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# Agri-Bio Innovations Across the Globe: A Comprehensive Review

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**ABSTRACT: Biotechnology, precision agriculture, and sustainable practices have facilitated transformative advancements in agriculture, enhancing productivity while mitigating adverse environmental impacts. Since the 1990s, precision agriculture has transformed farming through the application of contemporary technology and data analysis to enhance crop yields, minimize waste, and increase productivity, significantly advancing the use of GPS, GIS, and yield monitors. The global precision farming market is now valued at USD 10.50 billion in 2023 and is projected to grow at a compound annual growth rate (CAGR) of 12.8% from 2024 to 2030. Biotechnology holds promise for sustainable agriculture; nevertheless, its application is constrained by safety apprehensions. Although biotechnology methods in pest control and the notable achievements of tissue culture during the second Green Revolution demonstrate the sector's potential, their application remains limited. Agricultural biotechnology yields superior outcomes compared to conventional methods by maintaining soil stability and fertility, enhancing productivity, and offering resilience against extreme environmental stressors like drought and salinity, in addition to safeguarding against pests and diseases. Worldwide, innovations include genetically modified (GM) crops, CRISPR gene editing, precision agriculture technologies, biofortification and nutraceuticals, and laser land levelling are facilitating more sustainable and productive agricultural practices. This article examines the significance, usefulness, and future potential of agricultural biotechnology advancements, contrasting India's contributions with global trends.**

**Keywords:** Agri-bio innovations, biotechnology, drones, precision farming, sustainable agriculture

## INTRODUCTION

The current farming upheaval is being driven by innovation and information research, and it appears to have enormous potential for improved efficiency as well as monetary success (Himesh *et al.,* 2018). To guarantee worldwide food security, innovation mediations in the rural business are turning out to be progressively unmistakable and exact. The computerized farming transformation is arising concurrently with the fourth modern upheaval, or 'Industry 4.0,' and has been seen as somewhat important to Indian agriculture following the green unrest, because these advanced advancements offer new opportunities to remember smallholders for a carefully determined agrifood framework (Chand and Singh 2023). It involves applying inputs in the fields utilizing information examination from information driven frameworks, guaranteeing exact organization of water, supplements, composts, and different synthetic compounds when and where they are required thus guaranteeing manageability (Chandra and Collis 2021). Right now, the worldwide accuracy cultivating market size is esteemed at USD 6.96 billion and is supposed to extend at a pace of 12.8% somewhere in the range of 2022 and 2030. Albeit in the ongoing status of accuracy agriculture, there are a few issues, for example, impractical asset use, long haul monoculture, serious animal cultivating, natural trade-offs, lopsided circulation of digitization, sanitation issues, wasteful agri-food production network, and absence of familiarity with and dormancy toward novel changes (Trendov *et al.,* 2019). These issues forestall accomplishing effectiveness, efficiency, and supportability from agrarian creation and raise accidental effects on biological systems.

## MATERIAL AND METHODS

Methods for evaluating secondary sources are the subject of this systematic study, which aims to analyze and synthesize that research. According to Srivastava and Lal (2021); Kumar *et al.* (2022); Lal *et al.* (2023), secondary data analysis is the process of analyzing data that has been gathered by other researchers in the past and researchers adds value to a primary source. Many different databases, such as Google Scholar, IEEE Xplore, PubMed, Research Gate, Science Direct, Taylor & Francis, Elsevier, and Springer Nature, were searched in order to conduct an exhaustive literature search (Arya *et al.,* 2023; Arya *et al.,* 2024).

## RESULT AND DISCUSSION

### *A. Biotechnology Innovations*

**(i) Gene-Editing Technologies.** Genome Editing techniques have upset crop rearing in numerous researchers who perform genome Editing currently use CRISPR. Specialists presently ordinarily use CRISPR to control the genome for various applications, including practical genomics, diagnostics, DNA imaging, and therapeutics. CRISPR-Cas9 innovation caused a significant mix in the field of genome designing when it was first portrayed as an Editing device in 2012, and it has gained surprising headway in the mediating years. From that point forward, researchers have gone through many years attempting to uncover ways of editing the genome that offset explicitness with time and cost (Public Human Genome Exploration Foundation (NHGRI, 2019). Here are the 7 fruitful methodologies that researchers have used to adjust DNA up to this point (Fig. 1, 2 & Table 1).


