through symbiosis with soil microorganisms, and capacity to contribute organic matter to the soil.

Its benefits extend beyond soil fertility to include nutrient recycling, weed suppression, soil protection and potential livestock-feed supplementation. Thus, Dhaincha is more than a green manure crop; it is a valuable agricultural resource that can support soil health, crop and livestock production, and farm resilience. Its multifunctional role makes it a promising component of sustainable farming systems.

## DHAINCHA AT A GLANCE

Dhaincha (Sesbania aculeata) is a fast-growing leguminous plant belonging to the family Fabaceae. It is widely valued as a green manure crop because it produces substantial biomass within a relatively short period and fixes atmospheric nitrogen through root nodules. When incorporated into the soil, its biomass supplies organic matter and nitrogen and can support microbial activity and nutrient cycling.

Dhaincha is particularly useful in rice-based and other intensive cropping systems. Depending on crop establishment and management, it can also suppress weeds, protect the soil surface and recycle nutrients. Tender biomass may serve as supplementary green fodder under appropriate feeding practices.

Its relatively low input requirements and multiple functions make Dhaincha a practical option for improving soil fertility and supporting sustainable agriculture. By contributing biologically fixed nitrogen and organic residues, it may reduce dependence on external nitrogen fertilizers and improve nutrient-use efficiency.

**Table 1. Biomass production and nitrogen contribution of selected green manure and leguminous crops**

| Crop | Botanical name | Dry matter accumulation (t $ha^{-1}$) | Nitrogen contribution (kg $ha^{-1}$) |
|---|---|---|---|
| Dhaincha | *Sesbania aculeata* | 23.2 | 80–140 |
| Cowpea | *Vigna unguiculata* | 23.2 | 40–70 |
| Sunn hemp | *Crotalaria juncea* | 30.6 | 80–100 |
| Mung bean (moong) | *Vigna radiata* | 25.0 | 25–50 |
| Cluster bean | *Cyamopsis tetragonoloba* | 3.2 | 40–60 |

Source: TNAU Agritech Portal (n.d.); values reproduced from the supplied draft and requiring verification against the original source.

## GREEN BIOMASS TO SOIL WEALTH

Dhaincha's value lies not only in its ability to fix atmospheric nitrogen but also in the benefits obtained when its biomass is returned to the soil. The crop is commonly incorporated during the vegetative stage, often around 45–60 days after sowing, depending on crop growth, local conditions and the requirements of the succeeding crop.

Following incorporation, soil microorganisms decompose the plant residues and gradually release nutrients into the soil. The relatively low carbon-to-nitrogen ratio of young Dhaincha biomass can favour decomposition and nitrogen mineralization. Its residues also contribute organic matter and provide substrates for soil microorganisms.

Nitrogen release depends on biomass quality, soil temperature, moisture, aeration and microbial activity. Consequently, the timing of incorporation is important for synchronizing nutrient availability with the nutrient requirements of the subsequent crop. Incorporating Dhaincha sufficiently before crop establishment, where appropriate, can help improve nutrient availability and reduce the risk of a mismatch between nitrogen release and crop demand (Rani et al., 2022).

Through these processes, Dhaincha converts green biomass into a valuable source of nutrients and organic matter, contributing to soil fertility and the sustainability of intensive cropping systems.



**Fig. 1. Dhaincha (*Sesbania aculeata*) growing as a green manure crop**

## DHAINCHA: MORE THAN A GREEN MANURE

Dhaincha offers several benefits beyond improving soil fertility. Its rapid growth, biomass production and adaptability make it useful for soil protection, weed suppression, nutrient recycling and selected livestock-feeding applications. Its major uses are summarized below.

1. ***Weed suppression:*** A rapidly developing canopy can suppress weeds by competing for sunlight, water, space and nutrients. The degree of suppression depends on crop density, establishment and management.
2. Soil protection: Its vegetation provides ground cover, while its roots help stabilize the soil and may reduce erosion.

3. ***Mulching and composting:*** Harvested biomass can be used as mulch or incorporated into compost, returning organic matter and nutrients to the farming system.
4. ***Cover cropping:*** Dhaincha can provide ground cover during suitable fallow periods, helping protect the soil surface and improve nutrient cycling.
5. ***Brown manuring:*** When grown alongside a main crop, such as rice, Dhaincha can be knocked down to form surface residues that suppress weeds and contribute nutrients as they decompose (Melavanki et al., 2024).
6. ***Nutrient recycling:*** Its root system and biomass contribute to nutrient retention and recycling within the farming system.
7. ***Management of selected salt-affected soils:*** Dhaincha can tolerate certain saline conditions and contribute organic residues to the soil. Its effectiveness depends on the severity and type of salinity, drainage, irrigation-water quality and other soil-management practices.

These multifunctional uses make Dhaincha a valuable component of integrated soil fertility management and diversified cropping systems.

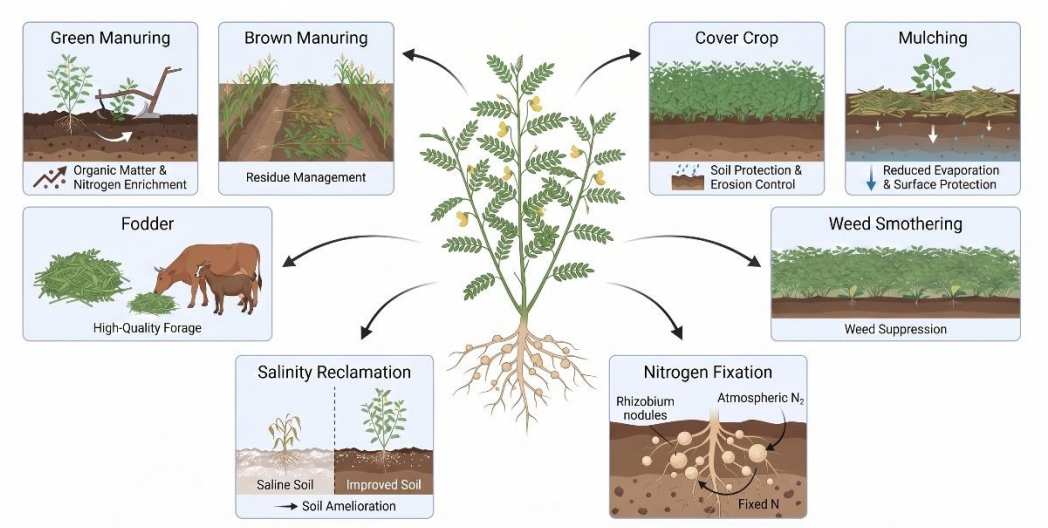



**Fig. 2. Multipurpose uses of Dhaincha (*Sesbania aculeata*)**

## DHAINCHA AS SUPPLEMENTARY GREEN FODDER

Dhaincha may provide supplementary green fodder for cattle, buffaloes, sheep and goats, particularly during periods of limited green-forage availability. Its young biomass can contribute protein and other nutrients to livestock diets, but its suitability depends on the stage of growth, forage composition and the overall feeding system.

Fernandes and Kamble (2011) reported that Dhaincha harvested during the rainy season contained 20.11% crude protein and had an in vitro dry matter digestibility of 71.69%. These findings indicate its potential as a supplementary forage resource under the conditions studied.

For improved tenderness and palatability, Dhaincha may be harvested during the vegetative stage, often around 45–60 days after sowing, depending on growth and local conditions. It should be introduced gradually and fed as part of a balanced ration rather than used as the sole feed. Appropriate feeding recommendations should account for the nutritional requirements of the animal, forage quality and any relevant antinutritional factors.

Thus, the judicious use of Dhaincha as supplementary green fodder can provide an additional benefit by linking soil fertility management with crop–livestock integration.

## DHAINCHA IN RICE-BASED FARMING SYSTEMS

Dhaincha is particularly relevant to rice-based cropping systems, where it can be grown before rice establishment and incorporated into the soil as green manure. Its biomass contributes organic matter and biologically fixed nitrogen, potentially improving nutrient availability and supporting soil biological activity.

Green manuring with Dhaincha has been associated with improvements in rice productivity under suitable management conditions. However, the magnitude of any yield increase depends on biomass production, soil fertility, variety, water management, fertilizer application and local climatic conditions. Any general claim of a 10–25% yield increase should therefore be supported by a relevant field study and interpreted according to the conditions under which the results were obtained.

In salt-affected rice-growing areas, Dhaincha may provide additional benefits through biomass production and organic matter inputs. Nevertheless, it should be considered part of an integrated management approach rather than a stand-alone solution for salinity. Effective drainage, appropriate irrigation practices and management of salt accumulation remain essential.

When appropriately integrated into rice-based rotations, Dhaincha can help improve nutrient management, diversify production practices and support the long-term sustainability of intensive farming systems.

## DHAINCHA FOR CLIMATE-SMART AGRICULTURE

Dhaincha has potential to contribute to climate-smart agriculture through biological nitrogen fixation, organic matter inputs and improved nutrient cycling. Its incorporation can help reduce reliance on external nitrogen fertilizers when its nitrogen contribution is appropriately accounted for in fertilizer recommendations.

However, its influence on greenhouse-gas emissions, particularly methane ($CH_4$) and nitrous oxide ($N_2O$), depends on the production system and management practices. In flooded rice fields, incorporating fresh organic biomass may increase methane production by supplying readily decomposable carbon to soil microorganisms. Conversely, replacing part of the synthetic nitrogen requirement with biologically fixed nitrogen may reduce emissions associated with fertilizer production and, under suitable conditions, nitrogen-related field emissions.

The overall effect depends on biomass quantity and quality, incorporation timing, soil properties, water management and the amount of fertilizer nitrogen applied. Therefore, Dhaincha should not automatically be considered a greenhouse-gas mitigation measure in every situation. Its climate benefits need to be evaluated within the context of the complete cropping system, including changes in methane and nitrous oxide emissions and the potential benefits of improved soil fertility.

Integrating Dhaincha into climate-smart farming strategies requires site-specific management that balances nutrient benefits, crop productivity, water use and environmental outcomes.

## CONCLUSION

As agriculture moves towards more sustainable production systems, Dhaincha offers a practical example of how a traditional green manure crop can help address contemporary agricultural challenges. Its ability to fix atmospheric nitrogen, produce substantial biomass, contribute organic matter, suppress weeds and support crop–livestock integration makes it much more than a source of green manure.

When appropriately managed, Dhaincha can improve nutrient cycling and support soil fertility in rice-based and other cropping systems. It may also contribute to supplementary livestock feeding and the management of selected salt-affected soils. Nevertheless, its benefits depend on local growing conditions, biomass management and the requirements of the succeeding crop.

Wider adoption, supported by quality seed, scientific management, farmer awareness and locally appropriate recommendations, can help realize its potential. Although simple in appearance, Dhaincha can contribute to the health of agricultural soils, the productivity of crops and livestock, and the resilience

of farming systems. These multiple benefits make it a promising "Green Gold" for sustainable agriculture.

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# MORINGA: A MIRACLE FEED FOR GOAT KIDS

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## *ABSTRACT*

*Goat farming is a vital livelihood source for Indian smallholders, but post-weaning nutritional stress can impair growth and increase kid mortality. Cultivating Moringa oleifera along farm boundaries offers a low-cost, climate-resilient fodder resource. Supplementing goat kids with Moringa leaves during the transition from milk to solid feed may improve weight gain, rumen development, and immune function. This protein-rich supplement can reduce dependence on expensive commercial concentrates, lower feeding costs, promote healthier kids, accelerate market readiness, and enhance the profitability and sustainability of smallholder goat farming.*

**KEYWORDS:** Goat kids, Health, Moringa, Supplementation

## INTRODUCTION

Goat rearing is a vital economic pillar for small and marginal farmers across rural India, making up 27.74% of the national livestock population, directly supporting the livelihoods of nearly 35 million farmers. However, the ultimate profitability of this enterprise depends entirely on successfully rearing goat kids but maximizing kid growth is severely restricted by a lack of quality fodder (Damor et al., 2017). As traditional grazing lands shrink, farmers are forced to rely on poor-quality roughages which are highly deficient in vital nitrogen, vitamins and minerals, yet contain large amounts of indigestible fibers like lignin and cellulose. This poor digestibility reduces daily feed intake and severely stunts the average weight gain of growing kids. Furthermore, while commercial concentrate mixtures can bridge this nutritional gap, their high prices make them completely unaffordable for most smallholders. This chronic protein deficiency ultimately leads to weakened immune systems and increased mortality rates. To overcome this major nutritional hurdle, tree leaves offer a highly practical, low-cost solution. Specifically, incorporating Moringa oleifera leaves into kid diets shows remarkable production benefits (Sultana, 2020). Beyond providing excellent crude protein, Moringa's powerful antioxidant and immune-modulating properties significantly improve metabolic health, making it a miracle feed.

## MORINGA OLEIFERA: A MIRACLE FODDER



*Moringa oleifera* trees (NDRI, Karnal)

Commonly known as the drumstick tree, Moringa oleifera is a fast-growing, drought-resistant plant globally recognized as a "wonder tree." Every part is highly valuable for livestock, with its leaves serving as nutritious green fodder and its stems utilized for silage. Growing up to 15 meters tall, Moringa thrives with minimal maintenance, generating massive biomass even in low-fertility or salty soils. Its greatest advantage is retaining lush green leaves during the harsh dry season when other fodder completely disappears (Melesse et al., 2009). By providing a reliable, year-round supply, Moringa acts as a highly cost-effective and environmentally friendly feed resource. Its rapid growth across diverse climates makes it incredibly viable for smallholder farmers. Incorporating locally grown Moringa into goat diets significantly improves livestock productivity while keeping input costs strictly minimal, directly supporting sustainable farming.

## NUTRITIONAL COMPOSITION OF *MORINGA OLEIFERA*

*Moringa oleifera* is widely recognized as a multipurpose evergreen tree with immense economic and nutritional value. Its foliage is uniquely packed with essential nutrients, making it a highly attractive and sustainable feed supplement for improving animal health and performance.

*Proximate Composition and Protein Quality*

As detailed in the Table 1, the remarkable feature of Moringa leaves is their exceptional crude protein content which can replace expensive commercial protein supplements and provides critical essential amino acids, like lysine and methionine, which standard pasture grasses lack. Furthermore, Moringa contains significantly lower structural fibers compared to common fodders like sorghum. For young kids, this low-fiber profile is crucial as it ensures quick digestion and rapid passage through the rumen, allowing the kids to maximize their daily dry matter intake, thereby providing the vital energy required to accelerate weight gain and reach market size faster.

**Table 1 Proximate composition of *Moringa oleifera***

| Parameter % | Concentration (%) |
|---|---|
| Dry matter | 91.80 |
| Organic matter | 91.68 |
| Crude protein | 19.61 |
| Ether extract | 4.27 |
| Total ash | 8.32 |
| Neutral detergent fiber | 24.83 |
| Acid detergent fiber | 16.58 |

(Source: Dixit *et al*., 2026)

*Mineral and Vitamin Density*

Moringa leaves are a powerhouse of essential micronutrients, including vitamins (A, C and E) and critical minerals (calcium, iron, phosphorus, potassium, magnesium and zinc) (Table 2). Moringa leaves contain 7 times more vitamin C than oranges, 10 times more vitamin A than carrots, 17 times more calcium than milk, 9 times more protein than yoghurt, 15 times more potassium than bananas and 25 times more iron than spinach (Sultana, 2020). This dense mineral and vitamin profile plays a direct role in strong bone development and healthy blood formation in growing kid.

