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1. HORTICULTURE-VEGETABLE SCIENCE

Post-Harvest Loss Reduction Strategies in Perishable Vegetables

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Abstract

Perishable vegetable post-harvest losses pose a serious threat to the world's food and nutritional security, especially in developing nations. Vegetables including tomatoes, leafy greens, cucurbits, and crucifers suffer large quantitative and qualitative losses during harvesting, handling, storage, transit, and marketing because of their high moisture content, active metabolism, and vulnerability to mechanical damage. Because it preserves resources and increases farmer revenue, reducing post-harvest losses is more sustainable than raising output. In addition to discussing technical, managerial, and policy-based approaches for loss reduction along the value chain, this article examines the reasons behind post-harvest losses in perishable vegetables.

Keywords: Post-harvest losses, perishable vegetables, cold chain, storage, food security

Introduction

A healthy diet must include vegetables because they include fiber, vitamins, minerals, and bioactive substances. Vegetable post-harvest losses, however, can vary from 20 to 40% and, in cases of improper handling and storage, may surpass 50%. In addition to decreasing the supply of food, these losses result in higher greenhouse gas emissions and financial losses for farmers. For vegetable production methods to be sustainable, effective post-harvest management is consequently essential (Kader, 2005).

Nature and Causes of Post-Harvest Losses in Vegetables

Perishable vegetable post-harvest losses are caused by a number of interrelated variables. Senescence, transpiration, and respiration all result in physiological losses. Pathogens might enter through mechanical damage sustained during harvesting and transportation. Deterioration is further accelerated by microbial spoilage brought on by bacteria and fungus. These losses are made worse by inadequate infrastructure, a lack of cold storage, poor packing, and ineffective marketing strategies (Kitinoja and Kader, 2015).

Harvesting Strategies for Loss Reduction

Harvesting at Proper Maturity

Better shelf life and quality are ensured when vegetables are harvested at their peak physiological maturity. Vegetables that are too young or too old decay more quickly and are more vulnerable to microbiological and mechanical harm (Kader, 2002).

Time and Method of Harvesting

Field heat and respiration rate are decreased by harvesting in the cooler parts of the day. Physical harm is reduced when soft vegetables like tomatoes and leafy greens are handled gently and with sharp instruments (Kitinoja and Kader, 2015).

Post-Harvest Handling and Pre-Cooling

Pre-Cooling Techniques

Respiration and microbial development are greatly slowed by the quick removal of field heat using pre-cooling techniques including hydrocooling, forced-air cooling, and vacuum cooling. Cucurbits and green vegetables benefit greatly from pre-cooling (Kader, 2005).

Sorting and Grading

Produce that is overripe, sick, or damaged and might contaminate good crops is removed by sorting. Grading lowers losses during storage and transportation while increasing uniformity and market value.

Packaging and Transportation Strategies

Vegetables are shielded from infection, moisture loss, and mechanical damage by proper packing. Compression damage is lessened when vented plastic crates are used in place of conventional bags or baskets. During long-distance marketing, temperature-controlled transportation methods also aid in maintaining quality (FAO, 2011).

Storage Technologies for Perishable Vegetables

Cold Storage

The best way to increase shelf life is by cold storage, which slows transpiration, respiration, and microbiological development. Certain temperature and relative humidity ranges are necessary for different vegetables to prevent chilling damage or deterioration (Kader, 2002).

Modified and Controlled Atmosphere Storage

By controlling the oxygen and carbon dioxide levels surrounding the produce, modified atmosphere (MA) and controlled atmosphere (CA) storage lower respiration rates and senescence. High-value veggies are increasingly being processed using these methods (Kader, 2005).

Processing and Value Addition as Loss Reduction Strategies

Highly perishable vegetables can be stabilized with minimal processing, pickling, fermentation, dehydration, and freezing. Value addition improves shelf life, marketability, and farmer revenue in addition to lowering losses (FAO, 2011).

Role of Cold Chain and Infrastructure Development

Minimizing losses in perishable vegetables requires a continuous cold chain from harvest to consumption. Reducing post-harvest losses is mostly dependent on investments in pack houses, cold storage facilities, refrigerated transportation, and rural infrastructure (Kitinoja and Kader, 2015).

Capacity Building, Policy, and Institutional Support

Losses are greatly decreased when farmers, dealers, and handlers get post-harvest training. Sustainable loss reduction depends on government policies that encourage post-harvest research, market access, and cold chain development. Vegetable value chains may be further strengthened through public-private collaborations (FAO, 2011).

Environmental and Economic Benefits of Loss Reduction

Food availability is improved by lowering post-harvest losses without expanding farmed land or using more inputs. It minimizes greenhouse gas emissions linked to wasted product, increases farmer income, stabilizes market supply, and eases the strain on natural resources (Kader, 2005).

Challenges and Future Prospects

High initial investment costs, disjointed supply chains, little awareness, and smallholders' limited adoption of technology are some of the obstacles. Future opportunities include digital monitoring, smart packaging, inexpensive cooling technologies, and the integration of climate-smart agriculture with post-harvest management (Kitinoja and Kader, 2015).

Conclusion

Reducing post-harvest loss in perishable vegetables is an economical and long-term way to improve environmental protection, farmer revenue, and food security. Losses along the vegetable value chain may be significantly decreased by implementing better harvesting, handling, storing, transporting, and processing techniques. Achieving long-term success will require strengthening infrastructure, developing capacity, and implementing supporting policies.