**Fig. 1.** Factor influencing Agri –bio innovation.

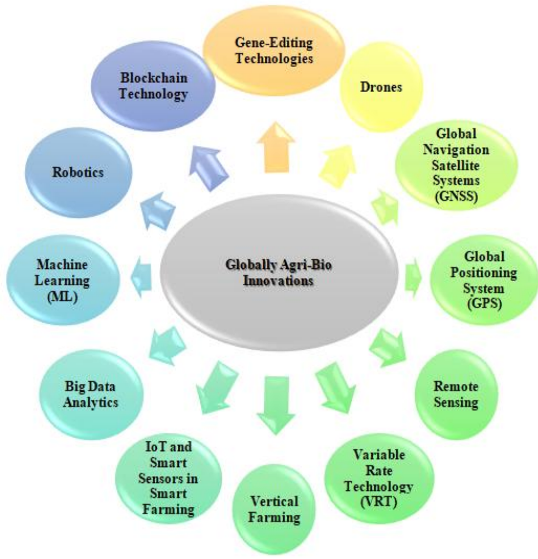


**Fig. 2.** Top 12 global agri–bio innovation.

**Table 1: Evolution of Gene-Editing Techniques with Key Features, Inventors, and Year of Discovery (Mah & Robers 2022).**

| Technique | Key Features | Year |
|---|---|---|
| **Restriction Enzymes** | Recognize specific DNA sequences and cut at those sites, allowing DNA insertion. Widely used in molecular cloning and DNA mapping. | 1970s |
| **Zinc Finger Nucleases (ZFNs)** | Fusion of FokI nuclease with zinc finger domains for site-specific DNA cutting. Used in HIV therapy and cancer treatment. | 1980s |
| **TALENs** | Use transcription activator-like effectors for single-nucleotide resolution. Improved specificity but high cost and complexity. | 2011 |
| **CRISPR-Cas9** | RNA-guided nuclease for precise and customizable DNA cutting. Revolutionized genome editing with high efficiency and accessibility. | 2012 |
| **Base Editing** | Uses a catalytically dead Cas9 fused with DNA deaminases to induce single nucleotide substitutions without double-strand breaks. | 2016 |
| **Prime Editing** | Combines Cas9 nickase with reverse transcriptase to allow insertions, deletions, and all transition mutations without double-strand breaks. | 2019 |
| **PASTE** | Integrates large DNA sequences into genomes using serine integrase and prime editing, avoiding double-strand breaks. | 2022 |

Certain example demonstrated gene-editing applications globally and in India:

- **Global Example:**

**— Golden Rice**, fortified with Vitamin A, has been developed to combat malnutrition.

**— Arctic Apples**: Engineered using gene-editing to prevent browning, enhancing shelf life and reducing food waste.

**— Drought Guard Maize**: Developed by Monsanto, this maize variety is genetically modified to tolerate drought conditions, improving yields in water-scarce regions.

**(ii) Biofertilizers and Biopesticides.** The expression "Biofertilizer", additionally named as bioinoculants or bioformulations, envelops natural items containing advantageous microorganisms as dynamic or dormant structures, ready to store the rhizosphere or the interior tissues of plants (Chaudhary *et al.,* 2022; Allouzi *et al.,* 2022; Nosheen *et al.,* 2021). These microorganisms upgrade a plant's development capacity to take-up fundamental supplements like nitrogen, phosphorus, and potassium, advancing supplement accessibility and take-up limit, which brings about expanded crop yields. In the first place, the easiest arrangement depends on the kind of microorganism utilized, essentially microbes and organisms, albeit the utilization of microalgae has been on the ascent lately. biofertilizers envelop a few gatherings of microorganisms, including nitrogen-fixing microbes; microorganisms fit for solubilizing fundamental supplements like phosphorus, potassium, or zinc; siderophore makers; natural corrosive originators; sulphur oxidizers; phytohormone makers; and plant development advancing rhizobacteria (Table 2).

Bio-pesticides are serious subclass of pesticides that are normally happening living beings or mixtures that stifle the development and multiplication of vermin's populace by assorted instruments of activity, barring those that impede irritations' sensory systems. They are ordered into three gatherings: microbial biopesticides, biochemical biopesticides, and PIPs. Models incorporate rejuvenating balm, semiochemicals, plant development advancing controllers, bug development controllers, auxiliary metabolites, and regular minerals.