**Table 2 Mineral composition of *Moringa oleifera***

| Minerals | Concentration (%/ppm) |
|---|---|
| Calcium (%) | 1.47 |
| Phosphorus (%) | 0.21 |
| Magnesium (%) | 0.46 |
| Sodium (%) | 0.018 |
| Potassium (%) | 1.31 |
| Iron (ppm*) | 352.35 |
| Manganese (ppm) | 58.60 |
| Zinc (ppm) | 38.61 |
| Copper (ppm) | 18.72 |

(Source: Dixit *et al*., 2026) *ppm: parts per million

*Bioactive Compounds and Rumen Health*

Moringa leaves are packed with natural health-promoting compounds like flavonoids, tannins and saponins. These powerful antioxidants reduce stress and strengthen a kid's immune system. When early-weaned kids consume Moringa, these compounds stimulate beneficial gut bacteria, ensuring faster rumen development. This improved digestion helps the animal utilize nitrogen much more efficiently, generating the massive energy required for rapid growth (Abdoun et al., 2024). Additionally, special carbohydrates in the leaves directly boost gut immunity and prevent inflammation. By acting as a natural health booster, Moringa allows farmers to reduce reliance on expensive synthetic antibiotics, making it a highly valuable functional feed.

## THE CRUCIAL NEED: WHY MORINGA FOR GOAT KIDS?

Early mortality in newborn kids remain major challenges in goat farming, severely reducing farm profits. Pre-weaning kid mortality causes heavy economic losses, threatening the farm's future (Chauhan et al., 2019). Because smallholders typically keep only 13 to 34 animals, losing even a single kid affects their income. Despite having the largest goat population globally, India faces high pre-weaning death rates of 10% to 30% due to disease and poor nutrition (Roy et al., 2022). Kids are highly vulnerable early in life since their immune systems are still developing. The first week of birth accounts for 37% of total deaths and survival rates decreases up to three months of age. Furthermore, as kids shift from digestible dam’s milk to coarse grasses, their underdeveloped rumens struggle to process fibrous feed. This causes "weaning shock" which results in severe weight loss and weak immunity. Moringa oleifera acts as the perfect nutritional bridge which provides easily digestible protein and essential nutrients without a heavy fiber load, preventing weaning shock in kids.

## BENEFITS OF MORINGA SUPPLEMENTATION

1. *Improvement of nutrient intake and rumen development of kids*

   The transition to solid feed is a critical period for goat kids. Supplementing Moringa actively promotes the functional development of the rumen and helps kids adapt to solid feed much faster. The leaves act as a natural prebiotic, supporting the maturation of the gut lining and promoting the growth of beneficial gut bacteria. This early physical and microbial development in the gut directly improves how efficiently early-weaned kids consume and utilize their daily feed intake. Furthermore, specific compounds in Moringa leaves, such as amides, alkaloids and organosulphur chemicals, actively

suppress harmful bacteria in the digestive tract (Farrag, 2024). Combined with strong immunomodulatory and anti-inflammatory properties, these bioactive substances strengthen the entire digestive and immune system, creating a healthy gut environment capable of processing higher feed volumes.

2. *Improvement of nutrient digestibility of kids*

Moringa supplementation in the diet significantly improves the overall digestibility of both dry matter and crude protein. This improvement is due to Moringa's high-quality protein and bioactive constituents, which actively stimulate digestive enzyme activity and enhance microbial fermentation in the rumen. Specifically, Moringa improves nitrogen utilization and retention. Under optimal feeding levels, nitrogen retention in the body increases by approximately 25% because the highly degradable protein and perfectly balanced amino acids found in Moringa leaves actively boost microbial protein synthesis, allowing the young ruminant to extract maximum nutritional value from its feed.

3. *Improvement of body weight and feed efficiency of kids*

Replacing standard feed with moderate amounts of Moringa promotes physical growth in goat kids. Inclusion of dried Moringa leaves to replace 10% to 20% of their expensive daily concentrate, or adding fresh leaves to replace 20% to 30% of standard dry roughage, a 25% to 35% increase in daily weight gain can be observed. Compared to kids grazing solely on poor-quality pastures, Moringa fed kids convert their feed into body weight much more efficiently. This rapid growth is fueled by a powerful combination of bone-building minerals (like calcium and phosphorus) and muscle-building amino acids naturally present in the moringa (Abdoun et al., 2024; Ukey et al., 2025). Because these kids reach highly profitable market weights much faster, farmers save significantly on housing, labor and long-term feeding costs. Ultimately, Moringa acts as a complete, natural growth promoter rather than just a simple green fodder.

4. *Enhancement of immunity and disease resistance in kids*

Nutritional stress severely weakens a kid's immune system, leaving them highly vulnerable to pneumonia and heavy parasite infections. Moringa provides a powerful natural defense and act as a strong antioxidant, actively reducing inflammation and protecting liver function (Arshad et al., 2025). Moringa consistently lowers the rate of respiratory and stomach infections in flocks and special compounds in Moringa act as mild natural dewormers to control internal worm burdens. This is crucial because heavy worm loads trigger severe anemia, causing weakness and stunted growth. By

naturally boosting hemoglobin levels and red blood cell formation, Moringa prevents anemia, ensuring young kids remain energetic, resilient and reach their maximum growth potential.

5. *Practical feeding strategies: preparation and creep feeding*

   Farmers can easily harvest fresh Moringa leaves and soft twigs directly from their field boundaries or dedicated fodder plots. Before feeding, the foliage must be chopped into small pieces (2 to 3 cm) using a sickle or chaff cutter to prevent the animals from wasting feed. Drying these fresh leaves in the shade for a few hours is highly recommended to reduce excess moisture, which helps prevent mild diarrhea in very young animals. This prepared fodder should be offered using a "creep feeder" which is a specifically designed, small fenced enclosure that allows only the nursing kids to enter while keeping hungry adult does out. Farmers should start offering this chopped Moringa to kids as early as 15 days of age. While they may only nibble initially, this early exposure rapidly develops their rumen. By weaning age (60 to 90 days), their digestive systems are fully adapted to handle solid forage efficiently.

6. *Economic viability for smallholder farmers*

   The true measure of any agricultural intervention is its economic benefit at the grassroots level. For smallholder goat farmers, feeding Moringa offers highly compelling financial returns by drastically cutting concentrate costs. By cultivating this high protein biomass on marginal lands or field boundaries, farmers can replace expensive protein ingredients, like soybean meal or groundnut cake. Additionally, Moringa promotes growth rates, enabling kids to reach the optimal market weight of 20 to 25 kg much faster. This rapid turnaround significantly reduces the total labor and feed cost required per animal. Furthermore, goats fed this nutrient dense diet develop superior muscle conformation, higher dressing percentages and shiny coats. These desirable physical traits command immediate premium prices from local butchers and buyers, ultimately maximizing the net profit per animal (Aye and Adegun, 2013).

## SUMMARY

The successful rearing of goat kids determines the overall profitability of any goat farming enterprise. Post weaning nutritional stress is a primary cause of stunted growth and high mortality in kids. Integrating *Moringa oleifera* into the daily feeding routine offers a highly practical, low-cost solution. By simply cultivating Moringa on farm boundaries or marginal lands, farmers can secure a year-round supply of protein-rich green fodder. Feeding chopped Moringa leaves during the critical weaning phase rapidly accelerates daily weight gain, improves gut digestion and strongly boosts immunity against common

diseases. Thus, adopting Moringa transforms goat rearing into a sustainable and highly profitable venture for smallholder farmers.

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# ARTIFICIAL INTELLIGENCE APPLICATIONS IN AGRICULTURE: TRANSFORMING FARMING FROM EXPERIENCE-BASED TO DATA-DRIVEN DECISION MAKING

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## ABSTRACT

*Agriculture is entering a technological era in which Artificial Intelligence (AI), Machine Learning (ML), IoT, remote sensing, drones, and robotics are transforming farm management. AI analyses data from weather stations, satellites, sensors, and crop records to support decisions on crop selection, irrigation, fertilization, pest management, disease detection, and yield forecasting. In India, these technologies offer opportunities for precision farming and climate-resilient agriculture. However, adoption requires reliable datasets, affordable technologies, connectivity, farmer training, data privacy, and locally validated models. AI should complement farmers' expertise through responsible, inclusive, and farmer-centred decision support.*

**KEYWORDS:** Agricultural robotics, Artificial intelligence, Crop disease detection, Drones, IoT, Machine learning, Precision agriculture, Remote sensing, Smart farming, Yield prediction

## INTRODUCTION

Agriculture is facing multiple challenges, including climate variability, declining natural resources, increasing production costs, labour shortages, emerging pests and diseases, and the growing demand for food. At the same time, farmers are expected to produce more food while using water, fertilizers, pesticides and energy more efficiently. These challenges have created a strong need for technologies capable of converting large amounts of agricultural data into practical decisions.

Artificial Intelligence provides an important opportunity in this context. AI refers to computer-based systems capable of learning from data, identifying patterns, making predictions and supporting decisions. In agriculture, AI can combine information from soil sensors, weather stations, satellite imagery, drones, machinery, market information and previous crop records. Recent reviews show that AI and deep learning

are increasingly being applied across crop monitoring, disease detection, yield prediction, resource management and livestock applications.

The concept is gradually shifting agriculture from reactive farming to predictive farming**.** Instead of waiting for a disease outbreak, water shortage or crop stress to become visible, AI systems can potentially identify risks at an early stage and recommend appropriate interventions.

## MAJOR APPLICATIONS OF AI IN AGRICULTURE

1. *Crop and Yield Prediction:* One of the important applications of AI is predicting crop yield before harvesting. Machine learning models can analyse historical yield data together with rainfall, temperature, soil properties, satellite observations and crop-management information. Such predictions can assist farmers, government agencies, agricultural planners and agribusinesses in making decisions related to crop planning, storage and marketing. Recent research has specifically examined AI-based prediction of crop performance under drought and water-stress conditions, demonstrating the potential of models such as artificial neural networks and random forests for agricultural decision-making.
2. *Early Detection of Diseases and Pests:* Crop diseases can cause substantial yield and economic losses when they are not identified in time. AI-powered computer vision systems can analyse photographs captured by smartphones, drones or field cameras and identify visual symptoms of diseases. Deep learning models, particularly convolutional neural networks (CNNs), have become important tools for automated plant disease identification. Their advantages include rapid, non-destructive assessment and the possibility of real-time monitoring. The next generation of disease-monitoring systems is moving beyond simple image classification toward early warning systems that combine images, weather conditions, crop growth stages and environmental data.
3. *Precision Irrigation and Water Management:* Water is one of the most critical agricultural resources. AI can support irrigation scheduling by analysing soil moisture, weather forecasts, crop growth stage, evapotranspiration and historical irrigation records. Instead of applying the same amount of water throughout a field, AI-enabled systems can identify areas requiring more or less irrigation. Integration of AI with IoT sensors can enable automated irrigation systems that respond to changing field conditions. This approach can improve water-use efficiency and is particularly important in areas facing groundwater depletion, drought and irregular rainfall.
4. *Soil and Nutrient Management:* AI can also assist in assessing soil properties and recommending appropriate nutrient management. Soil test results, remote sensing data, crop history and weather information can be combined to estimate spatial variation in soil fertility. AI-based soil analysis has been investigated for improving data accuracy, reducing analytical costs and supporting large-scale agricultural decision-making. Such systems can contribute to site-specific nutrient management, where fertilizers are applied according to actual crop and soil requirements rather than using uniform application rates.
5. *Weed Detection and Smart Spraying:* Weeds compete with crops for water, nutrients, sunlight and space. Traditional weed management often involves blanket herbicide application, which can increase production costs and

environmental impacts. AI-powered cameras mounted on tractors, robots or drones can distinguish crops from weeds. The system can then guide mechanical removal or targeted spraying. This approach has the potential to reduce unnecessary pesticide application and improve input-use efficiency.

6. *Drones and Remote Sensing:* Drones and satellites generate valuable information about crop condition over large areas. AI algorithms can interpret these images to identify crop stress, nutrient deficiencies, water stress, pest infestation and changes in vegetation. The combination of remote sensing + AI + GIS is becoming an important component of modern precision agriculture. FAO has also highlighted the importance of integrating Earth Observation and AI for agricultural information and statistics.
7. *Agricultural Robots and Autonomous Machinery:* AI is increasingly being integrated into agricultural machinery. Autonomous tractors, robotic weeders, harvesting machines and intelligent spraying systems can perform repetitive operations with limited human intervention. Recent reporting from India has highlighted the use of AI-enabled autonomous tractors for operations such as planting, spraying and harvesting, illustrating the growing practical interest in agricultural automation. Robotics may become particularly valuable where agricultural labour is scarce or expensive.
8. *Livestock and Dairy Farming:* AI is not limited to crop production. In dairy and livestock systems, AI can support animal identification, behaviour monitoring, disease detection, heat detection, milk-yield prediction and feed management. Sensors and cameras can continuously monitor animals and alert farmers when abnormal behaviour or health indicators are detected. This can improve animal welfare and farm productivity.

## AI AND CLIMATE-SMART AGRICULTURE

Climate change is making agricultural decision-making increasingly difficult because of unpredictable rainfall, heat waves, droughts, floods and changing pest populations. AI can analyse weather and crop data to identify potential climate-related risks. AI-based systems can support decisions such as when to sow, which crop or variety to select, when to irrigate and when to apply plant-protection measures**.** Consequently, AI can become an important component of climate-smart agriculture. However, AI predictions are only as reliable as the data used to develop them. Models trained in one geographical region may not perform equally well in another region because soil, climate, crop varieties and management practices differ.

## CHALLENGES IN AI ADOPTION

Despite its considerable potential, several challenges must be addressed before AI can become widely accessible to farmers. First, agricultural data are often fragmented, incomplete or collected in different formats. Recent work focusing on India has highlighted challenges involving spatial and temporal integration of agricultural datasets and data governance. Second, many advanced AI systems require high-quality sensors, computing facilities and reliable internet connectivity. These requirements can make

adoption difficult for small and marginal farmers. Third, AI models need to be locally validated**.** A model developed using data from Europe or North America may not automatically provide reliable recommendations for Indian agricultural conditions. Other concerns include data ownership, privacy, cybersecurity, algorithmic bias, lack of technical skills and the difficulty of explaining complex AI recommendations to farmers. Low-cost Edge AI and TinyML technologies are emerging as promising solutions because some AI processing can be performed locally on low-power devices rather than relying completely on cloud connectivity.

## THE FUTURE OF AI IN AGRICULTURE

The future is likely to involve greater integration of AI with IoT, drones, satellites, robotics, GIS, weather forecasting and agricultural machinery. Emerging technologies such as vision transformers, foundation models and multimodal AI are also being explored for agricultural applications. FAO's recent work on Digital Agriculture and AI emphasizes moving from problem identification and experimentation toward responsible deployment and scaling of digital agricultural innovations. For countries such as India, the greatest opportunity lies in developing affordable, multilingual, locally relevant and farmer-friendly AI solutions**.** Voice-based advisory systems could be particularly useful for farmers who have limited digital literacy. AI should complement agricultural extension workers and scientists rather than replace them.