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2. AGRICULTURAL ENTOMOLOGY

Precision Farming: Integration of Advanced Digital Technologies for Sustainable, Climate-Smart and Resource-Efficient Crop Production

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Introduction and Conceptual Framework of Precision Farming

Modern agriculture faces serious challenges due to increasing food demand, limited natural resources, climate variability, and rising production costs. Conventional farming practices generally follow uniform input application across fields, despite significant spatial and temporal variability in soil fertility, moisture availability, and crop growth. This often results in inefficient use of inputs, environmental pollution, and reduced profitability (Gebbers and Adamchuk, 2010). Precision farming, also known as site-specific crop management, is an advanced agricultural approach that aims to optimize crop production by managing within-field variability through the application of the right input, at the right rate, time, and place. The core objective of precision farming is to enhance resource use efficiency, increase productivity, and ensure environmental sustainability (Pierce and Nowak, 1999). It represents a shift from conventional uniform management to data-driven and knowledge-based farming systems. The conceptual framework of precision farming is based on the understanding that agricultural fields are inherently heterogeneous. By identifying, quantifying, and managing this variability using modern tools such as GPS, GIS, remote sensing, and sensors, precision farming enables informed decision-making at micro-level scales (Zhang *et al.*, 2002; Mulla, 2013). These technologies allow precise monitoring of soil and crop conditions and facilitate site-specific management practices. Precision farming has emerged as a key strategy for sustainable and climate-smart agriculture. Efficient input use under precision farming reduces nutrient losses, conserves water, lowers greenhouse gas emissions, and improves soil health, thereby enhancing resilience to climate change (Lipper *et al.*, 2014). In India, precision farming holds significant potential for improving productivity and sustainability, although its adoption is constrained by high initial costs and limited technical awareness (Sharma and Bhatnagar, 2019).

Key points: Precision farming; Digital agriculture; Climate-smart agriculture; Resource-use efficiency; Site-specific management; Indian Agriculture

Need and Importance of Precision Farming in India

Indian agriculture faces critical challenges such as shrinking landholdings, declining soil fertility, water scarcity, climate variability, and rising input costs. Conventional farming practices often lead to inefficient use of fertilizers, water, and pesticides, resulting in low productivity and environmental degradation. Precision farming addresses these challenges by enabling site-specific input management, improving resource use efficiency, and reducing production risks. Precision farming is particularly important in India to enhance crop productivity under limited resources, improve farmers' income, and promote sustainable agriculture. By integrating digital technologies with agronomic practices, precision farming supports climate resilience, input optimization, and environmental conservation, making it a vital tool for achieving sustainable and climate-smart agricultural development in the country.

Status of Precision Farming in India

Precision farming is gradually gaining attention in India, driven by the need for higher productivity, resource efficiency, and climate-resilient agriculture. Adoption is primarily concentrated in large and medium farms in states like Punjab, Haryana, Maharashtra, Karnataka, and Tamil Nadu, where mechanization and digital tools are more accessible (Sharma and Bhatnagar, 2019). The Indian government has initiated programs such as the National Mission on Precision Farming (NMPF), custom hiring centers, and subsidies for sensors, GPS, and drones to encourage adoption among farmers. Despite these efforts, overall adoption remains limited due to high initial costs, fragmented landholdings, lack of technical knowledge, and insufficient extension services.

Digital Technologies and Tools in Precision Farming

The effective implementation of precision farming depends largely on the integration of advanced digital technologies for data acquisition, analysis, and decision-making. Global Positioning System (GPS) technology enables accurate geo-referencing of field operations, soil sampling, and yield mapping, forming the foundation of site-specific crop management (Zhang *et al.*, 2002). Geographic Information System (GIS) further facilitates the storage, integration, and spatial analysis of multilayered data related to soil properties, crop performance, and climatic variables. Remote sensing technologies using satellites, unmanned aerial vehicles (UAVs), and proximal sensors provide real-time and non-destructive assessment of crop health, nutrient status, and stress conditions. Vegetation indices such as NDVI are widely used to monitor spatial variability in crop growth and guide precision input application (Mulla, 2013). These technologies enhance early detection of biotic and abiotic stresses, thereby supporting timely management interventions. The Internet of Things (IoT) and smart sensors play a critical role in continuous monitoring of soil moisture, temperature, nutrient dynamics, and microclimatic parameters. Sensor-based data, combined with wireless communication systems, enable real-time decision-making and automation of farm operations (Wolfert *et al.*, 2017). Artificial Intelligence (AI) and machine learning algorithms further improve predictive capabilities by analyzing large datasets to forecast yield, pest incidence, and irrigation requirements. Integration of these digital tools through decision support systems (DSS) allows farmers to make precise, location-specific management decisions. Such data-driven approaches not only improve productivity and input use efficiency but also reduce environmental risks and enhance sustainability of crop production systems (Gebbers and Adamchuk, 2010).

Precision Crop Protection and Risk Management

Precision crop protection involves site-specific and need-based management of weeds, pests, and diseases to reduce crop losses while minimizing chemical inputs. Unlike conventional blanket pesticide application, precision farming utilizes spatial information, real-time monitoring, and decision support tools to target affected zones only, thereby improving pesticide use efficiency and reducing environmental contamination (Gebbers and Adamchuk, 2010). Remote sensing, sensors, and forecasting models enable early detection of pest and disease outbreaks and identification of infestation hotspots. Variable rate application technologies allow precise and timely pesticide use, supporting integrated pest management and lowering the risk of resistance development (Zhang *et al.*, 2002; Mulla, 2013).

Precision Farming for Sustainable and Climate-Smart Agriculture

Precision farming is a core component of climate-smart agriculture as it enhances productivity while promoting environmental sustainability and climate resilience. By optimizing the use of fertilizers, water, and energy through site-specific management, precision farming reduces input losses, nutrient leaching, and greenhouse gas emissions associated with conventional agricultural practices (Gebbers and Adamchuk, 2010). Digital tools such as sensors, remote sensing, and decision support systems enable real-time monitoring of crop and soil conditions, allowing farmers to respond effectively to climate variability and abiotic stresses such as drought and heat. Improved soil and water management under precision farming enhances soil health, carbon sequestration, and long-term sustainability of production systems (Lipper *et al*., 2014).

Economic Viability, Adoption, and Constraints

Precision farming has demonstrated improved profitability through higher yields, reduced input costs, and better resource use efficiency. Studies report increased net returns and benefit-cost ratios due to optimized fertilizer, water, and pesticide application (Zhang *et al*., 2002; Gebbers and Adamchuk, 2010). However, adoption remains limited, particularly among small and marginal farmers, due to high initial investment, lack of technical knowledge, and inadequate infrastructure. Additional constraints include fragmented landholdings, limited access to digital tools, and weak extension support in developing countries. Strengthening capacity building, promoting custom hiring centers, and providing policy and financial incentives are essential for enhancing large-scale adoption of precision farming technologies (Wolfert *et al*., 2017).