**Table 2: Comparison of Chemical Inputs and Biological Inputs in Agriculture.**

| Parameter | Chemical Inputs | Bio Inputs |
|---|---|---|
| **Environmental Impact** | High, causing pollution and biodiversity loss | Minimal, eco-friendly, and non-toxic |
| **Cost** | Relatively high due to repeated applications | Economical, often with longer-lasting effects |
| **Soil Health** | Degrades over time, causing soil infertility | Enhances soil fertility and microbial activity |
| **Sustainability** | Unsustainable, with long-term negative impacts | Highly sustainable and promotes regeneration |
| **Effectiveness** | Quick and immediate results | Gradual but long-term benefits |
| **Residue Concerns** | Leaves harmful residues in crops and soil | Residue-free and safe for consumption |
| **Pest Resistance** | High potential for pest resistance development | Less likelihood of resistance development |
| **Water Quality Impact** | Contributes to water contamination and eutrophication | Safe for water systems and prevents pollution |
| **Health Risks** | Can pose risks to human health (e.g., cancer, toxicity) | Safe for humans and animals |
| **Regulatory Challenges** | Strict regulations due to environmental risks | Fewer regulatory hurdles |
| **Adaptability** | Limited adaptability to changing climates | Adaptable and effective in diverse environments |
| **Biodiversity Impact** | Harmful to non-target organisms and pollinators | Supports biodiversity and beneficial organisms |
| **Storage and Handling** | Requires careful storage and handling | Easier and safer to store and handle |
| **Carbon Footprint** | High, due to manufacturing and transport | Low, often produced locally and sustainably |
| **Long-Term Productivity** | Declines due to soil and pest issues | Sustains productivity through natural balance |

### *B. Precision Agriculture*

Precision agriculture utilizes state of the art advancements to increment farming efficiency while decreasing unfriendly effects on the climate utilized as the board system for tending to geological and transient fluctuation in agrarian fields that includes information and contemporary innovations. Precision agriculture is a cultivating approach that utilizations trend setting innovation and information investigation to boost crop yields, cut waste, and increment efficiency. It is a possible technique for handling a portion of the significant issues standing up to contemporary agriculture, like taking care of a developing total populace while diminishing ecological impacts. Precision cultivating was brought into the world with the presentation of GPSs (worldwide situating frameworks), GISs (geographic data frameworks), yield screens, and different information generators like Web of Things (IoT), large information, computerized reasoning (computer-based intelligence), advanced mechanics, and blockchain innovation in all are critical periods of agrarian activities (Filipe *et al.,* 2020; Liu *et al.,* 2021). Here are the absolute most recent patterns in agriculture innovation which are anticipated to all around the world impacting cultivation.

**(i) Drones in Agriculture.** Remote detecting has been viewed as a mechanical device with high potential to work on shrewd and accuracy agriculture. Satellites, human-manned airplane, and robots are famous remote-detecting advancements. Drones, famously known as Unmanned Aerial Vehicles (UAVs), Unmanned Aircraft Systems (UAS), and remotely directed airplane, are vital as they enjoy different benefits in correlation with other remote-detecting advancements. All in all, drones can shower water and pesticides in exact sums in view of ecological information. The advantages of robots in agribusiness are summed up beneath (Table 3).

**Table 3: Main benefits of drones in agriculture (Rejeb *et al*., 2022).**

| Sr. No. | Benefit |
|---|---|
| 1. | Enhance temporal and spatial sensing resolutions |
| 2. | Facilitate precision agriculture |
| 3. | Classification and scouting of crops |
| 4. | Usage of fertilizer |
| 5. | Monitoring of drought |
| 6. | Biomass estimation |
| 7. | Yield estimation |
| 8. | Disaster reduction |
| 9. | Conservation of wildlife and forestry |
| 10. | Assessment of water stress |
| 11. | Pest, weeds, and disease detection |

**(ii) Global Navigation Satellite Systems (GNSS).** Global Navigation Satellite Systems (GNSS) in precision agriculture (Dad) address a foundation for field planning, hardware direction, and variable rate innovation. In any case, late enhancements in GNSS parts (GPS, GLONASS, Galileo, and BeiDou) and novel remote detecting and PC handling based arrangements in Dad have not been completely dissected. GNSS advances, like GPS, GLONASS, Galileo, and BeiDou, have been broadly taken on in Dad applications around the world. GPS, starting from the US, has been used since its full functional ability was accomplished in 1995. The improvement can be traced back to the 1970s as a tactical endeavor. Endeavours ought to be made to further develop information assortment techniques, information combination, and information approval cycles to guarantee the accessibility of precise and great spatial information for Dad applications. Moreover, there is a requirement for easy to understand and interoperable Dad programming and equipment arrangements (Radočaj *et al.,* 2023).