## CONCLUSION

Artificial Intelligence is emerging as a powerful technology for transforming agriculture into a more precise, efficient and climate-resilient sector. From crop disease detection and yield forecasting to irrigation management, smart spraying, soil analysis, livestock monitoring and autonomous machinery, AI can support farmers throughout the agricultural production cycle. Recent research indicates rapid progress in deep learning, computer vision, remote sensing, IoT integration and predictive agriculture. Nevertheless, technology alone cannot solve all agricultural problems. The success of AI will depend on the availability of reliable data, affordable equipment, rural connectivity, farmer training, transparent algorithms and strong institutional support. The most effective agricultural future will therefore be one in which AI intelligence and farmer experience work together. When developed responsibly and made accessible to small as well as large farmers, AI can contribute significantly to higher productivity, efficient resource use, reduced production risks and more sustainable food systems.

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# FRAGRANCE ENGINEERING IN FLOWERS: MOLECULAR MECHANISMS, TOOLS & FUTURE PROSPECTS

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## ABSTRACT

*Floral fragrance engineering integrates plant molecular biology, genetics, and biotechnology to understand and improve scent in ornamental crops. Floral volatile organic compounds (VOCs), chiefly terpenoids, phenylpropanoids/benzenoids, and fatty-acid derivatives, mediate pollinator attraction, defence, and ecological interactions. Commercial breeding has often prioritized colour, flower size, and vase life, contributing to reduced fragrance in some cultivars. This review summarizes major scent pathways, genes, analytical tools, and improvement strategies, including conventional breeding, genetic engineering, metabolic engineering, and CRISPR-based editing. Recent crop studies illustrate opportunities and ecological considerations for developing fragrant, commercially valuable flowers.*

**KEYWORDS:** Floral fragrance, Volatile organic compounds, Terpenoids, Phenylpropanoids, Genetic engineering, CRISPR-Cas9

## INTRODUCTION

Floral fragrance is an important quality trait in ornamental crops, including rose, jasmine, tuberose, carnation, chrysanthemum, petunia and orchid. It contributes to consumer preference, commercial value, essential-oil production and the perfume and cosmetic industries. Ecologically, floral scent attracts pollinators, influences plant–insect interactions and may contribute to reproductive isolation and plant defence (Dudareva et al., 2004).

Fragrance engineering involves improving or modifying floral scent through conventional breeding, molecular genetics and biotechnology. Modern breeding has frequently prioritized flower colour, size and vase life, sometimes at the expense of fragrance. Because floral scent is controlled by complex biosynthetic and regulatory networks, molecular approaches offer opportunities to restore fragrance, enhance desirable compounds and develop novel scent profiles.

## MAJOR FLORAL VOLATILE COMPOUNDS AND THEIR FUNCTIONS

Floral fragrance consists of volatile organic compounds (VOCs), generally low-molecular-weight substances that evaporate readily and produce characteristic aromas. These compounds are classified into three principal groups.

1. ***Terpenoids:*** Terpenoids are derived from five-carbon isoprene units and constitute one of the largest groups of floral volatiles. Important examples include linalool, geraniol, nerol, ocimene and farnesene. They contribute to the characteristic aromas of rose, jasmine, lavender and chrysanthemum. Their emission can attract pollinators and influence interactions between flowers and insects.
2. ***Phenylpropanoids and benzenoids:*** These compounds are primarily associated with phenylalanine-derived biosynthetic pathways. Examples include eugenol, methyl benzoate, benzyl alcohol and phenethyl alcohol. They contribute to the fragrance of carnation, petunia, snapdragon, orchid and rose. Their production depends on biosynthetic enzymes and regulatory genes controlling precursor conversion and volatile emission.
3. ***Fatty-acid derivatives:*** Fatty-acid-derived volatiles include aldehydes, alcohols and related compounds that often produce fresh, green or fruity notes. Hexanal and hexanol are representative examples. These compounds may also participate in plant defence and signalling.

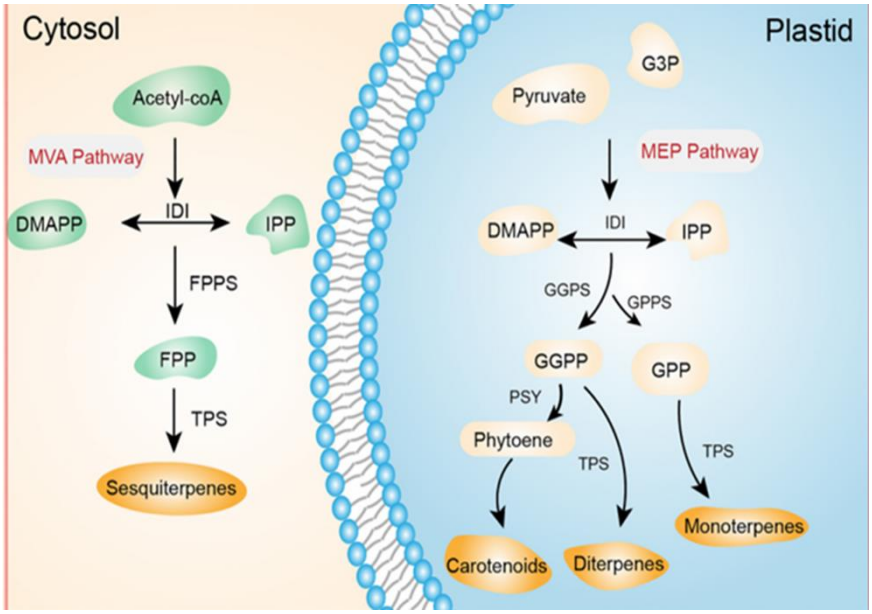



**Figure 1. A simplified schematic of terpenoid, biosynthetic pathways with their principal precursors and representative scent compounds**

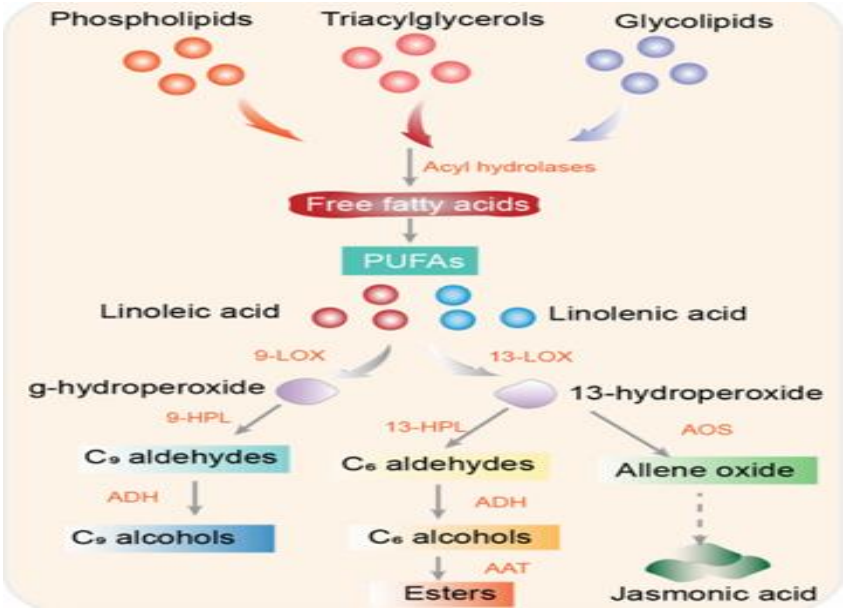



**Figure 2. A simplified schematic of the terpenoid phenylpropanoid biosynthetic pathways—with their principal precursors and representative scent compounds**

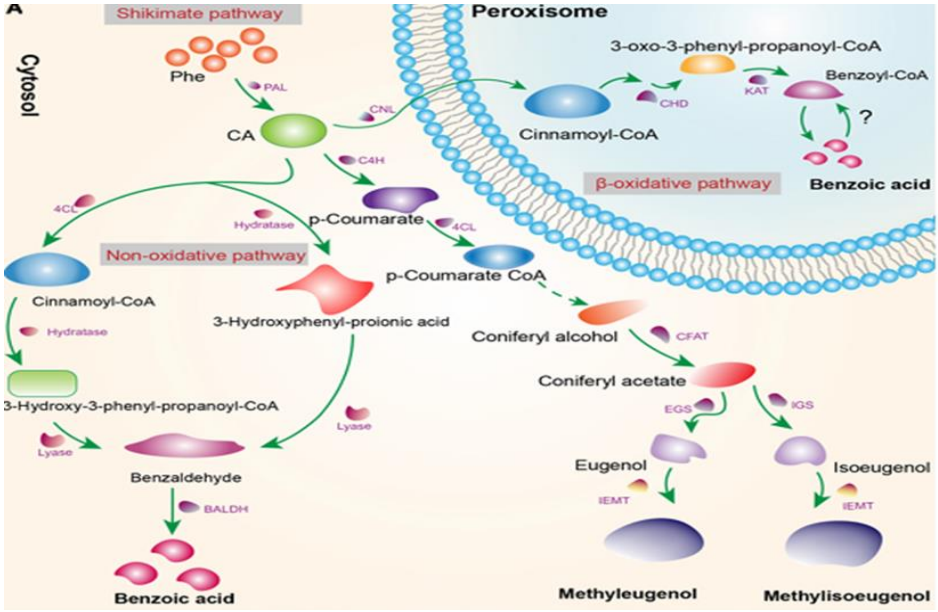



**Figure 3. A simplified schematic of the fatty-acid-derived biosynthetic pathways with their principal precursors and representative scent compounds**

Floral scent composition varies with species, cultivar, flower-development stage, environmental conditions and time of day. For example, jasmine fragrance includes compounds such as linalool, benzyl acetate, benzyl alcohol and methyl anthranilate, while rose fragrance commonly contains geraniol, citronellol and phenethyl alcohol.

## MOLECULAR MECHANISMS AND GENES REGULATING FRAGRANCE

Floral fragrance production involves biosynthetic enzymes, precursor availability, transcription factors and environmental signals. Terpene synthases (TPS) catalyse the formation of several terpenoid compounds, while phenylalanine ammonia-lyase (PAL) contributes to phenylpropanoid metabolism. Other enzymes, including methyltransferases and acyltransferases, help generate specific aromatic compounds.

In petunia, the transcription factor ODORANT1 (ODO1) regulates genes associated with benzenoid production. In rose, fragrance-related genes contribute to the biosynthesis and modification of compounds such as geraniol and citronellol. In orchids, terpene synthase activity is associated with scent production and emission.

Regulation may also depend on developmental and environmental signals. Yeh et al. (2022) demonstrated that CIRCADIAN CLOCK ASSOCIATED 1 (CCA1) regulates terpene synthase expression and daily fragrance emission in *Oncidium* hybrid orchids. This finding highlights the importance of biological rhythms when selecting sampling times and evaluating scent-related traits.

## TECHNIQUES FOR FRAGRANCE IMPROVEMENT

1. ***Conventional breeding:*** Selection, hybridization, backcrossing and recurrent selection can improve fragrance by exploiting existing genetic variation. For example, fragrant wild roses may be crossed with commercial cultivars to restore scent while retaining desirable ornamental characteristics. Similarly, hybridization can combine fragrance with flower colour, form and vase life. However, fragrance is often quantitatively inherited and influenced by multiple genes. Conventional breeding may therefore require several generations and may not produce specific fragrance profiles predictably.
2. ***Genetic engineering and genome editing:*** Genetic engineering enables targeted modification of fragrance-related genes. Overexpression of biosynthetic genes can increase the production of desired compounds, whereas gene silencing can alter pathways responsible for particular odours. Such modifications must be evaluated for their effects on the overall scent profile and other plant traits. CRISPR-Cas9 offers a more targeted approach to modifying DNA sequences associated with fragrance production. Potential applications include altering negative regulators, modifying biosynthetic enzymes and adjusting the balance of volatile compounds. However, successful improvement depends on understanding gene function, pathway interactions and possible unintended effects.

3. ***Metabolic engineering:*** Metabolic engineering modifies biochemical pathways to increase the availability of desired fragrance compounds. Strategies include enhancing precursor supply, increasing the expression of key biosynthetic enzymes and reducing competing metabolic routes. For example, changes in terpene synthase activity may influence monoterpene production, while modifications to phenylpropanoid metabolism may alter benzenoid accumulation.

These strategies require careful balancing because a change that increases one volatile may reduce another or affect plant growth and development.

## ANALYTICAL AND MOLECULAR TOOLS

Gas chromatography–mass spectrometry (GC–MS) is a central technique for identifying and quantifying floral VOCs. It supports fragrance profiling, cultivar comparison, essential-oil characterization and investigation of changes during flower development, storage and environmental stress. Transcriptomics, particularly RNA sequencing, identifies genes whose expression changes during scent production. Proteomics helps characterize enzymes involved in volatile biosynthesis, while metabolomics measures the chemical compounds accumulating in flowers. Integrating these datasets helps connect gene expression, enzyme activity and fragrance composition. Combining GC–MS with transcriptomic and metabolomic analyses can identify candidate genes and pathways for subsequent functional validation. Quantitative reverse-transcription PCR (qRT-PCR), gene-silencing experiments and overexpression studies can further test the roles of selected genes.

## RECENT RESEARCH HIGHLIGHTS

a. **Carnation:** An integrated transcriptomic and metabolomic investigation of carnation reported that eugenol, β-caryophyllene and cis-3-hexenyl benzoate were important scent constituents, with emissions varying across flower-development stages. Genes associated with phenylpropanoid and terpenoid biosynthesis showed relationships with volatile accumulation. Such findings support the identification of candidate genes for improving carnation fragrance.

b. **Chrysanthemum:** Wang et al. (2025) investigated the regulation of (E)-β-farnesene biosynthesis in chrysanthemum. Their study identified a regulatory module involving salicylic acid signalling, CmNPR3 and CmWRKY1 that influences the expression of the biosynthetic gene CmEβFS. The findings demonstrate how signalling pathways and transcriptional regulation can affect floral scent production.

c. ***Oncidium* orchid:** Yeh et al. (2022) showed that CCA1 contributes to the daily rhythm of terpene synthase expression and floral scent emission. This research indicates that fragrance improvement should consider not only the amount and composition of VOCs but also when flowers release them.
d. ***Rhododendron fortune:*** Qin et al. (2024) used transcriptomic and metabolomic approaches to investigate genes associated with fragrance-related metabolism in *Rhododendron fortunei*. Their findings highlighted candidate genes involved in aromatic-compound biosynthesis and demonstrated the value of integrated molecular analysis for identifying targets for further research.

## CHALLENGES AND FUTURE PROSPECTS

Fragrance engineering faces several challenges. Floral scent is genetically complex, and the functions of many transcription factors, transporters and regulatory elements remain incompletely characterized. Advanced analytical equipment, molecular facilities and skilled personnel may also increase research costs. Ecological safety is equally important. Altering floral scent could change pollinator attraction or other plant–insect interactions. Genetically modified flowers may also raise questions concerning consumer acceptance, regulation and environmental release. Rigorous ecological assessment and transparent communication should accompany the development of engineered cultivars.

Future research should focus on restoring fragrance in modern commercial varieties, developing customized scent profiles and improving fragrance stability under heat, drought and other environmental stresses. Integrating multi-omics, functional genomics and computational modelling may accelerate candidate-gene discovery and improve the precision of fragrance engineering. Sustainable production of valuable floral volatiles could also benefit the floriculture, perfume and cosmetic industries.

## CONCLUSION

Fragrance engineering provides opportunities to improve the aesthetic, ecological and commercial value of ornamental flowers. Understanding VOC biosynthesis and its genetic regulation, together with GC–MS, transcriptomics, proteomics and metabolomics, can support the identification of important scent-related genes. Conventional breeding, genetic engineering and genome editing offer complementary approaches to enhancing or restoring fragrance. Future progress will depend on reliable functional validation, balanced improvement of fragrance and flower quality, and careful evaluation of ecological effects.