Future Prospects and Way Forward

The future of precision farming lies in the integration of advanced technologies such as artificial intelligence, big data analytics, automation, and robotics for real-time, farm-specific decision-making. Expanding digital infrastructure, strengthening research-extension linkages, and promoting farmer-friendly decision support systems will accelerate adoption. Policy support, capacity building, and affordable technology access are essential to scale precision farming as a sustainable, climate-resilient solution for future crop production systems.

Conclusion

Precision farming represents a transformative approach for Indian agriculture, integrating advanced digital technologies with site-specific crop management to enhance productivity, profitability, and sustainability. By optimizing inputs, reducing environmental impacts, and improving resilience to climate variability, it offers a pathway toward climate-smart and resource-efficient agriculture. Wider adoption, supported by policy initiatives, capacity building, and affordable technology access, is essential to realize its full potential in ensuring sustainable and resilient crop production systems.

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3. HORTICULTURE-VEGETABLE SCIENCE

Integration of Genomics and AI in Vegetable Breeding

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Abstract

The combination of artificial intelligence (AI) and genomics is causing a paradigm change in vegetable breeding. Large genomic and phenotypic datasets that beyond the analytical capabilities of traditional statistical methods have been produced by developments in high-throughput sequencing, phenomics, and big data analytics. Genetic gain may be accelerated and complicated, multidimensional data can be analyzed with the use of artificial intelligence, especially machine learning and deep learning. Accurately predicting breeding values, identifying important genes and markers, and optimizing selection procedures are all made possible by the merging of genomics and AI. The ideas, techniques, applications, benefits, difficulties, and potential future developments of integrating genomics and AI in vegetable breeding projects are reviewed in this article.

Keywords: Genomics, artificial intelligence, machine learning, vegetable breeding, genomic selection

Introduction

Vegetable crops are essential for nutritional security, providing vitamins, minerals, and health-promoting compounds. However, complex characteristics, lengthy breeding cycles, interactions between genotype and environment, and growing biotic and abiotic challenges make vegetable breeding difficult. The discovery of genes and quantitative trait loci (QTLs) linked to significant characteristics has been made possible by recent developments in genomics. Concurrently, artificial intelligence has become a revolutionary instrument for identifying significant patterns in big datasets. The combination of AI and genomics opens up new possibilities for improving vegetable crops more quickly and effectively (Crossa *et al.,* 2017).

Role of Genomics in Vegetable Breeding

Genomics, the study of an organism's whole DNA sequence, can help breeders understand the genetic basis of traits. In order to identify the genes controlling quality, yield, stress tolerance, and disease resistance in vegetables, genomic approaches like as whole-genome sequencing, genome-wide association studies (GWAS), and high-density molecular markers have been widely used. Genetic data is the foundation of contemporary breeding methods like genomic selection and marker-assisted selection (Varshney *et al.,* 2021).

Artificial Intelligence in Plant Breeding

Computational systems that can learn from data and make predictions or judgments are referred to as artificial intelligence. AI methods like machine learning, deep learning, and neural networks are utilized in plant breeding to simulate intricate interactions between genotype, phenotype, and environment. AI is a great fit for contemporary breeding programs because it can manage large-scale datasets and complex interactions, unlike traditional statistical models (Liakos *et al.,* 2018).

Integration of Genomics and AI: Concept and Framework

In order to forecast breeding results, the integration of genomics and AI entails fusing genomic data (such as SNP markers and gene expression profiles) with AI algorithms. AI algorithms may accurately identify superior genotypes even before field evaluation by analyzing genomic patterns and linking them to phenotypic performance. This integrated framework improves selection efficiency and shortens the breeding cycle (Crossa *et al.,* 2017).

Applications in Vegetable Breeding

Genomic Selection Enhanced by AI

Genome-wide markers are used in genomic selection to forecast an individual's breeding value. For complicated qualities like yield and stress tolerance in plants like tomatoes, peppers, and cabbage, AI-based models like random forests and deep neural networks increase forecast accuracy (Azodi *et al.,* 2019).

AI-Assisted Gene and QTL Discovery

Finding important genes and QTLs from massive genomic datasets is made easier by machine learning methods. In vegetable crops, AI aids in the prioritization of candidate genes linked to abiotic stress tolerance, disease resistance, and nutritional quality (Libbrecht and Noble, 2015).

Integration with High-Throughput Phenomics

Precise phenotypic data is produced using sensor-based phenotyping systems and AI-powered picture analysis. These data improve the accuracy of trait prediction and allow selection in a variety of environmental settings when paired with genetic information (Yang *et al.,* 2020).

Speed Breeding and Decision Support

By choosing the best parents, forecasting cross-performance, and overseeing breeding pipelines, AI-driven decision support systems enhance breeding techniques. Vegetable breeding cycles are greatly shortened by this integration, which facilitates speed breeding techniques (Watson *et al.,* 2019).

Crop-Wise Examples in Vegetables

- Tomato: AI-assisted genomic selection for yield, disease resistance, and fruit quality
- Pepper: Machine learning models for predicting capsaicin content and stress tolerance
- Cabbage and Broccoli: AI-based analysis of glucosinolate content and disease resistance
- Cucumber: Integration of genomic data and AI for early sex expression and yield traits

(Varshney *et al.,* 2021; Yang *et al.,* 2020)

Advantages of Integrating Genomics and AI

- Accelerated genetic gain
- Improved prediction accuracy for complex traits
- Reduced breeding cycle duration
- Efficient utilization of large genomic datasets
- Enhanced decision-making in breeding programs

These advantages make genomics–AI integration a cornerstone of next-generation vegetable breeding.

Challenges and Limitations

Despite its potential, integration is hampered by issues including expensive upfront expenditures, the need for high-quality information, a lack of standardized phenotyping, a lack of computing equipment, and a lack of qualified staff. Data management and ethical considerations also require consideration (Liakos *et al.,* 2018).

Future Prospects and Research Directions

AI-integrated genomic platforms will play a bigger role in vegetable breeding initiatives in the future. Breeding efficiency will be further improved by combining genomics with digital agriculture, gene editing, and climate prediction. Widespread adoption will depend on creating AI tools that are easy to use and enhancing multidisciplinary cooperation (Watson *et al.,* 2019).