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# MEALYBUGS: A POLYPHAGOUS PEST OF FIELD AND HORTICULTURE CROPS

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## ABSTRACT

*Mealybugs (Hemiptera: Coccoidea) are destructive, polyphagous pests affecting diverse field, horticultural, and plantation crops worldwide. Their sap-sucking activity causes plant deformation, honeydew secretion, sooty mold development, and substantial yield losses. Some species also transmit economically important plant viruses. Their waxy covering, cryptic behaviour, rapid reproduction, and microbial associations complicate management. Sustainable control requires integrated pest management combining cultural, biological, botanical, and chemical approaches. Eco-friendly biological control agents and microbial-based interventions offer promising alternatives for long-term suppression of mealybug populations and reduced dependence on synthetic pesticides.*

**KEYWORDS:** IPM, Phloem feeders, Polyphagous pests

## INTRODUCTION

Mealybugs (Hemiptera: Coccoidea) are slow-moving insects that have obvious segmentation, elongate-oval in shape and are soft in their female form with the worldwide distribution of about 2000 species and 290 genera. A mealy or cottony wax secretion, which frequently spreads along the sides in a succession of tiny filaments and typically has two longer ones at the posterior end of the body, covers them either thinly or thickly. They are among the most dangerous pests of plant life because their mouthparts, which resemble threads and are frequently longer than the body itself, are inserted through the tough tissue or bark to suck juices from the host. They range in size from extremely small young (0.50 mm) to fully grown adult females (up to 8.00 mm or possibly 9.00 mm) (Mckenzie, 2023).

Mealybugs are serious insect pests of diverse cropping systems the world over with over 160 species of mealybugs being labelled as polyphagous pests. Mealybugs are phloem feeders and the characteristic

leaf-curling damage by them might be the result of calcium extraction linked to pectin degradation by salivary pectin esterases. Many of the mealybug pests also act as vectors for various virus diseases. They are hard to be controlled by insecticides due to its morphological, structural and behavioural adaptability with the tendency to aggregate and settle themselves in cracks or crevices in tree barks, under the leaf sheath, under fruit sepals, etc. The female individuals of various mealybug species are found to release pheromone through abdominal scent glands to attract the males for mating and this phenomenon has been exploited to develop sex pheromones for monitoring and control. Herbivore-induced plant volatiles (HIPVs) play a significant role in attracting natural enemies of mealybug and the same could be exploited for conservative biological control. The presence of symbiotic microbes in the saliva of phloem-sucking hemipterans, including mealybugs, enables these insect pests to defeat host plant defences and detoxify insecticides. Gut endosymbionts, wax-degrading bacteria and entomopathogenic fungi are other promising eco-friendly agents that can channel to suppress populations of this polyphagous insect pest. Mealybugs are also successfully used as biocontrol agents for controlling weeds (Subramanian *et. al.*, 2021; Namadara *et. al.*, 2025).

## LIFE CYCLE OF MEALYBUG

Majority of mealybugs reproduce by parthenogenetically, some (like *M. hirsutus*) reproduce sexually. They were typically found in groups, primarily in the plant canopy, albeit they might sometimes be found elsewhere. There can be up to 600 eggs in each egg sac. Males had four nymphal phases, while females had three. If the climate is warm, they can breed all year long.



**Eggs: 3-9 days**



**Adult: 30-60 days**

**General life cycle of mealybug**



**Nymph: 22-25 days**



**Fig 1. Infestation of papaya mealybug on fruits**

## HOSTS PLANTS

Mealybugs can be found on plants in nurseries, greenhouses and landscapes. Nearly 5000 different species of mealybugs live on about 246 different plant families worldwide. With 585 species, Poaceae are the most common host plants for mealybugs, whereas Cyperaceae has the fewest host plants (75 species). Weeds such as *Amaranthus vividus*, *Bidens Pilosa*, *Sonchus oleraceus*, *Chenopodus ambrosoides*, *Commelina sp*., *Cucumis anguria*, *Momordica charantia*, *Cyperus rotundus*, *Chamaesyce hirta*, *Croton sonderianus*, *Jatropha urens*, *Mimosa pudica*, *Piptadenia moniliformis*, *Serra macranthera*, *Herissanthia crispa*, *Sida cordifolia*, *Malva sylvestris* L., Redroot pigweed, *Amaranthus retriflexus* L., Crimson clover, *Trifolium incarnatum* L., *Linaria sp*. and *Chorizococcus rostellum* also serve as host plants for mealybugs.

## TRANSMISSION OF PLANT VIRUSES:

Mealybugs transmit few genera of plant viruses, in contrast to aphids and whiteflies. They are less efficient than aphids, leafhoppers and other insect vectors at spreading plant viruses because they are less mobile. Virus transmission rates are also influenced by the age and sex of mealybugs. For instance, older female mealybugs are less effective at spreading plant viruses. Additionally, the nymph life phases influence how quickly viruses spread (adults are more effective than nymphs). Mealybugs transmit viruses of the genus Ampelovirus and some Closteroviruses, of the Closteroviridae family. Mealybugs also transmit badnavirus of the Caulimoviridae family. Closteroviridae generally consists of four genera- Closterovirus, Ampelovirus and Crinivirus, Velarivirus. Some studies have also confirmed the transmission of vitiviruses

**Table 1: Common mealybugs and their associated hosts plants**

| S.N. | Comon name | Scientific name | Host plants/crops |
|---|---|---|---|
| 1 | Solanum mealybug | *Phenacoccus solani* | Solanaceous crops, cotton, brinjal, okra, tomato, sesame, sunflower and china rose etc. |
| 2 | Pink sugarcane mealybug | *Saccharicoccus sacchari* | Sugarcane, reeds, some grasses etc. |
| 3 | Long-tailed mealybug | *Pseudococcus longispinus* | Citrus, grapes, pear, pineapple, avocado, ornamentals, orchids and common in greenhouse plants etc. |
| 4 | Striped mealybug | *Ferrisia virgata* | Guava, sapota, cotton, tomato, brinjal, pepper, hibiscus, sugar apple, cocoa, cassava, amaranth and plumeria etc. |
| 5 | Citrus mealybug | *Planococcus citri* | Ornamentals, vegetables, grapes, annona, lily, citrus, coconut, coleus, cactus, croton, muskmelon, primrose, yam, mango, banana, date palm, guava, soya bean, tulip and cacao etc. |
| 6 | Pineapple mealybug | *Dysmicoccus brevipes* | Pineapple, citrus, capsicum, coffee, ficus, hibiscus, banana, potato, clove, cocoa, maize, ginger, grapes etc. |
| 7 | Hibiscus mealybug | *Maconellicoccus hirsutus (Phenacoccus hirsutus)* | Hibiscus, acalypha, acacia, asparagus, cabbage, cauliflower, banyan, Fig, rubber plant, cotton, sunflower, jasmine, sapota, guava etc. |
| 8 | Mango Mealybug | *Drosicha mangiferae* | Mango, neem tree, navel orange, sweet potato, bottle guard, lantana, tobacco, black night shade etc. |
| 9 | Cotton mealybug | *Phenacoccus Solenopsis* | Cotton, apple of sodom, Indian laburnum, watermelon, bermuda grass, carrot, pepper mint, date palm etc. |
| 10 | Papaya mealybug | *Paracoccus marginatus* | Papaya, cashew nut, pine apple, jatropha, banana, beans, cowpea etc. |
| 11 | Rice mealybug | *Brevennia rehi* | Rice and other grasses |

by some mealybug species. These viruses trigger leaf discoloration, deformation, mottling and leaf yellowing. Pathogen transmission by mealybugs have been reported on guava, citrus, pomegranate, grapes, sugarcane, banana, black pepper, pineapple plantation, stone fruit, berries, yam, cassava, cashew, papaya, pawpaw and cocoa.

## INTEGRATED PEST MANAGEMENT

*Cultural Control*

In the early stages of infestation, a strong jet of water can be used to wash away mealybugs from the infested plant parts. Ant populations should be controlled by using an ant barrier or fence around the field to reduce the spread of mealybugs. Heavily infested plant parts should be removed and destroyed. Weeds around the field should be removed regularly to prevent the spread of mealybugs. Farm machinery, tools, and equipment should be cleaned and sanitized regularly to prevent secondary infestation. In perennial crops, mealybugs hiding under the bark should be removed. The stem can also be treated with dichlorvos 76 EC @ 2 ml + fish oil resin soap @ 2 g per litre of water.

*Biological Control*

Biological control agents such as *Cryptolaemus montrouzieri*, *Anagyrus pseudococci*, *Hypoaspis* spp., *Leptomastix dactylopii*, *Verticillium lecanii* and *Beauveria bassiana* can be used to control mealybugs. The predatory mite *Hypoaspis* feeds on young mealybugs (crawlers) and helps reduce their population. Other beneficial insects, such as *Cheilomenes sexmaculata*, *Nephus regularis*, *Scymnus coccivora* and *Rodolia fumida*, feed on mealybugs and can be encouraged and conserved in the field. Predatory beetles can be released at about 5,000 beetles per hectare, one to three times depending on the crop and level of mealybug infestation. In tree crops, about 10 predatory beetles per tree can be released. Release parasitoid, *Coccidoxenoides perminutus* (Hymenoptera: Encyrtidae) on all instars. During periods of high humidity, spray *Verticillium lecanii* or *Beauveria bassiana* at $2 \times 10^8$ CFU/ml to help reduce the mealybug population.

*Chemical Control*

Use pesticides that are relatively safer for beneficial insects and natural enemies. To control ants, Chlorpyriphos 20 EC @ 2.5 ml/litre of water or 5% Malathion dust @ 25 kg/ha can be applied. Mealybugs are difficult to control with contact insecticides because they hide in cracks and crevices and are protected by a waxy covering. Therefore, systemic insecticides may be more effective. Depending on the crop and local recommendations, the following insecticides or botanical pesticide can be used: Neem

oil @ 30 ml/litre of water, Imidacloprid 200 SL @ 1 ml/litre of water, Malathion 50 EC @ 2 ml/litre of water, Dimethoate 30 EC @ 2 ml/litre of water, Methyl demeton 25 EC @ 2 ml/litre of water, Phosphamidon 40 SL @ 1.25 ml/litre of water and Monocrotophos 36 WSC @ 2 ml/litre of water

*Nanotechnology*

Silver nanoparticles of ginger extract recorded to cause mortality of 2$^{nd}$ and 3$^{rd}$ instars.

## CONCLUSION

Mealybugs are serious, polyphagous pests that damage many crops by sucking plant sap and transmitting plant viruses. Their waxy covering and hiding behaviour make them difficult to control. Therefore, an integrated pest management approach involving cultural, biological, botanical and botanicals based chemical methods is essential for effective and sustainable management. Emerging approaches may also provide promising eco-friendly control.

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# CLIMATE CHANGE AND CROP PRODUCTION: IMPACTS, RISKS, ADAPTATION STRATEGIES AND PATHWAYS FOR CLIMATE-RESILIENT AGRICULTURE

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## ABSTRACT

*Climate change threatens sustainable crop production and global food security through rising temperatures, erratic rainfall, extreme weather events, and changing pest and disease patterns. Its impacts vary with crop species, growth stages, soil conditions, and management practices. Although elevated atmospheric $CO_2$ may enhance photosynthesis and water-use efficiency, these benefits are often constrained by heat, drought, and nutrient limitations. Climate-resilient varieties, improved water management, conservation agriculture, integrated nutrient management, agroforestry, precision agriculture, and weather-based advisories are essential for reducing climate risks and strengthening agricultural resilience and sustainability.*

**KEYWORDS:** Adaptation, Climate change, Climate-resilient agriculture, Crop productivity, Crop production, Drought, Food security, Heat stress

## INTRODUCTION

Agriculture is highly dependent on temperature, rainfall, solar radiation, soil moisture and other climatic factors. Climate change is altering these factors at regional and global scales, creating new challenges for crop production. The Food and Agriculture Organization (FAO) identifies increasing temperatures, changing precipitation patterns and more frequent extreme events as major climate-related threats to agricultural production. Recent research shows that climate impacts on crops are becoming increasingly important because both average climatic conditions and extreme events influence crop growth. A 2025 global assessment found that warming is likely to reduce yields of several major crops by 2050 even when adaptation is considered, demonstrating the need for accelerated climate adaptation in agriculture.

## EFFECTS OF CLIMATE CHANGE ON CROP PRODUCTION

1. *Rising Temperature:* Temperature is a critical factor controlling germination, crop development, flowering, grain formation and maturity. Excessive temperature during sensitive growth stages can reduce pollen viability, accelerate crop maturity and decrease grain filling. Wheat, maize and rice are particularly vulnerable to heat stress during flowering and reproductive stages. Recent synthesis research indicates that under severe climate change, major staple crops may experience substantial yield losses without effective adaptation.
2. *Changes in Rainfall and Water Availability:* Climate change is modifying the timing, intensity and distribution of rainfall. Prolonged dry periods can cause soil moisture deficiency and drought stress, whereas intense rainfall can result in flooding, waterlogging, soil erosion and nutrient losses. Drought is particularly important because even moderate water stress can reduce crop productivity before visible symptoms of severe drought appear.
3. *Extreme Weather Events:* Heat waves, droughts, floods and storms can cause sudden and severe crop losses. Compound heat and moisture extremes are particularly damaging because heat stress and water stress can occur simultaneously. Such combined events have already been associated with major yield losses in several agricultural regions, including India, Europe, the United States and other major producing areas.
4. *Pests, Diseases and Weeds:* Changes in temperature and humidity can modify the geographical distribution, reproduction and survival of agricultural pests and pathogens. Warmer conditions may allow some pests to expand into new areas or produce more generations during a growing season. Consequently, farmers may face increased pest-management costs and greater uncertainty in crop protection.
5. *Effects on Crop Quality and Food Security:* Climate change affects not only yield but also crop quality. Heat and water stress can alter grain composition, protein concentration, oil content and other quality characteristics. Declining and increasingly variable crop production can increase food prices and threaten food security, particularly among vulnerable farming communities.

## POSITIVE AND NEGATIVE EFFECTS OF ELEVATED $CO_2$

Increasing atmospheric $CO_2$ can enhance photosynthesis and water-use efficiency, particularly in C3 crops such as wheat and rice. However, the benefits of $CO_2$ fertilization are not sufficient to compensate for all climate-related stresses. High temperature, drought and nutrient limitations can substantially

reduce the potential benefits. C4 crops such as maize, millet and sorghum generally show smaller direct $CO_2$ benefits than C3 crops.

## ADAPTATION STRATEGIES FOR CLIMATE-RESILIENT CROP PRODUCTION

Climate adaptation should combine genetic, agronomic, engineering and technological approaches. Important strategies include:

- Development and adoption of heat-, drought- and flood-tolerant crop varieties.
- Adjustment of sowing dates and crop calendars according to changing climatic conditions.
- Efficient irrigation systems such as drip and sprinkler irrigation and improved irrigation scheduling.
- Rainwater harvesting, farm ponds and watershed management to improve water availability.
- Conservation agriculture involving minimum soil disturbance, residue management and crop rotation.
- Integrated nutrient management to improve soil health and nutrient-use efficiency.
- Agroforestry and diversified cropping systems to improve farm resilience.
- Use of weather forecasts and agro-advisories for timely farm-level decisions.
- Application of remote sensing, GIS, satellite data and precision agriculture for crop monitoring and stress detection.
- Use of crop and climate models to identify vulnerable areas and develop location-specific contingency plans.

FAO's recent scientific assessment emphasizes the importance of integrating adaptation, mitigation and sustainable agricultural practices in response to climate change.

## FUTURE PERSPECTIVES

Future agricultural research should focus on integrating climate projections, crop modelling, remote sensing, artificial intelligence and field observations. Location-specific climate-smart agriculture strategies are particularly important because climate impacts differ substantially among crops and regions. Combining improved genetics with efficient water and nutrient management can provide greater

resilience than relying on a single adaptation measure. The development of digital agriculture and satellite-based crop monitoring can further improve early detection of drought, heat stress and crop damage. Such technologies can support timely irrigation, pest management and contingency planning, particularly in climate-sensitive agricultural regions.

## CONCLUSION

Climate change represents a significant and growing threat to crop productivity, agricultural sustainability and food security. Rising temperatures, changing rainfall, drought, floods and extreme heat events can reduce crop yields and increase production uncertainty. Although elevated $CO_2$ may provide some benefits to selected crops, these advantages are often constrained by heat, drought, nutrient deficiencies and other stresses. Climate-resilient agriculture therefore requires an integrated approach involving improved crop varieties, efficient water management, conservation agriculture, diversified farming systems, weather-based advisories, precision agriculture and advanced climate modelling. Greater investment in climate-smart technologies, farmer capacity building and location-specific adaptation strategies will be essential to maintain crop production and strengthen food security under future climate conditions.

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# GREEN TECHNOLOGIES FOR SUSTAINABLE FOOD PRODUCTION

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## ABSTRACT

*Agriculture faces growing challenges from climate change, water scarcity, soil degradation, and increasing food demand. Green technologies offer sustainable solutions through precision farming, smart irrigation, renewable energy, biofertilizers, conservation agriculture, circular farming, protected cultivation, rainwater harvesting, and organic farming. These innovations conserve resources, improve soil health, reduce pollution, and enhance productivity and climate resilience. However, their adoption requires overcoming financial, technical, and awareness barriers. Government support, farmer training, and accessible digital tools can accelerate adoption, strengthen food security, and promote environmentally sustainable agriculture for future generations.*

**KEYWORDS:** Climate-smart agriculture, Green technologies, Organic farming, Renewable energy, Smart irrigation

## INTRODUCTION

Agriculture is the foundation of our food supply and the main source of livelihood for millions of people across the world. However, modern farming faces many challenges such as climate change, water scarcity, declining soil fertility, environmental pollution and an increasing demand for food. Traditional farming practices that rely heavily on chemical fertilizers, pesticides and excessive use of natural resources are becoming less sustainable. To ensure food security while protecting the environment, agriculture must adopt smarter and more sustainable approaches.

Green technologies are emerging as powerful solutions to these challenges. They combine scientific innovation with environmentally friendly practices to improve farm productivity while conserving natural resources. Technologies such as precision agriculture, smart irrigation, renewable energy, biofertilizers, conservation agriculture and digital farming help farmers produce more with fewer inputs, reduce waste and minimize environmental impact.

These technologies not only enhance crop yields and farm profitability but also improve soil health, conserve water, reduce greenhouse gas emissions and strengthen the resilience of farming systems to climate change. As governments, researchers, and farmers increasingly recognize the importance sustainable agriculture, these innovations are playing a vital role for ensuring both food security and environmental protection.

This article explores the concept of green technologies, highlights the major innovations shaping modern farming, discusses their benefits and challenges, and examines how they can contribute to sustainable food production for present and future generations.

## WHAT ARE GREEN TECHNOLOGIES?

Green technologies are eco-friendly innovations that helps to protect the environment while improving agricultural productivity. They conserve natural resources, reduce pollution and support sustainable food production. The main aim of green technologies is simple to produce more with less. By saving water and energy, reducing the use of chemicals, improving soil health and lowering pollution these technologies help farmers increase productivity while protecting the environment. As agriculture faces the challenges of climate change and rising food demand, green technologies are becoming essential for building a more resilient, profitable and sustainable food production system.

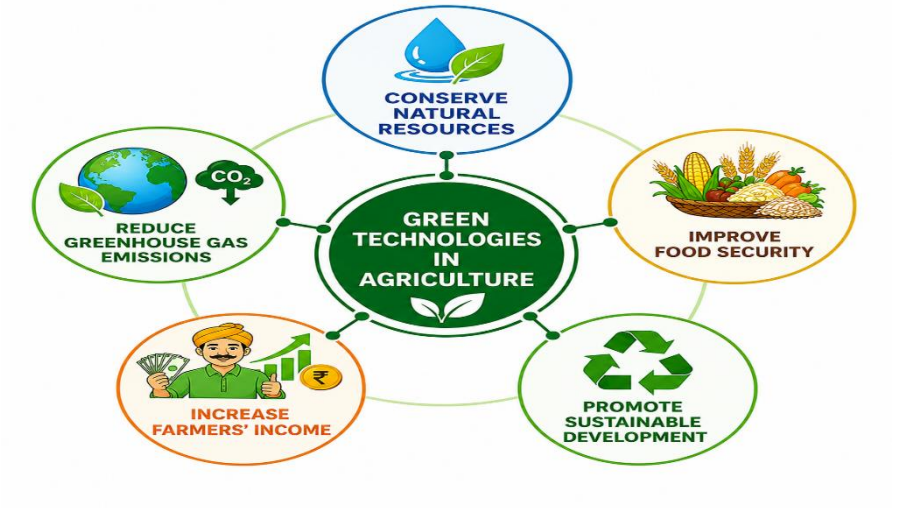



**Fig. 1. Key benefits of green technologies in agriculture**

## WHY ARE GREEN TECHNOLOGIES IMPORTANT?

As agriculture faces growing environmental and economic challenges, the adoption of green technologies has become increasingly important. These technologies support sustainable farming by improving

efficiency, reducing environmental impacts and strengthening the resilience of agricultural systems. Their key contributions are summarized in Fig. 1.

## MAJOR GREEN TECHNOLOGIES IN AGRICULTURE

1. *Precision Agriculture:* Precision agriculture, a modern farming approach that uses data and smart technologies to make better decisions in the field. Instead of treating an entire farm the same way, farmers use tools such as GPS, drones, agricultural robots, soil and crop sensors, satellite imagery and mobile apps to monitor crop growth, soil conditions and weather in real time, so that water, fertilizers, pesticides and seeds are applied only where and when they are needed. According to Gebbers and Adamchuk (2010), precision agriculture has the potential to increase food production while protecting ecosystems, making it a key strategy for achieving global food security.
2. *Smart irrigation system:* Water is one of the most precious resources in agriculture, but it is becoming scarce in many parts of the world. Smart irrigation technologies help farmers to use water more efficiently by combining micro-irrigation methods, such as drip and sprinkler irrigation, with modern technologies like soil moisture sensors, weather-based controllers, automated valves and mobile apps. Instead of watering the entire field on a fixed schedule, these systems supply the right amount of water to crops only when it is actually needed. Drip irrigation delivers water directly to the plant roots, minimizing losses through evaporation and runoff, while smart sensors and weather data help farmers avoid unnecessary irrigation. This not only saves water but also reduces energy use, lowers labour costs and improves fertilizer efficiency through fertigation. As a result, crops grow healthier, yields increase and farmers can better cope with water scarcity and changing climate conditions. By making irrigation more precise and sustainable, smart irrigation systems are playing a key role in building climate-resilient agriculture. The Food and Agriculture Organization (FAO, 2021) highlights efficient irrigation as one of the most effective ways to address water scarcity while maintaining agricultural productivity.
3. *Renewable Energy:* Renewable energy is becoming an integral part of modern agriculture, enabling farmers to increase productivity while protecting the environment. As the cost of fossil fuels continues to rise and concerns about climate change grow, farmers are increasingly adopting clean energy sources such as solar power, biogas, wind energy, and biomass to meet their energy needs. Solar-powered irrigation pumps provide a reliable and eco-friendly way to lift water for irrigation, reducing fuel costs and greenhouse gas emissions. Biogas plants convert cattle dung and crop residues into clean fuel that can be used for cooking, heating, electricity generation and even running farm

equipment. The leftover biogas slurry is a valuable organic fertilizer that improves soil fertility. In windy regions, small wind turbines can generate electricity for pumping water and powering farm operations. Crop residues such as rice husk, sugarcane bagasse, maize stalks and straw can also be converted into biomass energy instead of being burned, reducing pollution while creating an additional source of income for farmers. By lowering energy costs, reducing carbon emissions and making farms less dependent on conventional fuels, renewable energy technologies are helping to build a cleaner, more profitable and climate-resilient agricultural future (FAO & IRENA, 2021).

4. *Biofertilizers and Biopesticides:* Synthetic fertilizers and pesticides have played an important role in increasing crop yields and ensuring food security. However, their excessive and repeated use has also created serious environmental challenges such as soil degradation, water pollution, the decline of beneficial organisms and the development of resistance to pests. To address these concerns, farmers are increasingly adopting biofertilizers and biopesticides as safe and more sustainable alternatives. By reducing dependence on synthetic chemicals, these biological inputs promote healthier soils, improve biodiversity and support long-term agricultural sustainability. According to Vessey (2003), plant growth-promoting microorganisms not only enhance nutrient uptake and plant growth but also enhance overall soil health, making biofertilizers an important tool for achieving productive and environmentally friendly agriculture.
5. *Conservation Agriculture:* Conservation agriculture is a sustainable farming approach that helps produce more food while protecting natural resources for future generations. It is based on three key principles: minimizing soil disturbance through reduced or zero tillage, keeping the soil permanently covered with crop residues or cover crops and practicing crop rotation or crop diversification. These practices improve soil structure, enhance water infiltration and moisture conservation, reduce soil erosion, suppress weeds, and promote beneficial soil organisms. Conservation agriculture also lowers fuel and labour costs by reducing tillage operations and increases the soil's ability to store carbon, making farming more resilient to climate change. By improving soil health, conserving water, and maintaining long-term productivity, conservation agriculture offers a practical and environmentally friendly pathway toward sustainable agriculture and food security. According to Hobbs *et al.* (2008), conservation agriculture offers one of the most practical pathways for maintaining long-term agricultural productivity while protecting natural resources.
6. *Circular Agriculture:* Circular agriculture focuses on reducing waste by reusing and recycling resources within the farming system. Crop residues, livestock manure and food waste are converted into valuable products such as compost, organic fertilizers and biogas instead of being discarded. This

approach improves soil health, reduces environmental pollution and lowers the need for synthetic inputs, creating a more sustainable and resource-efficient food system. As noted by Velasco-Muñoz *et al*. (2021), circular agriculture enhances resource efficiency by closing nutrient and energy cycles while supporting resilient and climate-smart food production.

7. *Protected Cultivation:* Protected cultivation is helping farmers grow crops more efficiently by creating a safer and more controlled environment for plants. Instead of exposing crops to harsh weather in open fields, farmers grow them inside greenhouses, polyhouses, or shade-net houses. These protective structures shield crops from excessive heat, heavy rainfall, strong winds, pests and diseases, allowing plants to grow healthier and produce better-quality yields. This technology makes it possible to cultivate vegetables, fruits, flowers, and nursery plants throughout the year, even during the off-season. Since water and nutrients are supplied precisely through systems like drip irrigation and fertigation, farmers can reduce wastage, save resources, improve crop productivity and earn higher incomes (Singh, 2014).
8. *Rainwater Harvesting and Water Recycling:* Rainwater harvesting involves collecting and storing rainwater in farm ponds, tanks, or reservoirs so it can be used during dry periods instead of relying entirely on groundwater. This simple practice improves water availability and strengthens farm resilience during droughts. Water recycling is another sustainable approach, where treated wastewater is safely reused for irrigation whenever appropriate. Together, these practices reduce pressure on freshwater resources, improve water-use efficiency and support sustainable farming, especially in regions facing frequent water shortages (UNESCO World Water Development Report, 2023).
9. *Organic Farming and Integrated Pest Management:* As more people choose healthy and chemical-free food, sustainable farming practices are becoming increasingly important. Organic farming focuses on nurturing the soil and crops naturally by using compost, green manures, biofertilizers and biological methods instead of synthetic fertilizers and pesticides (Lampkin, 2002). At the same time, Integrated Pest Management (IPM) helps farmers keep pests under control by combining methods such as crop rotation, resistant varieties, beneficial insects, mechanical control and careful, need-based use of pesticides.

## BENEFITS

1. Green technologies are helping farmers to produce more food while using fewer natural resources.
2. By making better use of water, fertilizers, pesticides and energy, these innovations reduce production costs and improve crop yields.

3. Technologies such as precision agriculture, smart irrigation, and renewable energy help minimize waste and lower greenhouse gas emissions, making farming more climate-friendly.
4. At the same time, practices like using biofertilizers and biopesticides improve soil health, protect beneficial organisms and reduce pollution.
5. Green technologies also make farms more resilient to droughts, erratic rainfall and other climate-related challenges.
6. Overall, they support sustainable food production, conserve natural resources and contribute to healthier ecosystems and better livelihoods for both present and future generations

**CHALLENGES TO ADOPTION**

Despite their many benefits, green technologies face several barriers to adoption. High initial costs, limited technical knowledge, poor digital infrastructure and inadequate access to credit and extension services make it difficult, especially for small and marginal farmers, to adopt these innovations. Small landholdings and uncertainty about economic returns also discourage investment. Improving farmer training, financial support, infrastructure and government policies is essential to accelerate the adoption of green technologies and promote sustainable agriculture.

**GOVERNMENT INITIATIVES**

Many countries including India, have launched programs to promote sustainable agriculture. Initiatives such as the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), National Mission on Sustainable Agriculture (NMSA), Soil Health Card Scheme and PM-KUSUM encourage efficient irrigation, renewable energy use, soil health management and sustainable farming practices. These programs provide financial assistance, technical guidance and infrastructure support to farmers adopting green technologies.

**FUTURE PROSPECTS**

The future of agriculture lies in integrating digital technologies with environmentally sustainable practices. Artificial intelligence, robotics, drones, remote sensing, blockchain, nanotechnology and renewable energy are expected to revolutionize farming. As technology becomes more affordable and accessible, green agriculture will play a crucial role in achieving global food security while protecting natural resources and combating climate change.

## CONCLUSION

Green technologies are transforming agriculture into a more productive, resilient, and environmentally responsible sector. By combining innovation with sustainability, these technologies enable farmers to produce more food while conserving water, improving soil health, reducing pollution, and protecting biodiversity. The widespread adoption of green technologies is essential for ensuring food security, enhancing farmers' livelihoods, and building a sustainable future. Governments, researchers, extension agencies, private industries, and farmers must work together to accelerate the transition toward climate-smart and environmentally friendly agriculture.