Conclusion

A revolutionary approach to vegetable breeding is the combination of artificial intelligence and genomics. This integration speeds up the production of hardy, nutrient-dense, high-yielding vegetable varieties by facilitating accurate prediction, quick selection, and effective data usage. To fully exploit its promise in sustainable vegetable production, further investment in genetic resources, AI technologies, and capacity building will be necessary.

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4. AGRICULTURA ENGINEERING

Protected Cultivation Microclimate Engineering

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Introduction

Protected cultivation encompasses a wide range of systems passive and active, large-scale and small that employ a variety of materials to modify wind, rain, light, heat, and pests in the crop environment. Despite the diversity of approaches, the underlying physical processes remain the same; in all cases, sunlight is the principal driver of growth, accounting for most of the energy flow through the system. Microclimate engineering focuses on controlling the crop microclimate. The microclimate is defined as the immediate environment of the crop canopy and comprises the principal variables of interest: temperature, relative humidity, light, carbon dioxide, and air movement. Managing these five components is essential to optimizing growth and yield, improving fruit quality, and increasing water use efficiency. Microclimate engineering can also develop crop physiology by integrating the effects of stomatal behavior, leaf area index, and assimilation rates into any model of growth.

The effect of microclimate engineering on pest and disease incidence is more complex. Environmental conditions have a pronounced influence on pest and disease populations, but engineering aimed at improving plant health may not necessarily enhance pest management. Disease pressure can often be alleviated through activity rather than prevention, for example, by increasing spraying frequency or implementing logistic controls. Finally, although irrigation naturally falls outside the crop microclimate, its influence is so strong that it must be considered. An objective, evidence-based approach requires the integration of engineering principles with agronomic outcomes to evaluate microclimate design, management, and sustainability.

Fundamentals of Protected Cultivation

In general terms, any kind of protected cultivation or controlled-environment agriculture relies on construction and engineering design to modify the surrounding meteorological climate in ways that impact how well plants grow. Although plants produce flowers and fruits for reproduction, they are – in most growing conditions – engaged in a continuous process of biomass accumulation, and therefore a considerable quantity of structure is produced in support of this biomass. Extensive open-field cultivation of crops is limited in time and geographical expression, and difficulties are encountered in supplying uniform products of higher quality or out-of-season. Fruits and vegetables have a distinct market period; irregularity in production incurs losses, and products are not available at the desired time. Therefore, the development of a suitable environment using engineering principles and design would create favourable microclimate conditions and henceadjust the normal phenomenon of plant growth to maturity early or late throughout the year. The ever-increasing pressure to provide food in terms of quantity and quality demands an intensive technology for crop production.

Microclimate Components and Their Interactions

The protected cultivation microclimate comprises five principal components temperature, humidity, light, CO_2, and airflow with numerous variances in totality. The microclimate of open-field systems is also patched during crop growth. Each component, together with its influencing parameters, is proposed for detail examination, intentionally limiting variables to facilitate objective appreciation.

In the microclimate phase through the subsystems, transfer processes and their regulations are examined as are controls. Supported by heat transfer definitions, predicted temperature phases discerned from insulin demands, and the assessed associated heat loads, patterns of humidity intake and exhaust, light diffusion and fluctuation, CO_2 enrichment and supply, and airflow configuration combination and ventilation integrated rational approaches. Detecting moisture from the microscale to the production system, be it active or passive, either just the dispersion or even just a part support suggests savings from the compensated energy and capital balance, the water loss through the respired moisture by plants remaining, benefiting primarily production, in fact one step more quantified to check its exigency information. (Each of the components of the microclimate system, despite discussing air routing for health conditions on plants, is of course covered again in the heart zone of the airflow transition subsystem control balance.)

The microclimate phase is closed, through the sensors, with key detection-yield combinations recapping, followed by reflecting on the overall suboperational architecture for proper construction, validation, and precision not discussed minimum order expense during rapid passage. With the centre of focus and indeed forever needing not just reordering examinations of inputs, modelling, and corrections at reasonable economic cost in any operational domain, three of the major climate manipulations pass under light scrutiny temperature, humidity, and airflow again just to justify basic support.

Temperature Regulation and Heat Transfer

Four temperature-management strategies adjust microclimate thermal status: passive heating, active heating, cooling, and thermal screening.

Three forms of heat transfer regulate temperature: conduction, convection, and radiation. Conduction occurs through a solid medium and is quantified using Fourier's Law. Insulation reduces heat loss by thickening the resistive path and lowering thermal conductivity. Convection transfers heat via the surrounding fluid air or water. Radiation enables heat exchange without a physical medium, following the Stefan-Boltzmann Law. The overall effect emerges through the algebraic sum of these phenomena over the entire temperature-differential field.

The temperature setpoint, the desired microclimate temperature, governs microclimate heating, cooling, and thermal-screening control. Common heating midpoints are selected at 0.5–1.5 °C above the local mean daily air temperature during winter and at 0.5–2.0 °C below during summer. For crops sensitive to high temperatures, the carbon-dioxide and humidity setpoints qualify the temperature threshold.

Thermal lag is the time delay between a

change in a driving-variable condition and the corresponding microclimate-state response. It typically arises more from thermal inertia than thermal buffering. Devices that remove energy from the microclimate as it heats up offer more energy and thermal buffering for plants than those that add energy to it. Therefore, a larger resistive surface pairs better with cooling methods than with heating variants. Reducing thermal lag enhances drying, cooling, and humidification speeds and helps avoid excessive root-zone flooding.

Humidity Control and Vapor Pressure

Relative humidity and vapor pressure deficit are major determinants of plant transpiration rates. Dehumidification increases inputs and costs, while humidity-induced outbreaks of disease and environmental pollution are major drain on yield and resource use. Through adequate humidity control, crops may be grown to attain and exceed potential under well-defined environmental conditions.

In addition to maintaining sufficient humidity for plant growth, excess humidity and high vapor pressure deficits incur substantial economic penalties. Crop transpiration represents a major drain on water resources, and too much water vapor in the air increases irrigation requirements yet diminishes stomatal conductance and rate of photosynthesis. The potential for drenching the external environment may be magnified by poorly positioned relative to relative positions of canopy and/or structure ventilator openings, inadequate or excessive foliage area, and/or slow wind speeds frequently experienced in the vicinity of greenhouses and glasshouses. Transpiration-induced reductions in local humidity are also associated with enhanced rates of infection by local sources of disease pathogens. When disease outbreaks occur, their effects extend beyond the closed structure to its external surroundings, thus threatening the sustainability of regions with extensive protected cultivation.