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# APPLICATION OF DRONE TECHNOLOGY IN PLANT PROTECTION

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## ABSTRACT

*Unmanned aerial vehicles (UAVs), commonly known as drones, are transforming precision plant protection through early crop-stress detection, pest surveillance, and targeted pesticide application. Equipped with RGB, multispectral, and thermal sensors, drones facilitate crop monitoring, mapping, and precision spraying. Multirotor, fixed-wing, single-rotor, and hybrid vertical take-off and landing (VTOL) platforms serve diverse agricultural needs. Emerging applications include sterile insect technique (SIT), pheromone deployment, and targeted release of beneficial organisms. Despite challenges related to cost, payload, battery life, weather, and regulations, advances in artificial intelligence and autonomous navigation enhance sustainable plant protection.*

**KEYWORDS:** Disease detection, Integrated pest management, Plant protection, Precision agriculture, Remote sensing, Unmanned aerial vehicle

## INTRODUCTION

A drone, or unmanned aerial vehicle (UAV), is an aerial platform that operates without a human pilot on board. It may be remotely controlled or programmed to fly autonomously and uses aerodynamic forces to remain airborne. Although UAVs were initially developed largely for military and surveillance purposes, they are now used in many civilian fields, including agriculture, environmental monitoring, traffic observation, and weather-related applications. In crop production, drones can collect field-level information and support timely, targeted plant-protection decisions.

The development of agricultural drone technology has progressed alongside improvements in navigation, imaging, sensors, and data processing. Early UAV development during the 1910s–1930s was closely associated with military aviation. In the 1980s, Japan introduced the Yamaha R-50 for agricultural pesticide spraying, including in rice fields. During the 1990s and 2000s, GPS and remote-sensing

technologies expanded the potential for crop monitoring and mapping. In the 2010s, commercial platforms became more accessible for spraying and precision-agriculture applications. During the 2020s, AI-enabled systems increasingly supported crop-health assessment, disease surveillance, yield estimation, and automated farm operations. In India, government initiatives such as the Sub-Mission on Agricultural Mechanization (SMAM) have supported the promotion of agricultural mechanization, including drone applications.

## TYPES OF UAVS USED IN PLANT PROTECTION

### *1. Multirotor UAVs*

Multirotor UAVs use several rotors to generate lift and are generally manoeuvrable and comparatively straightforward to operate. They are useful for close-range observation, photography, crop scouting, and field inspection. Their ability to hover and fly at low speeds makes them suitable for detailed monitoring and targeted operations, particularly in small or fragmented fields (Fig. 1).



**Fig. 1. Multirotor UAV (Yinka-Banjo and Ajayi, 2029)**

### *2. Fixed-Wing UAVs*

Fixed-wing UAVs have an aircraft-like structure and can cover relatively large areas efficiently. They are useful for field mapping, crop surveillance, and monitoring extensive agricultural landscapes. Compared with multirotor platforms, they generally require more space or a suitable arrangement for take-off and landing and are less suited to hovering over a specific point (Fig. 2).




**Fig. 2. Fixed wing multirotor UAV (Yinka-Banjo and Ajayi, 2029)**

### *3. Single-Rotor UAVs*

Single-rotor UAVs resemble helicopters and use one main rotor to generate lift. Depending on their design, they may offer greater payload capacity or flight endurance than small multirotor platforms. Potential agricultural applications include carrying specialized sensors, LiDAR-based surveying, and collecting data over larger areas (Fig. 3).



**Fig. 3. Single-rotor UAV (Yinka-Banjo and Ajayi, 2029)**

### *4. Fixed-Wing–Multirotor Hybrid UAVs*

Hybrid UAVs combine the vertical take-off and landing (VTOL) capability of multirotor systems with the forward-flight efficiency of fixed-wing aircraft. This combination can allow operation from constrained launch areas while supporting longer-distance monitoring and mapping. Such platforms may be useful where both access flexibility and broad-area coverage are required (Fig. 4).



**Fig. 4. Fixed-wing multirotor hybrid UAV (Yinka-Banjo and Ajayi, 2029)**

## APPLICATIONS OF DRONES IN PLANT PROTECTION

### *1. Disease Detection and Crop-Stress Monitoring*

Drones can survey crop fields using high-resolution RGB, multispectral, and thermal cameras. These sensors record changes in colour, spectral reflectance, and canopy temperature that may be associated with disease or other forms of crop stress. For example, reductions in chlorophyll content or changes in canopy temperature may indicate that plants are under stress. Such observations can help identify areas

that require closer field inspection and may, under suitable conditions, reveal stress before symptoms become obvious to the naked eye. However, remote-sensing indicators are not always disease-specific; nutrient deficiencies, water stress, and other factors can produce similar signals, so field validation is important.

The Normalized Difference Vegetation Index (NDVI) is one commonly used indicator of vegetation condition. It is calculated from near-infrared (NIR) and red reflectance as follows:

**NDVI = (NIR − Red) / (NIR + Red)**

where NIR is the near-infrared light reflected by vegetation and Red is the red light reflected by vegetation. Healthy vegetation typically absorbs much of the red light used in photosynthesis and reflects more near-infrared radiation. Stress can alter this pattern and reduce NDVI values. Images captured by a drone can be processed to produce spatial maps of vegetation condition, helping identify areas for targeted scouting and management. NDVI should be interpreted alongside field observations and other relevant information rather than treated as a definitive diagnosis of a particular disease.

***2. Precision Pesticide Application***

Agricultural drones can apply pesticides using programmed flight paths, spray nozzles, and flow-control systems. When combined with field scouting, mapping, or sensor-based detection, they can direct applications towards identified infestation zones rather than treating the entire field uniformly. This site-specific approach may reduce unnecessary chemical use, save time, and improve the timeliness of plant-protection operations. Application performance depends on factors such as droplet size, flight height, speed, wind, canopy structure, formulation, and equipment calibration.

Key potential advantages include:

- Reduced time and labour requirements for spraying.
- More controlled application when the equipment is correctly calibrated.
- Reduced direct exposure of operators to spray mixtures.
- Access to some difficult, uneven, muddy, or waterlogged field areas.
- Potential reduction in pesticide wastage through targeted application.

***3. Drone-Assisted Sterile Insect Technique and Mating Disruption***

The sterile insect technique (SIT) is a species-specific pest-management approach in which sterile insects—typically males—are released into a target population. When sterile males mate with wild

females, viable offspring are not produced, which can reduce pest populations over time when releases are sufficiently frequent and well coordinated. Drones may help distribute sterile insects across orchards or other target areas. Their use can improve the logistics of releases, although success depends on the target species, release timing, insect handling, and an appropriate area-wide management programme.

Drones may also be used to distribute pheromones for mating disruption. These pheromones interfere with the ability of male insects to locate females, reducing successful mating. The source text reports that, in early 2018, approximately 20,000 sterile codling moth males (*Cydia pomonella*) were released by drone in apple orchards in Central Hawke's Bay, New Zealand. This example should be checked against the original source before publication.

***4. Precision Release of Natural Enemies***

Drones can support biological control by releasing beneficial organisms, including parasitoids and predators, into crop fields. These natural enemies can suppress pests such as aphids, borers, and caterpillars, thereby complementing other integrated pest management (IPM) practices. GPS-guided routes and field maps can help direct releases towards selected areas, while suitable release devices can improve the distribution of beneficial organisms.

One potential application is the distribution of Trichogramma parasitoid eggs to help manage lepidopteran pests, including the maize stem borer (*Chilo partellus*) and rice stem borer (*Chilo suppressalis*). The suitability of a drone-based release depends on the organism, release formulation, crop structure, weather, and the need to maintain the viability and effective distribution of the biological control agent.

Potential benefits of drone-assisted biological control include:

- Reduced reliance on chemical insecticides when integrated into an effective IPM programme.
- Faster distribution over large or difficult-to-access fields.
- More targeted placement of beneficial organisms.
- Potential savings in labour and time.

***5. Insect Pest Detection and Surveillance***

Drones can strengthen insect-pest surveillance by providing repeated, georeferenced observations of crop condition and field-level damage. Their applications include the following:

a. *Early detection of crop stress:* RGB, multispectral, and thermal imagery can reveal changes such as discolouration, leaf curling, or canopy-temperature differences that may be associated with pest

injury. These signals can guide field inspection, although direct confirmation is often needed to distinguish pest damage from other causes of stress.

b. *Monitoring pest populations and damage:* High-resolution images may help identify visible pest colonies, damaged plants, feeding marks, holes, webbing, or wilting. Image-analysis tools, including AI-based approaches, may assist in estimating pest abundance or tracking damage patterns where image quality and validation are adequate.

c. *Pheromone-trap surveillance:* Drone imagery may be used to inspect pheromone traps and, where image resolution permits, support the counting of captured insects. Repeated observations can help identify changes in pest activity and inform the timing of field scouting or control.

d. *Hotspot mapping and targeted management:* Combining drone observations with GPS and geographic information system (GIS) tools can produce maps of suspected pest hotspots. These maps help direct ground surveys and, where justified, site-specific interventions. Targeted spraying should follow confirmation of the pest problem and consideration of economic thresholds, beneficial organisms, and applicable label directions.

e. *Surveillance across large areas:* Drones can survey orchards and field crops such as rice, cotton, and maize more rapidly than many manual scouting methods. Repeated flights can provide a record of crop condition over time and help identify where additional inspection is needed.

## ADVANTAGES OF AGRICULTURAL DRONES

- **Time efficiency:** Drones can collect field imagery and survey large areas in less time than many ground-based monitoring methods.
- **Labour savings:** They can reduce the manual effort required for some monitoring, mapping, and spraying tasks.
- **Precision management:** Georeferenced data can help target pesticides or other interventions to areas where they are needed.
- **Earlier identification of problems:** Remote sensing can highlight crop-stress patterns and guide timely field inspection.
- **Improved crop monitoring:** Repeated flights provide spatial information that supports field-level decision-making.
- **Access to challenging terrain:** Drones may be useful in muddy, uneven, waterlogged, or otherwise difficult-to-access fields.

- **Potential reduction in chemical overuse:** Targeted application may reduce unnecessary pesticide use when supported by reliable diagnosis and appropriate calibration.
- **Support for digital agriculture:** Integration with GPS, sensors, GIS, and AI-based image analysis can improve the use of crop-monitoring information.

## LIMITATIONS AND CHALLENGES

- **High initial cost:** Drones, sensors, spraying systems, and data-processing tools may be expensive, particularly for small-scale farmers.
- **Training and technical skills:** Operators need appropriate training in flight planning, equipment handling, data interpretation, and safe application practices.
- **Limited battery endurance:** Flight duration is constrained by battery capacity, payload, and operating conditions; recharging or battery replacement may interrupt work.
- **Weather sensitivity:** Wind, rain, and extreme temperatures can affect flight safety, image quality, and spray deposition.
- **Maintenance and software:** Equipment upkeep, repairs, calibration, and software updates add to operating costs.
- **Regulatory requirements:** Drone operations and agricultural spraying must comply with applicable aviation, pesticide-use, and other relevant rules.
- **Payload constraints:** Smaller platforms have limited capacity for spray mixtures, sensors, and other equipment, which may restrict operational coverage.

## FUTURE PROSPECTS

Further progress in artificial intelligence, machine learning, sensor miniaturization, autonomous navigation, and data integration is likely to expand the role of drones in plant protection. Automated image analysis may help identify crop-stress patterns and prioritise scouting, while improved navigation and coordinated or swarm operations could increase monitoring efficiency. Advances in batteries, payload design, and spray-control systems may also improve operational performance. For these technologies to deliver reliable benefits, their use should be supported by field validation, operator training, economic assessment, and compliance with relevant regulations. Shared-service models, custom-hiring centres, and suitable support programmes may help make drone services more accessible to farmers.

## CONCLUSION

Drone technology is creating new opportunities for plant protection through crop-stress monitoring, pest and disease surveillance, precision pesticide application, and the targeted release of sterile insects and natural enemies. Sensors, NDVI-based mapping, GPS, GIS, and AI-assisted image analysis can support more timely and site-specific decisions, potentially reducing labour demands and unnecessary chemical applications. Nevertheless, drones do not replace field scouting or expert diagnosis, and their effectiveness depends on suitable equipment, validated data, correct operation, and integration with broader integrated pest management practices. High costs, limited battery life and payload, weather constraints, technical requirements, and regulation remain important barriers. Training, supportive policies, and accessible service models will be important for wider adoption. Used appropriately, drones can contribute to more efficient and sustainable plant protection.

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# IN VITRO MUTAGENESIS IN CHRYSANTHEMUM: PROTOCOLS, STABILIZATION, AND PROSPECTS FOR CLIMATE RESILIENCE

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## ABSTRACT

*In vitro mutagenesis offers an effective approach to improving chrysanthemum (Chrysanthemum morifolium), an ornamental crop constrained by polyploidy and complex breeding behaviour. This review examines gamma irradiation and ethyl methanesulfonate (EMS) treatments, mutant stabilization through successive vegetative generations, and molecular validation using ISSR and IRAP markers. Mutagenic responses vary with cultivar, dose, and treatment conditions, influencing survival, regeneration, and desirable phenotypes. Integrating mutagenesis with omics, functional validation, and genome editing could broaden genetic variation and support the development of climate-resilient chrysanthemum cultivars.*

**KEYWORDS:** Chrysanthemum, Chimaera stabilisation, Climate resilience, Gamma irradiation, In vitro mutagenesis, Molecular markers

## INTRODUCTION

Chrysanthemum (*Chrysanthemum morifolium*) is an economically important ornamental crop valued for its diverse flower colours, forms, and commercial applications. Conventional improvement through hybridization and selection is constrained by polyploidy, complex inheritance, and breeding incompatibilities. Induced mutagenesis offers an alternative for generating novel variation, particularly in flower colour, plant architecture, and stress-related traits.

In vitro mutagenesis enables controlled treatment of cultured plant material and facilitates the multiplication and selection of desirable mutants. Gamma irradiation and ethyl methanesulfonate (EMS) are commonly used mutagens. However, successful improvement requires suitable treatment doses, efficient regeneration, stabilization of chimeric shoots, and reliable assessment of genetic variation.

## MUTAGENIC TREATMENT PROTOCOLS

1. ***Gamma irradiation:*** Gamma irradiation induces DNA damage and other cellular changes that may generate useful phenotypic variation. The response depends on cultivar, explant type, physiological condition, and radiation dose. The median lethal dose ($LD_{50}$) is a useful reference for selecting treatment levels, although it must be established experimentally for each material.

   The supplied literature reports $LD_{50}$ values around 20–25 Gy for some chrysanthemum cultivars. Lower doses may preserve regeneration capacity, whereas excessive exposure can cause chlorosis, reduced growth, and impaired photosynthesis. Irradiated explants should therefore be evaluated for survival, shoot regeneration, morphological variation, and subsequent flowering performance.
2. ***Ethyl methanesulfonate (EMS):*** EMS is a chemical mutagen that predominantly induces point mutations, including G to A transitions. Concentrations of approximately 0.1–0.5% have been reported for chrysanthemum mutagenesis, but the effective concentration depends on treatment duration, explant characteristics, and cultivar sensitivity. Excessive EMS exposure can reduce survival and regeneration. Preliminary dose-response experiments should determine treatment conditions that balance mutation induction with the recovery of viable plants. Treated material must also be thoroughly rinsed and handled using appropriate chemical-safety procedures.
3. ***Comparative considerations:*** Gamma irradiation can generate conspicuous changes in flower colour and plant architecture, while EMS may produce less visible genetic changes. The effectiveness of either mutagen should be assessed through survival, regeneration, mutation frequency, and stability rather than dose alone. Combined treatments should be considered only after their individual effects and potential interactions have been evaluated.

## CHIMERA MANAGEMENT AND MUTANT STABILIZATION

Mutagenesis in chrysanthemum frequently produces chimeras, in which genetically different cell populations coexist within a shoot. Such plants may display altered flower colour or form initially, but these traits can revert or segregate during subsequent growth.

The VM1–VM4 approach involves successive vegetative propagation and selection to identify and stabilize desirable mutants. Repeated nodal or shoot-tip subculturing can help recover genetically uniform shoots, although stabilization is not guaranteed. The process should include careful selection of individual shoots, repeated evaluation of the target phenotype, and confirmation of uniformity across flowering cycles.

Because mutations may affect different meristematic cell layers, visual selection alone may not establish genetic stability. Cytological and molecular assessments can strengthen the evaluation. Stable mutants should ultimately be assessed under production conditions for trait consistency, plant vigour, flowering characteristics, and commercial suitability.

## MOLECULAR VALIDATION

Molecular markers can help distinguish putative mutants from untreated plants. Inter-simple sequence repeat (ISSR) and inter-retrotransposon amplified polymorphism (IRAP) markers are useful for detecting DNA polymorphisms and assessing genetic relationships among regenerated plants.

However, marker polymorphism does not necessarily identify the mutation responsible for a particular phenotype or establish that the desired trait will remain stable. Molecular results should therefore be interpreted alongside morphological observations and repeated phenotypic assessments.

Emerging approaches, including single-nucleotide polymorphism (SNP) genotyping, transcriptomics, and metabolomics, can provide additional information. For example, transcriptomic and metabolomic analyses may help investigate changes in pigment biosynthesis associated with flower-colour variation. Combining these methods offers a more comprehensive framework for identifying, validating, and selecting useful mutants.

## COMPARATIVE OUTCOMES AND CLIMATE-RESILIENCE APPLICATIONS

Mutagenic outcomes vary considerably with genotype and treatment conditions. The supplied literature reports gamma-irradiation $LD_{50}$ values of approximately 20–25 Gy and flower-colour mutation frequencies near 2% in some experimental contexts. EMS treatments around 0.2–0.4% have been associated with detectable polymorphism and phenotypic variation. These values are indicative rather than universal recommendations and require confirmation under specific experimental conditions.

Beyond ornamental traits, induced mutagenesis may contribute to climate-resilient breeding by generating variation in heat tolerance, antioxidant responses, and other stress-related characteristics. The supplied manuscript describes heat-tolerant EMS-derived material as a potential avenue for lowland cultivation; however, such claims require validation using accessible primary research evidence.

Future selection programmes should evaluate mutants under relevant heat, drought, and other environmental stresses. Replicated trials across environments are essential to distinguish stable tolerance from temporary responses and to determine whether stress adaptation is maintained without compromising flower quality or yield.

## FUTURE PROSPECTS

The integration of in vitro mutagenesis with genomic, transcriptomic, and metabolomic tools can improve the identification and characterization of useful variation. Functional studies can help connect genetic changes with observable traits, while genome editing may provide complementary opportunities for targeted improvement.

Future research should prioritize reproducible treatment protocols, efficient regeneration, reliable chimera stabilization, and rigorous evaluation of stress tolerance. Combining genetic diversity with molecular validation and multi-environment testing could accelerate the development of chrysanthemum cultivars with desirable ornamental characteristics and improved environmental adaptability.

## CONCLUSION

In vitro mutagenesis provides a valuable approach to expanding genetic variation in chrysanthemum. Gamma irradiation and EMS can generate useful phenotypic diversity, while successive vegetative propagation and molecular assessment support the identification of stable mutants. Integrating these methods with omics technologies and genome editing may improve selection efficiency and broaden breeding objectives. Nevertheless, cultivar-specific optimization, genetic uniformity, and field validation remain essential for developing commercially viable and climate-resilient chrysanthemum varieties.

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# COMPUTER MODELS FOR AGRICULTURE: APPLICATIONS, ADVANCES AND FUTURE PROSPECTS

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## ABSTRACT

*Agriculture faces growing challenges from climate variability, resource scarcity, soil degradation, and emerging pests and diseases. Computer-based models support scientific decision-making by simulating agricultural processes using weather, soil, crop, water, management, and socioeconomic data. Traditional crop models, including DSSAT, APSIM, AquaCrop, and WOFOST, estimate crop growth, yield, and environmental responses. Recent advances in artificial intelligence, machine learning, remote sensing, IoT, and digital twins have expanded predictive capabilities. This article reviews agricultural modelling approaches, applications, advantages, limitations, and future prospects, emphasizing integrated, accurate, and sustainable decision-support systems.*

**KEYWORDS:** Artificial intelligence, Computer modelling, Crop yield prediction, Decision support system, Machine learning, Precision agriculture, Remote sensing, Smart agriculture

## INTRODUCTION

Agricultural production is a complex system involving interactions among soil, crop, atmosphere, water, nutrients and management practices. Farmers must make decisions regarding sowing dates, crop varieties, irrigation, fertilization, pest management and harvesting under uncertain environmental conditions. Computer models provide a systematic method for representing these interactions and evaluating different management scenarios.

Crop models have traditionally been developed using mathematical equations describing physiological and environmental processes. They can simulate crop growth and development under different combinations of weather, soil and management conditions. Recent reviews indicate that models such as APSIM, DSSAT, AquaCrop, WOFOST and ORYZA have important applications in crop production, water management and food-security assessment.

The rapid development of artificial intelligence has introduced a new generation of computer models. Machine-learning and deep-learning models can identify relationships within large datasets without requiring all relationships to be explicitly represented through mathematical equations. Consequently, computer modelling in agriculture is moving from conventional simulation toward integrated, data-driven and intelligent systems.

## MAJOR TYPES OF COMPUTER MODELS IN AGRICULTURE

1) *Crop Simulation Models:* Crop simulation models represent crop growth and development as a function of environmental and management variables. Important inputs include temperature, solar radiation, rainfall, soil properties, crop genotype, planting date, irrigation and fertilizer application. Models such as DSSAT, APSIM, AquaCrop and WOFOST can estimate biomass production, crop phenology, yield and water-use efficiency. These models are particularly useful for evaluating alternative management practices and studying the effects of climate change. Recent research emphasizes that crop models can support decisions related to productivity, sustainability, climate adaptation and resource management. Model ensembles and coupled models can also reduce some limitations associated with individual models.
2) *Statistical and Machine-Learning Models:* Machine learning uses historical datasets to establish relationships between agricultural inputs and outputs. Common techniques include linear regression, decision trees, random forests, support vector machines, artificial neural networks and gradient-boosting methods. For example, a crop-yield prediction model can use rainfall, temperature, soil characteristics, fertilizer application, satellite-derived vegetation indices and historical yield data to estimate expected production. Recent reviews demonstrate the increasing use of machine learning and deep learning for agricultural yield prediction. The major advantage of ML models is their ability to handle large and nonlinear datasets. However, their reliability depends strongly on the quality, quantity and representativeness of training data.
3) *Deep-Learning and Computer-Vision Models:* Deep learning has become particularly important for agricultural image analysis. Convolutional neural networks (CNNs), recurrent neural networks (RNNs), long short-term memory networks (LSTMs) and transformer-based models can analyse images obtained from smartphones, drones and satellites.

These models can be used for:

- Crop disease identification
- Weed detection

- Plant counting
- Crop-stage identification
- Fruit detection
- Crop stress assessment
- Yield estimation
- Remote-sensing image classification

A major advantage of deep learning is its ability to automatically extract complex features from images and other high-dimensional datasets. Recent research also highlights the potential of advanced deep-learning architectures and vision transformers for agricultural applications.

## APPLICATIONS OF COMPUTER MODELS IN AGRICULTURE

Computer models have applications throughout the agricultural production cycle.

a) *Crop Yield Prediction:* Yield prediction is one of the most important applications. Models can combine weather records, satellite observations, soil information and historical yield data to provide early estimates of production. Such information is useful for farmers, agricultural planners, commodity markets and policymakers.

b) *Irrigation Management:* Computer models can estimate crop evapotranspiration, soil-water balance and crop water requirements. These predictions can help determine when irrigation should be applied and how much water should be supplied. This is particularly important in water-scarce regions.

c) *Fertilizer and Nutrient Management:* Models can estimate nutrient demand and evaluate fertilizer strategies. By integrating soil information, crop growth and weather conditions, computer models can support site-specific fertilizer recommendations and improve nitrogen-use efficiency.

d) *Pest and Disease Management:* AI-based models can analyse crop images and environmental conditions to identify disease symptoms and estimate pest risks. Early detection allows farmers to take preventive action and potentially reduce unnecessary pesticide applications.

e) *Climate-Change Impact Assessment:* Crop models are widely used to evaluate the potential effects of temperature increases, changing rainfall patterns, elevated atmospheric carbon dioxide and extreme weather events. Such simulations can help identify suitable adaptation strategies, including changes in planting dates, cultivars, irrigation and crop-management practices.

f) *Precision Agriculture*: The combination of GPS, sensors, drones, satellites, IoT and AI enables

spatially and temporally specific agricultural management. Computer models transform these data into useful information for variable-rate irrigation, fertilizer application, crop protection and harvesting.

## INTEGRATION OF AI AND TRADITIONAL CROP MODELS

An important development is the integration of process-based crop models with machine learning. Traditional models have the advantage of representing biological processes, whereas machine-learning models are effective at identifying complex patterns in large datasets. Hybrid models can therefore combine the strengths of both approaches. Remote sensing and real-time sensor data can also be incorporated to continuously update crop-model predictions. Recent research identifies model coupling, remote sensing, real-time observations, AI and digital twins as important directions for improving agricultural decision-support systems. Foundation models represent another emerging area. Recent reviews indicate that agricultural foundation models could integrate diverse agricultural datasets and support applications such as crop monitoring, disease diagnosis, agricultural knowledge services and intelligent machinery.

## CHALLENGES AND LIMITATIONS

Despite considerable progress, several challenges remain. Agricultural datasets are often fragmented, geographically limited and inconsistent in quality. A model trained in one agro-climatic region may not perform equally well in another region. Model interpretability is another important issue. Farmers and agricultural scientists need to understand why a model has generated a particular recommendation. Data privacy, computational requirements, infrastructure costs and digital literacy can also restrict adoption, especially among small and marginal farmers. Therefore, model calibration and validation using independent field observations are essential. Recent research emphasizes systematic model selection, sensitivity analysis, uncertainty assessment and multi-model approaches to improve prediction reliability.

## FUTURE PROSPECTS

The future of agricultural modelling will increasingly involve multimodal and hybrid systems**.** Weather stations, soil sensors, drones, satellites, farm machinery and historical databases will provide continuous streams of information. Digital twins could provide virtual representations of agricultural fields and allow alternative management scenarios to be tested before implementation. Federated learning may also allow models to learn from distributed datasets while reducing the need to centralize sensitive farm data. Recent research highlights federated learning, deep learning and real-time data integration as promising

developments for agricultural modelling. Agricultural foundation models and large agricultural models are also developing rapidly. A recent 2026 review reports increasing research activity in agricultural large models and applications ranging from agricultural knowledge services and disease diagnosis to livestock management and intelligent agricultural machinery.

## CONCLUSION

Computer models have evolved from conventional mathematical crop simulations into sophisticated systems incorporating machine learning, deep learning, remote sensing, IoT, artificial intelligence and foundation models. They provide valuable opportunities for improving crop-yield prediction, irrigation scheduling, nutrient management, pest and disease detection, climate-risk assessment and precision agriculture. Traditional crop models remain important because they represent biological processes, while AI-based models offer powerful capabilities for analysing large and complex datasets. The most promising future direction is therefore not the replacement of conventional agricultural models by AI, but their integration into hybrid modelling frameworks**.** Such systems can combine biological knowledge with real-time observations and data-driven learning to provide more accurate and practical recommendations. Continued development of high-quality datasets, regional calibration, explainable AI, uncertainty analysis and farmer-oriented decision-support platforms will be essential. Properly implemented, computer models can become a major component of climate-resilient, resource-efficient and sustainable agriculture.

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# MILLETS: THE FUTURE SMART FOOD

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## ABSTRACT

*Millets are nutrient-rich cereal crops valued for their climate resilience, low input requirements, and adaptability to marginal environments. They provide dietary fibre, protein, essential minerals, vitamins, and antioxidants, contributing to improved nutrition and dietary diversity. Their ability to tolerate drought, withstand high temperatures, and perform under rainfed conditions makes them suitable for sustainable agriculture. Millets can help address malnutrition, water scarcity, and climate change challenges. Promoting their cultivation, processing, and consumption is essential for strengthening food and nutritional security while supporting farmers' livelihoods and environmentally sustainable food systems.*

**KEYWORDS:** Climate resilience, Dryland farming, Future smart food, Millets, Nutritional security, Sustainable agriculture

## INTRODUCTION

Millets are among the oldest cultivated cereal crops and have traditionally formed an important part of human diets. India is a major millet-producing country, cultivating finger millet, pearl millet, foxtail millet, little millet, kodo millet, barnyard millet, proso millet, and browntop millet. However, their cultivation and consumption declined with the expansion of rice and wheat production during the Green Revolution.

Growing concerns about malnutrition, climate change, water scarcity, and agricultural sustainability have renewed interest in millets. Their nutritional richness, short growing seasons in many production systems, and adaptability to diverse environments make them promising crops for future food systems.

## NUTRITIONAL IMPORTANCE OF MILLETS

Millets provide dietary fibre, protein, minerals, B-complex vitamins, antioxidants, and other beneficial

phytochemicals. Their nutritional composition varies among species and varieties. Finger millet is particularly rich in calcium, while barnyard and little millets can provide substantial dietary fibre and iron. Foxtail and proso millets are notable for their protein content.

**Table 1. Selected nutritional components of millets compared with rice and wheat (per 100 g; Jacob et al., 2024).**

| Crop | Protein (g) | Fibre (g) | Calcium (mg) | Iron (mg) |
|---|---|---|---|---|
| Finger millet | 7.3 | 3.6 | 344 | 3.9 |
| Foxtail millet | 12.3 | 8.0 | 31 | 1.1 |
| Pearl millet | 11.6 | 1.3 | 42 | 2.8 |
| Barnyard millet | 6.2 | 10.1 | 20 | 15.0 |
| Kodo millet | 8.3 | 9.3 | 27 | 0.6 |
| Little millet | 7.7 | 7.6 | 17 | 9.3 |
| Proso millet | 12.5 | 2.5 | 14 | 3.8 |
| Brown top millet | 9.0 | 7.3 | 28 | 7.7 |
| Rice | 6.4 | 0.3 | 2 | 0.6 |
| Wheat | 11.8 | 2.0 | 29 | 3.9 |

Millets can support dietary diversity and improve the intake of essential nutrients. Their fibre content may support digestive health, while low glycaemic responses reported for some millet-based foods may assist blood glucose management. However, health effects depend on the millet species, processing method, preparation, and overall diet.

## AGRICULTURAL BENEFITS OF MILLETS

1. ***Climate resilience and water conservation:*** Millets generally perform well under rainfed conditions and are more drought-tolerant than water-intensive crops such as rice. Their adaptability to high temperatures, variable rainfall, and marginal soils makes them valuable in dryland farming and climate-resilient cropping systems. Water requirements vary with species, climate, and management.
2. ***Low input requirements:*** Many millet production systems require comparatively modest external inputs and can be cultivated by resource-limited farmers. Appropriate varieties, balanced nutrient management, weed control, and locally adapted agronomic practices remain important for achieving good yields.
3. ***Soil health and biodiversity:*** Millets can contribute to diversified cropping systems and provide residues that support soil organic matter when appropriately managed. Their inclusion in crop rotations can help diversify production and reduce dependence on a narrow range of staple crops.