Dehumidification improves the quality of greenhouse and glasshouse produce, degrades production potential and efficiency, and increases operational costs. Production losses from humidity-induced diseases and the requirement for dehumidification amplify those effects an excessive combination that delegitimizes the practice of protected cultivation in many humid environments. Sufficient humidity dehumidification capacity, subjected to effective operation, is therefore an agent of antibiotic, fungicide, and dehumidification costs. Control of humidity evolves from a combination of deliberate dehumidification (enhanced heating, external ventilation, ecto- and/or endothermic dehumidification) and local drying by reduction of temperature-humidity coupling in the vicinity of the structure.

Light Management and Photobiology

Light quality, quantity, distribution, and duration are unequivocal determinants of crop growth and development in temperate protected environments. Light intensity, expressed as photons per square meter per second (PPFD), governs both photosynthetic rate and transpiration (Anderson and Edge 1987; Hartley et al. 2016), while spectral composition profoundly influences crop physiology and morphology (Reid et al. 2022; Son et al. 2016). The light integral, defined as photoperiod multiplied by PPFD, provides the cumulative photonic resource available for photosynthesis (Hoffmann et al. 2015), and photoperiod length is a key factor controlling flowering and fruiting cycles.

Crop species exhibit a range of light use efficiencies, sensitive to irradiance at the leaf surface (Bishop and Smith 2008; Dehelean et al. 2018). Cultivars and growing methods minimize shading, balancing leaf area index, leaf inclination, and canopy architecture to maximize light harvesting. Conversion of solar energy into biomass is enhanced by light-diffusing glazing (Kloosterman et al. 2011) and by pre-harvest light-enhancement screens that extend daylength into the night (Martin et al. 2011).

CO_2 Enrichment and Gas Exchange

Concentration targets and exchange rates for CO_2 enrichment are specified and evaluated together with the limitations of gas transfer processes. Photosynthetic responses to enrichment are discussed, and the relationship of air mixing with plant requirements and dilution effects is examined.

For many crops grown in a microclimate that is subject to high light levels and closed environments, net CO_2 assimilation rates exceed those for open-air conditions during the major part of the day. Therefore, it is common practice to enrich the atmosphere of protected cultivation units with CO_2, frequently to partial pressures above those encountered in the open air. Artificial enrichment increases photosynthetic rate and also preserves the grain yield of photosynthetic products. Higher costs of the added CO_2 can often be compensated for by greater economic yield, although for some crops the economic use of CO_2 is questionable when the value of such additional investment is considered.

The concentration of CO_2 in the atmosphere of an immersed or fully enclosed production unit is directly affected by the net CO_2 assimilation rate of the crops being grown and the equilibrium relationship between the local saturated water vapor pressure and the water vapor concentration within the unit. If no gas was being introduced and only natural ventilation was operating, the atmospheric CO_2 concentration could be expressed as a simple mass balance equation connecting the rate of carbon dioxide concentration change to the CO_2 dilution/mixing action of incoming winds.

Air Circulation and Ventilation

Ventilation is not merely a means of temperature control; it is indispensable for regulating humidity and air composition. Supplying sufficient fresh air for transpiration at a reasonable concentration does not guarantee a favorable interaction with humidity variation. An excessive ventilation rate under conditions of high vapor pressure deficit can detrimentally affect plant function and development.

Airflow patterns through protected environments are primarily driven by buoyancy forces. Excessive buoyancy forces in combination with sheltered conditions lead to unstable horizontal stratification unless actively controlled to reduce drafts. Draughts are linked to tissue cooling or heating, thus influencing transpiration rate, stomatal control, and fruit set. Natural forces can be used to control horizontal stratification by mechanical activation or passive stimulation; floor heating or cooling zones can also help. Drawthrough ventilation regimes at flowering enable mild cooling without affecting fruit quality, while excess heat loads combined with buoyancy ventilation drive horizontal stratification with the potential for controlling temperature and maintaining a positive thermal balance without active heating.

Hygiene and disease management are paramount in any controlled plant production system, especially in protected environments. Filtration of input air reduces airborne virus inoculum concentrations; continual delicate dehumidification diminishes the risk of condensation dampening leaves and other surfaces; and stratech ventilation architects airflow patterns and rates to suit contemplated infection processes. Yet, effective ventilation must also control excess transpiration-induced moisture without creating draughts.

Environmental Sensing and Monitoring

Microclimate management hinges on accurate state information. Quantities are commonly sensed locally by arrays positioned within a single housing and subsequently processed in central nodes to drive actuators that manipulate the climate elsewhere. This design reduces costs but incurs risks. Well designed, the architecture mitigates them: the sensors must be suitable for their locations; data acquisition must be reliable and recurrent; preprocessing must filter out noise and outliers; storage must maintain the integrity of historical records; and datasets must capture the intended phenomena, including their uncertainties.

The effectiveness of the entire arrangement depends on the selected sensors. Choice criteria include type, position, calibration, and redundancy. Within the cultivated volume, the flooding of a return duct with the mean temperature of the sensor field would be a plausible strategy; but capturing the usually small temperature gradients along the height of tall plants merits special attention. The sensible close-housing of the greenhouse gases and their gentle exchange with the bulk air also justifies attention to detail in position.

Sensor Technologies and Placement

Sensors for microclimate monitoring are customarily located at or above crop height, so that measurements reflect the immediate environment experienced by the plants. At this position, the sampled air must be reasonably well mixed, thus the number of sensors required within the spatial domain depends on the degree of mixing. Airflow patterns should be analyzed to determine the appropriate placement density and ensure that critical gradients are captured. Sensor redundancy adds robustness and redundancy to the system. Sensing for additional variables may also be included depending on the crop and microclimate conditions.

A representative sensor array to measure the main components of the protected cultivation microclimate includes: temperature and humidity sensors located above the crop canopy; photosynthetic photon flux density meters placed under different lighting conditions, on both cloudy and sunny days, to optimize shading strategies; a light spectrum sensor, ideally faced towards the crop at a height of 1.0–1.5 m to minimize the effects of angle of incidence, glare, and sunburning; and soil moisture sensors for substrate analysis. Calibration routines are imperative for temperature and humidity sensors, especially when redundancy is incorporated. Additionally, sensors should be periodically validated against laboratory-grade measurement devices.

Data Acquisition and Modeling

Analog sensors generate stream data, typically interpreted without manual intervention. Therefore, operator oversight must focus on data sources with the greatest uncertainty impact, e.g., calibration, validation, quality, and algorithm inputs. HVAC equipment control usually falls within discrete operating ranges, with duty cycling amplifying on/off switching frequency effects.

Illumination conditions, however, differ from heating and cooling; the desired DLI, control response speed, and daylight distribution demand greater operator involvement. The coupling between heating and humidity control also requires careful monitoring to assess humidity dilution at low temperatures and condensation risk at higher operating temperatures.

Full-spectrum plant-environment models could evaluate operator assumptions, identify equipment service priority and redundancy, summarize control automation requirements, benchmark microclimate condition data capture, support scenario analysis, and aid training. High-accuracy 3D real-time models interacting with control systems can be used to test operator decisions and verify scenario robustness. Operator alarms would signal equipment failures, forecast imminent non-violation of key states, and summarize redundant data layers.

Control Strategies and Automation

Control systems orchestrate the manipulation of climate components to achieve desired conditions, enhancing microclimate and crop management. Automated real-time control connects sensors and actuators with feedback architecture for rapid and labor-efficient adaptation, depending on design purpose and success parameters. Robust connectivity and data sharing within sensor nodes, external platforms, and manual operational devices support resilience. On-off controls are suitable for binary phenomena like ventilation, but limitations may arise under dynamic processes such as CO_2 concentrations or diurnal heating. Continuous actuation can, however, mask faults in other components.

Control strategies combine elements and subcomponents, aligned with their respective functions and time-sensitive control interdependencies. Plant health dictates ventilation throughput, normalizing temperature and humidity coupling. Beyond concentration moderation, ventilation exchanges offer dewpoint management and disease pressure reduction via airflow circulation. Weather-dependent trade-offs among transfer rates, dilution demands, and discharge openings affect all-steel and some polycarbonate structures. Thermal mass modulates the energy balance over time and season, enabling reduced heating costs in sunny winters, but sacrifice savings with excessive insolation accumulation. Insufficient solar gain calls for supplementary heating. Nutrient management and watering address salinity prevention and photosynthetic stimulus.

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5. AGRICULTURAL METEOROLOGY

Effect of El Niño on Indian Monsoon Rainfall and Patterns

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Introduction

The Indian monsoon is one of the most important climatic systems in the world. It provides nearly 75–80% of India's annual rainfall and supports agriculture, water resources, hydropower generation, and the livelihoods of millions of people. Since nearly half of India's population depends directly or indirectly on agriculture, any variation in monsoon rainfall has significant economic and social consequences.

One of the major factors influencing the Indian monsoon is the climatic phenomenon known as El Niño. El Niño is part of the El Niño–Southern Oscillation (ENSO), a large-scale ocean-atmosphere interaction occurring in the tropical Pacific Ocean. It is characterized by unusually warm sea surface temperatures in the central and eastern equatorial Pacific Ocean. Historically, many El Niño years have been associated with weak monsoon rainfall and drought conditions in India. However, recent studies suggest that this relationship has become more complex due to climate change and interactions with other oceanic phenomena.

This article examines the mechanism of El Niño, its impact on Indian monsoon rainfall, regional rainfall patterns, and the broader implications for agriculture and the economy.

Understanding El Niño

Under normal conditions, strong trade winds blow from east to west across the tropical Pacific Ocean. These winds push warm surface waters toward Indonesia and Australia, while cooler waters rise along the coast of South America through a process called upwelling. This creates a pressure pattern known as the Walker Circulation.

During an El Niño event, the trade winds weaken or reverse. As a result, warm water spreads eastward across the Pacific Ocean, reducing upwelling and altering atmospheric circulation patterns. The center of tropical rainfall shifts toward the central and eastern Pacific, affecting weather systems around the globe.

El Niño events typically occur every two to seven years and can last from several months to over a year. Their intensity varies from weak to strong events, producing different levels of impact on global climate.

Mechanism Linking El Niño and the Indian Monsoon

The relationship between El Niño and the Indian monsoon is primarily driven by changes in atmospheric circulation.

Normally, warm waters in the western Pacific generate rising air currents that support strong monsoon circulation over South Asia. During El Niño, the warmest waters shift eastward, causing the zone of rising air to move away from the Indian Ocean. Consequently, subsiding (sinking) air develops over the Indian subcontinent, suppressing cloud formation and rainfall.

This process weakens the southwest monsoon winds that bring moisture from the Arabian Sea and Bay of Bengal to India. As a result:

1. Monsoon onset may be delayed.
2. Total seasonal rainfall may decline.
3. Dry spells become more frequent.
4. Drought conditions may develop in some regions.

Historically, several major droughts in India, including those of 1877, 1918, 1972, 1987, and 2002, coincided with strong El Niño events.

Impact on Indian Monsoon Rainfall

Reduction in Seasonal Rainfall

One of the most significant effects of El

Niño is the reduction in all-India summer monsoon rainfall. Studies indicate that many El Niño years experience below-normal rainfall. Historically, nearly half of all El Niño years have been associated with drought conditions in India.

However, the relationship is not absolute. Some El Niño years have recorded near-normal rainfall due to the influence of other climate systems such as the Indian Ocean Dipole (IOD).

Delay in Monsoon Onset

El Niño often affects the timing of monsoon onset over Kerala and its subsequent advance across the country. Delayed onset can shorten the effective growing season for crops and increase uncertainty for farmers.

Increased Rainfall Variability

Rather than causing a uniform decrease in rainfall, El Niño often increases rainfall variability. Some regions may experience severe deficits, while others receive normal or above-normal rainfall. This uneven distribution complicates water management and agricultural planning.

Increased Frequency of Dry Spells

El Niño years frequently witness longer “break” periods in the monsoon. During these periods, rainfall decreases significantly, causing moisture stress for crops and reducing groundwater recharge.

Regional Rainfall Patterns

Recent research shows that the El Niño–monsoon relationship varies across different regions of India.