## HEALTH AND NUTRITIONAL SECURITY

Regular inclusion of millets in a balanced diet can improve nutrient diversity and contribute to dietary fibre, mineral, and protein intake. Calcium-rich finger millet may support bone health, while iron-containing millets can contribute to dietary iron intake. Whole-grain millet foods may also support digestive health.

Millets are naturally gluten-free, although cross-contamination during processing must be considered for people with coeliac disease. They can help diversify diets for different age groups and contribute to efforts to address micronutrient deficiencies. Nevertheless, millets should be considered part of a balanced diet rather than a standalone solution to health problems.

## MILLETS AND SUSTAINABLE AGRICULTURE

Millets can strengthen sustainable food systems through their adaptability to rainfed environments, relatively low water demand, and contribution to crop diversification. Their cultivation may reduce pressure on irrigation resources and support agricultural resilience under changing climatic conditions. The environmental benefits depend on production practices, yield levels, and local conditions.

Promoting millet-based foods can also create opportunities for farmers, processors, entrepreneurs, and rural enterprises through value addition and the development of nutritious food products.

## GOVERNMENT INITIATIVES AND CHALLENGES

The *International Year of Millets 2023*, declared by the United Nations, increased global awareness of millet production, nutrition, and consumption. In India, promotional efforts have included farmer training, millet-based product development, market development, and efforts to incorporate millets into nutrition programmes.

Despite these opportunities, millet production and consumption face several constraints, including limited consumer awareness, inadequate processing and storage facilities, insufficient market infrastructure, variable availability of quality seed, and changing dietary preferences. Strengthening research, extension services, supply chains, and consumer awareness is essential to overcome these barriers.

## CONCLUSION

Millets are nutritious, climate-resilient crops with considerable potential to address food and nutritional insecurity, water scarcity, and agricultural sustainability challenges. Their diverse nutritional composition and adaptability to marginal environments make them valuable components of future food systems.

Strengthening production, processing, value addition, and market access can improve farmers' livelihoods while encouraging healthier and more diverse diets. Coordinated efforts by researchers, policymakers, farmers, and the food industry will be essential to realize their potential as the "*Future Smart Food*."

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# MECHANIZATION TECHNOLOGIES FOR EFFICIENT AND SUSTAINABLE CHICKPEA SOWING

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## ABSTRACT

*Mechanization improves the timeliness, precision, and efficiency of chickpea (Cicer arietinum L.) sowing. This article reviews manually operated seeders, power-tiller-operated machines, tractor-operated seed drills, multi-crop planters, zero-till drills, pneumatic planters, and broad bed furrow (BBF) planter-cum-fertilizer applicators. Their operating principles and specifications are discussed, focusing on power requirements, seed metering, row spacing, fertilizer placement, and field capacity. Selecting and calibrating suitable machinery according to soil conditions, seed characteristics, and farm size can enhance crop establishment, operational efficiency, and resource-use efficiency, thereby supporting sustainable chickpea production.*

**KEYWORDS:** Agricultural mechanization, Broad bed furrow, Chickpea, Precision planting, Seed-cum-fertilizer drill, Seed drill, Zero tillage

## INTRODUCTION

Chickpea (Cicer arietinum L.), also known as gram or Bengal gram, is an important pulse crop grown in India. It is cultivated during the rabi season under rainfed and irrigated conditions. Sowing time varies with region, variety, soil moisture, and local climate; therefore, region-specific agronomic recommendations should be followed. In South India, the first fortnight of October to the first fortnight of November is often cited as a general sowing window, but local recommendations should take precedence.

Timely and uniform sowing is essential for establishing a good crop stand. Manual sowing over large areas can make it difficult to place seed and basal fertilizer consistently. Variation in sowing depth, row spacing, seed rate, and plant spacing may affect crop establishment and subsequent field operations.

Mechanized sowing can improve operational timeliness and placement uniformity, reduce labour demand, and support more efficient use of seed and fertilizer. The choice of machine should be based on farm size, soil condition, available power, seed characteristics, and the intended planting system.

## MECHANIZATION TECHNOLOGIES FOR CHICKPEA SOWING

The following machinery is reported as potentially relevant to chickpea sowing. Specifications are reproduced from the manuscript and cited technical descriptions where available. Values that depend on a particular model or require confirmation are identified accordingly; they should be checked against the manufacturer's or developing institute's original specification before publication.

### *1 Single-row inclined-plate planter*

The pull-type, single-row inclined-plate planter developed by ICAR–Central Institute of Agricultural Engineering (CIAE) is described as a multi-crop implement for crops including groundnut, maize, pigeon pea, mustard, chickpea, and soybean. Its suitability for small fields depends on the model and operating conditions.

| Specification | Details |
|---|---|
| Power source | Manual/pull-type (confirm exact model) |
| Number of rows | 1 |
| Seed-metering mechanism | Inclined plate; confirm exact model |
| Field capacity | 0.05–0.08 ha/h (verify source) |
| Field efficiency | 85–90% (verify source) |

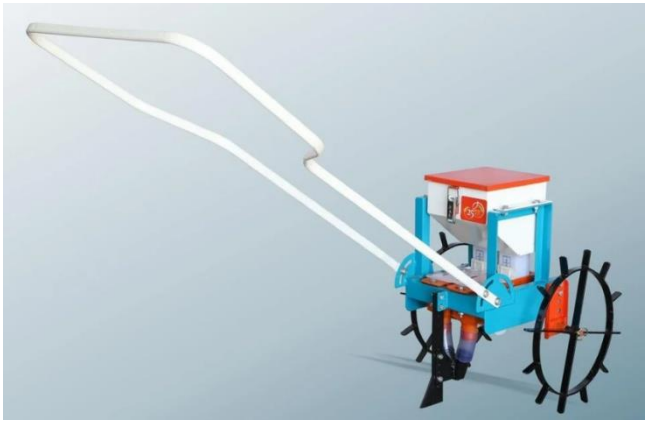


**Figure1. Single row inclined plate planter**

***2 Manually operated seed-cum-fertilizer drill***

A manually operated, portable seed-cum-fertilizer drill can place seed in rows and apply fertilizer during the same operation. The crops listed for this equipment include cotton, soybean, groundnut, maize, beans, gram, pea, pigeon pea, and mung bean. Confirm the exact model and its crop suitability before recommending it for chickpea.

| **Specification** | **Details** |
|---|---|
| Number of outlets | 14 |
| Adjustable outlet/plant spacing | 9–14 inches (verify whether this refers to row or plant spacing) |
| Sowing depth | 5.5 cm (verify model-specific recommendation) |
| Seed-box capacity | 3.5 kg |
| Fertilizer-box capacity | 5.7 kg |
| Number of seed rollers | 8 |




**Figure 2. Manual Seed cum fertilizer drill**

***3 Power-tiller-operated till-plant machine***

This machine is designed to perform tillage and planting in one pass and can sow two rows simultaneously. ICAR reports its use for wheat, soybean, Bengal gram, and sorghum in medium and heavy soils. The reported power-tiller requirement is 7.5–9.0 kW.

| Specification | Details |
|---|---|
| Number of rows | 2 |
| Power source | Power tiller |
| Power requirement | 7.5–9.0 kW |
| Operations | Tillage and planting in one pass |
| Seed and fertilizer boxes | Provided |
| Depth control | Gauge wheels |
| Effective field capacity | 0.15 ha/h |




**Figure 3. Power-Tiller Operated Till-Plant Machine**

(Source: ICAR-AICRP on FIM)

***4 Power-tiller-operated zero-till drill***

The manuscript describes an eight-row zero-till drill developed by NDUAT, Faizabad, for operation with a 10–12 hp power tiller. It is intended to place seed and fertilizer without conventional seedbed preparation. Chickpea suitability should be confirmed for the specific model and local soil conditions before making a crop-specific recommendation.

| Specification | Details |
|---|---|
| Number of rows | 8 (verify model) |
| Power source | Power tiller |
| Power requirement | 10–12 hp |
| Furrow openers | Rigid or zero-till type (verify terminology) |
| Seed and fertilizer metering | Cup-cell mechanism (verify model) |
| Hopper capacity | Seed: 15 kg; fertilizer: 20 kg |



**Figure 4. Zero-till drill machine**

***5 MPKV multi-crop planter***

The MPKV multi-crop planter is reported as suitable for groundnut, sunflower, chickpea, soybean, jowar, and wheat. It uses a vertical seed plate with peripheral cells and a fluted roller for granular fertilizer. The number of rows can be adjusted according to crop and configuration.

| **Specification** | **Details** |
|---|---|
| Number of rows | 5–9 |
| Tractor power requirement | 35 hp or above |
| Seed metering | Vertical plate with peripheral cells |
| Fertilizer metering | Fluted roller |
| Furrow openers | Spear-head type |




**Figure 5. MPKV Multi-Crop Planter**

(Source: DARE/ICAR Annual Report 2003–2004)

### *6 Mahindra multi-crop planter*

The Mahindra multi-crop planter is designed for planting a range of crops. The available configuration, seed plate, row spacing, and seed size should be checked to confirm suitability for chickpea. Avoid claiming yield improvement unless supported by comparative field data.

| Specification | Details |
|---|---|
| Number of rows | 2, 3, 4, or 6 (model dependent) |
| Tractor power requirement | 25–35 hp; 35–45 hp; or 60–75 hp, depending on configuration (verify manufacturer data) |
| Seed metering | Rotating disc with peripheral cells (verify model) |
| Fertilizer metering | Agitator and sliding orifice (verify model) |
| Maximum row spacing | 24 inches; adjustable with U-clamps (verify model) |
| Furrow openers | Shovel type for prepared/tilled fields |




**Figure 6. Mahindra multi-crop planter**

### *7 Tractor-operated zero-till seed-cum-fertilizer drill*

ICAR describes a 9-, 11-, or 13-row zero-till seed-cum-fertilizer drill developed for direct sowing of wheat in rice-harvested fields without seedbed preparation. Its reported specifications should not be assumed to establish suitability for chickpea without crop-specific validation.

| Specification | Details |
|---|---|
| Number of rows | 9, 11, or 13 |
| Power source | Tractor |
| Tractor requirement | 26 kW |
| Seed metering | Fluted roller |
| Fertilizer metering | Agitators over adjustable openings |
| Furrow opener | Inverted T-type |
| Field capacity | 0.3–0.4 ha/h |




**Figure 7. Zero-Till Seed-Cum-Fertilizer Drill**

(*Source:* ICAR-Sowing and Planting equipment)

***8 Mahindra pneumatic planter***

The pneumatic planter uses a vacuum-based metering system for precision placement. It may be considered for chickpea only if a compatible seed plate and metering configuration are available and its performance has been validated for the seed size and planting conditions.

| **Specification** | **Details** |
|---|---|
| Number of rows | 4 or 6 (model dependent) |
| Tractor requirement | 50–60 hp or above 70 hp, depending on configuration (verify model) |
| Seed metering | Vacuum-operated disc; verify model-specific mechanism |
| Fertilizer metering | Agitator and sliding orifice (verify model) |
| Minimum row spacing | 30 cm (verify model) |
| Fertilizer hopper capacity | 130 L (verify model) |
| Seed hopper capacity | 27 L (verify model) |




**Figure 8. Mahindra Pneumatic Planter**

(Source: Mahindra Pneumatic Planter – Official specifications)

***9 Conventional seed-cum-fertilizer drill***

A conventional seed-cum-fertilizer drill places seed and basal fertilizer during a single field pass. The number of rows, power requirement, metering system, and opener type vary with the model. Government of India SMAM guidelines include different tine configurations; the exact machine specifications should be taken from the selected model.

| **Specification** | **Details** |
|---|---|
| Number of rows/tines | 9, 11, or 13, depending on model |
| Power source | Tractor |
| Tractor requirement | Model- and soil-dependent |
| Seed metering | Fluted roller (where fitted) |
| Fertilizer metering | Adjustable metering system |
| Furrow opener | Shoe or tine type |
| Operation | Seed and fertilizer placement in one pass |




**Figure 9. Tractor-drawn Seed-Cum-Fertilizer Drill**

**(*Source*:** SMAM 2024 Guidelines – Government of India)

***10 Tractor-operated six-row inclined-plate planter***

The CIAE tractor-operated inclined-plate planter is a multi-crop planter. The manuscript reports adjustable row and plant spacing. Confirm that the cited specifications refer to the same model and that the selected plate is appropriate for chickpea seed.

| **Specification** | **Details** |
|---|---|
| Number of rows | 6 |
| Power source | Tractor, 35 hp or above (verify model) |
| Row spacing | 250–450 mm, adjustable (verify model) |
| Plant spacing within rows | 150–300 mm, adjustable (verify model) |
| Seed metering | Inclined plate |
| Fertilizer metering | Fluted rollers |
| Furrow opener | Shoe type |
| Time required | 2–2.5 h/ha (verify source; this is time per area, not field capacity) |



**Figure 10. Tractor-operated 6-row inclined planter**

***11 Broad bed furrow (BBF) planter-cum-fertilizer applicator***

A tractor-operated BBF planter-cum-fertilizer applicator forms broad beds and furrows while placing seed and applying fertilizer in a combined operation. Broad beds and furrows can help manage surface drainage and soil moisture where the system is appropriate. Its performance depends on soil, slope, bed dimensions, and rainfall; verify chickpea-specific performance and model specifications before making a recommendation.

| Specification | Details |
|---|---|
| Number of rows | 4 (verify model) |
| Power source | Tractor, 35 hp or above (verify model) |
| Seed metering | Inclined plate (verify model) |
| Fertilizer metering | Fluted rollers (verify model) |
| Furrow openers | Shovel type (verify model) |



**Figure 11. Broad bed furrow (BBF) planter cum fertilizer applicator**

## CONSIDERATIONS FOR SELECTING SOWING MACHINERY

- *Farm size and field layout*: manually operated or small power-tiller machines may suit small or irregular fields, whereas tractor-operated equipment may be more practical for larger fields.
- *Soil and moisture conditions*: conventional drills, zero-till drills, and BBF systems have different operating requirements. Zero-till suitability depends on residue, soil moisture, soil strength, and opener design.
- *Seed characteristics and metering*: the seed plate, roller, or pneumatic system must be compatible with chickpea seed size and shape to reduce skips, doubles, and seed damage.
- *Sowing depth and spacing*: adjust the machine to the locally recommended chickpea spacing and depth, and check seed placement in the field before full-scale operation.
- *Fertilizer placement*: calibrate fertilizer delivery separately and ensure that seed and fertilizer are placed safely according to agronomic recommendations.
- *Capacity and calibration*: report field capacity in ha/h and time required in h/ha as separate measures. Performance varies with field size, speed, turning time, soil condition, and operator skill.
- *Evidence and suitability*: distinguish manufacturer-reported specifications from measured field performance. Do not assume that a machine's general multi-crop designation proves suitability for chickpea without an appropriate seed plate and field validation.

## CONCLUSION

Mechanization offers opportunities to improve the timeliness, uniformity, and operational efficiency of chickpea sowing. Manually operated seeders, power-tiller-operated machines, tractor-mounted seed drills, multi-crop planters, zero-till drills, and broad bed furrow (BBF) planter-cum-fertilizer applicators provide options for different farm sizes and production conditions. Their performance depends on appropriate machine selection, seed-metering configuration, calibration, soil conditions, and correct adjustment of sowing depth and spacing. Equipment specifications and crop suitability should be verified against reliable technical sources before recommendation. Wider access to affordable and properly operated machinery can support efficient and sustainable chickpea production.

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