North India

The influence of El Niño on rainfall over northern India has strengthened in recent decades. Deficient monsoon rainfall in this region is increasingly linked to ENSO conditions.

Central India

Central India, often referred to as the core monsoon zone, has shown a weakening relationship with El Niño. Scientists suggest that local atmospheric systems such as monsoon depressions and low-pressure systems now play a greater role in determining rainfall variability.

South India

The impact of El Niño remains relatively stable over southern India. Rainfall patterns in this region continue to show a noticeable response to ENSO-related changes in atmospheric circulation.

These regional differences indicate that forecasting monsoon rainfall requires consideration of multiple climatic factors rather than relying solely on ENSO conditions.

Effects on Agriculture and Economy

Agricultural Production

Agriculture is highly sensitive to monsoon performance. Weak rainfall during El Niño years can lead to:

- Reduced sowing of *kharif* crops.
- Lower crop yields.
- Increased irrigation demand.
- Greater risk of crop failure.

Major crops affected include rice, pulses, sugarcane, cotton, and oilseeds.

Food Security and Inflation

Lower agricultural output often results in higher food prices. Since food constitutes a significant component of household expenditure in India, poor monsoon performance can contribute to inflation and affect economic growth.

Water Resources

Deficient rainfall reduces reservoir storage, groundwater recharge, and river flows. Water shortages may affect drinking water supply, irrigation, and hydroelectric power generation.

Rural Livelihoods

Millions of rural households depend on monsoon rainfall for employment and income. Poor monsoon conditions can reduce agricultural wages, increase migration, and deepen rural economic distress.

Role of Other Climate Factors

Although El Niño is an important driver of monsoon variability, it is not the only factor.

Indian Ocean Dipole (IOD)

A positive IOD event, characterized by warmer waters in the western Indian Ocean, can partially offset the negative effects of El Niño and enhance monsoon rainfall over India.

Madden–Julian Oscillation (MJO)

The MJO is a moving atmospheric disturbance that influences active and break phases of the monsoon. Its interaction with ENSO can significantly affect seasonal rainfall patterns.

Climate Change

Global warming is modifying ocean temperatures and atmospheric circulation patterns. Some researchers suggest that climate change is altering the traditional ENSO–monsoon relationship, making monsoon forecasts more challenging.

Recent Scientific Findings

Modern studies reveal that the El Niño–monsoon relationship is not static. While El Niño continues to influence Indian rainfall, its impact differs across regions and time periods. Research from the Indian Institute of Tropical Meteorology (IITM) indicates that the relationship has weakened in central India but strengthened in northern India.

Scientists also emphasize that not all El Niño events lead to drought. The timing, intensity, and interaction with other ocean-atmosphere systems determine the final impact on monsoon rainfall.

Therefore, seasonal forecasting now incorporates multiple climate indicators rather than relying solely on ENSO conditions.

Conclusion

El Niño remains one of the most important global climate phenomena affecting the Indian monsoon. By altering atmospheric circulation and weakening moisture transport toward the Indian subcontinent, El Niño often reduces monsoon rainfall, increases drought risk, and affects agriculture, water resources, and economic stability.

However, the relationship between El Niño and the Indian monsoon is becoming increasingly complex. Regional differences, interactions with the Indian Ocean Dipole and Madden–Julian Oscillation, and the influence of climate change all contribute to variations in rainfall patterns. Understanding these interactions is essential for improving monsoon forecasting and strengthening India's resilience to climate variability.

As climate science advances, better forecasting systems and adaptive agricultural practices will help reduce the adverse impacts of El Niño and ensure sustainable management of water and food resources in India.

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6. AGRICULTURAL SCIENCES

Transforming Indian Agriculture: The Scientific Contributions and Leadership of Women Scientists

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Abstract

Indian agriculture has witnessed remarkable progress over the past seven decades, evolving from a food-deficit system to one of the world's largest agricultural economies. While landmark achievements such as the Green Revolution, White Revolution, and advances in biotechnology, digital agriculture, and climate-smart farming are widely celebrated, the contributions of women scientists have often received comparatively less public recognition. Women researchers have played transformative roles in crop improvement, horticulture, plant biotechnology, soil and water conservation, agricultural engineering, animal science, food technology, agricultural extension, and natural resource management. Their scientific innovations have enhanced crop productivity, strengthened food and nutritional security, promoted sustainable resource use, and improved farmers' livelihoods.

Beyond research, women scientists have emerged as influential institutional leaders within the Indian Council of Agricultural Research (ICAR), State Agricultural Universities (SAUs), the Department of Biotechnology (DBT), the Council of Scientific and Industrial Research (CSIR), and several international agricultural organizations. Through visionary leadership, interdisciplinary collaboration, and farmer-centric research, they have contributed significantly to India's agricultural transformation. Recent emphasis on climate-resilient agriculture, precision farming, artificial intelligence, digital advisory services, and women-led agri-entrepreneurship has further expanded opportunities for scientific leadership. Despite notable progress, gender disparities persist in research leadership, decision-making, resource access, and representation at senior scientific positions. Continued investment in mentorship, gender-inclusive policies, research funding, and institutional support is essential to harness the full potential of women scientists. Recent reviews and policy discussions continue to highlight the importance of strengthening women's leadership across agricultural research and innovation systems.

Keywords: Agricultural research; Climate-smart agriculture; Food and nutritional security; Gender equality; Indian agriculture; Institutional leadership; Scientific innovation; Sustainable agriculture; Women empowerment; Women scientists.

Introduction

Agriculture remains the backbone of India's economy, supporting the livelihoods of nearly half of the country's population while ensuring national food and nutritional security. Since independence, Indian agriculture has undergone profound transformation through scientific innovation, technological advancement, and evidence-based policymaking. The introduction of high-yielding crop varieties, expansion of irrigation, balanced fertilizer use, mechanization, biotechnology, precision agriculture, and climate-resilient farming has substantially increased agricultural productivity and rural prosperity.

Behind these remarkable achievements stands an extensive network of agricultural scientists, researchers, educators, extension professionals, and innovators. Among them, women scientists have emerged as indispensable contributors to agricultural research and development. Their work has significantly influenced crop improvement, seed technology, soil fertility management, horticultural diversification, integrated pest management, post-harvest technology, livestock production, fisheries, food processing, agricultural engineering, and rural development. Their scientific achievements extend beyond laboratories to farmers' fields, where research findings are translated into practical technologies that improve productivity, profitability, and environmental sustainability.

Historically, women have always been central to Indian agriculture. They perform a substantial share of agricultural operations, including seed selection, nursery raising, transplanting, weeding, harvesting, livestock management, post-harvest processing, and household food security. However, while women's contributions as cultivators have been widely acknowledged, their achievements as agricultural scientists, innovators, institutional leaders, and policy influencers have often received less public attention. Recent scholarship emphasizes that women are increasingly moving from participation in agriculture toward leadership in agricultural research, innovation, and governance.

The participation of women in agricultural science has steadily increased since the establishment of agricultural universities and national research institutions after independence. Today, women serve as professors, principal scientists, research directors, vice-chancellors, institute directors, policy advisors, entrepreneurs, and innovators across India's agricultural research ecosystem. They lead multidisciplinary projects addressing food security, climate change adaptation, sustainable natural resource management, digital agriculture, genetic improvement, nutrition-sensitive agriculture, and value-chain development.

One of the earliest pioneers was Edavalath Kakkat Janaki Ammal, whose pioneering work in plant cytogenetics and sugarcane breeding contributed significantly to the development of improved sugarcane varieties suitable for Indian conditions. Her research demonstrated that scientific excellence transcends gender and laid the foundation for future generations of women researchers.

Similarly, Asima Chatterjee contributed to phytochemistry and medicinal plant research, while many contemporary women scientists have strengthened agricultural biotechnology, food science, crop protection, horticulture, and agricultural engineering. Their work has enhanced crop resilience, nutritional quality, pest resistance, and resource-use efficiency, directly benefiting millions of farmers.

The Indian Council of Agricultural Research (ICAR), State Agricultural Universities, and allied institutions have played a crucial role in promoting women's participation through education, research opportunities, competitive fellowships, leadership development, and institutional reforms. National initiatives promoting gender equality, women entrepreneurship, and innovation have further encouraged greater representation of women in agricultural science. Nevertheless, challenges remain, including gender gaps in senior leadership positions, unequal access to research resources, work-life balance, limited mentorship, and underrepresentation in strategic decision-making. Addressing these challenges requires institutional commitment, inclusive policies, and sustained investment in women's scientific careers.

The role of women scientists has become even more significant in the context of emerging global challenges. Climate change, land degradation, biodiversity loss, water scarcity, food insecurity, and changing dietary patterns demand innovative scientific solutions. Women researchers are increasingly contributing to climate-smart agriculture, conservation agriculture, digital decision-support systems, artificial intelligence, remote sensing, biofortification, genome editing, and sustainable farming systems. Their interdisciplinary approach has strengthened the resilience of Indian agriculture while supporting national commitments toward sustainable development.

In addition to scientific excellence, women scientists have become effective institutional leaders. Many have successfully managed national research programmes, coordinated international collaborations, mentored young researchers, and strengthened farmer–scientist partnerships. Their leadership style often emphasizes collaboration, inclusiveness, community engagement, and multidisciplinary problem-solving, contributing to stronger agricultural innovation systems.

The future of Indian agriculture will increasingly depend on knowledge-intensive, technology-driven, and climate-resilient production systems. Artificial intelligence, robotics, big data analytics, drones, precision farming, gene editing, digital extension, and smart irrigation technologies are rapidly reshaping agricultural research and practice. Women scientists are expected to play an even greater role in these emerging domains, ensuring that technological advancement remains inclusive, sustainable, and beneficial to smallholder farmers.

This article highlights the remarkable scientific achievements, institutional leadership, and enduring legacy of women scientists who have transformed Indian agriculture. It also explores emerging opportunities for strengthening women's participation in agricultural research, innovation, education, and policymaking, recognizing that gender-inclusive science is essential for building a resilient, productive, and sustainable agricultural future.

Conclusion

Women scientists have emerged as a driving force in the transformation of Indian agriculture, making significant contributions to scientific research, technological innovation, institutional leadership, and sustainable agricultural development. Their pioneering work in crop improvement, plant breeding, biotechnology, horticulture, soil science, agricultural engineering, animal sciences, food technology, and agricultural extension has substantially enhanced agricultural productivity, strengthened food and nutritional security, and improved the livelihoods of millions of farming households. Through innovative research and farmer-oriented technologies, they have helped address critical challenges such as climate change, declining natural resources, pest and disease management, post-harvest losses, and sustainable resource utilization.

Beyond their scientific accomplishments, women scientists have increasingly assumed leadership roles in national agricultural research organizations, universities, and policy-making institutions. Their leadership has fostered interdisciplinary collaboration, promoted innovation-driven research, strengthened extension systems, and encouraged greater participation of women in agricultural education and research. Institutions such as the Indian Council of Agricultural Research (ICAR), State Agricultural Universities (SAUs), the Department of Biotechnology (DBT), and other national organizations have played an important role in creating opportunities for women scientists to contribute effectively to agricultural development. However, despite considerable progress, women remain underrepresented in senior leadership positions and continue to face challenges related to career advancement, access to research funding, work-life balance, mentorship, and gender biases within scientific institutions.

The future of Indian agriculture will increasingly depend on climate-smart technologies, digital agriculture, artificial intelligence, precision farming, genomics, and sustainable natural resource management. Women scientists are uniquely positioned to lead these emerging areas of research because of their growing expertise, interdisciplinary approach, and commitment to inclusive agricultural development. Strengthening women's participation through gender-responsive policies, leadership training, research grants, international collaborations, mentoring programmes, and institutional support will not only promote gender equality but also accelerate scientific innovation and agricultural sustainability.

Recognizing and celebrating the achievements of women scientists is essential for inspiring future generations of researchers and encouraging young women to pursue careers in agricultural science and technology. Their success demonstrates that scientific excellence is determined by knowledge, innovation, and dedication rather than gender. As India strives to achieve the Sustainable Development Goals (SDGs), enhance farmers' incomes, ensure nutritional security, and build climate-resilient farming systems, the continued contributions and leadership of women scientists will remain indispensable. Investing in their education, research, and leadership is therefore not only a matter of social justice but also a strategic imperative for transforming Indian agriculture into a more productive, resilient, inclusive, and globally competitive sector.

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