**(iii) Global Positioning System (GPS).** Observing and performing rural practices over an enormous spatial inclusion frequently require progressed and exact positional data to improve the functional expenses as well as diminish assessed season of finishing. Agricultural practices with enormous ranches are trying to work from remote detecting until exact positional data isn't accessible, which requires the utilization of Global Positioning System (GPS) for gaining test position utilizing Global Navigation Satellite System (GNSSs). The fundamental finish of this part is to make mindful about the developing GPS applications and advancement of Brilliant cultivating, that is to say, carefully utilizing Web for accuracy applications (Pandey *et al*., 2021).

**(iv) Laser Land Levelers.** Land levelling technology is essential for land development and is a significant help for feasible farming turn of events. Current status of land-evening out executes, including dry-land and paddy-field evening out carries out. Second, two accuracy land-evening out innovations, laser-controlled frameworks and the Global Navigation Satellite System (GNSS), are surveyed. Laser-controlled innovation was first presented for farming creation in the US in the 1970s. It was in this way generally took on in many created nations, including the Unified Realm, Japan, and the Soviet Association, and created in emerging nations, like Southeast and East Asia, during the 1990 s (Kan *et al.,* 2001). The genuine advantages of land-evening out innovation applied to the creation of various harvests are measurably investigated utilizing measurements including further developed land usage, water reserve funds, and expanded yields. This procedure is generally taken on in India, particularly in water-scant areas.

**(v) Remote Sensing.** Agriculture provides humans with food, fiber, fuel, and natural compounds required for human activity. Today, this work must be completed in a context of natural supportability and environmental change, along with an outstanding but growing human population, while maintaining the practicality of rural activities to provide both means and vocations. Remote detection has the potential to assist the varied evolution of agronomic methods in meeting this big challenge by providing redundant data on crop status throughout the season at various sizes and for diverse uses. It generally tended to from different perspectives, in some cases in view of explicit applications (for example, accuracy cultivating, yield forecast, water system, weed discovery), on unambiguous remote detecting (Weiss *et al.,* 2020).

**(vi) Variable Rate Technology (VRT).** Consistent rate compost application across whole field can bring about finished or under joining of supplements. Variable rate technology (VRT) is an info application innovation that considers the utilization of contributions at a specific rate, time, and put in light of soil properties and spatial variety in the field or plants. There are two approaches for doing VRT: i) sensor-based and ii) map-based. The map-based technique employs lattice testing and soil inspection to create a solution map. The microprocessor determines the optimal application rate based on the dirt and yield circumstances. This article evaluates two VRT strategies for compost application in plantations and field crops. The application of this advanced invention absolutely improves compost use proficiency; further enhance agricultural production and benefit with less climate effects. (Pawase and Walunj 2023).

### *C. Agri-Tech Innovations Worldwide*

**(i) Vertical Farming.** Kabir *et al.* (2023) Vertical cultivating innovation is encountering quick and various progressions including different degrees of harvest developing stages, is acquiring consideration for its capability to increment crop yield per unit area of land. The underlying period of indoor cultivating was principally focused on checking and controlling variables like lighting, supplements, temperature, and mugginess. In any case, late improvements have driven producers to embrace novel advancements for information assortment and examination, pointed toward streamlining crop yield. This pattern is especially encouraging for improving food manageability in metropolitan regions and presents amazing chances to decidedly affect the climate, society, and economy. Albeit vertical ranches have shown their true capacity for creating a wide cluster of yields, further exploration is fundamental to accomplish specialized and financial enhancement.

**(ii) IoT and Smart Sensors in Smart Farming.** Farming should defeat heightening issues to take care of a developing populace while saving the climate and normal assets. The cutting edge in IoT and sensor advances for agriculture is analyzed, alongside a portion of their likely purposes, including 1) water system checking frameworks, 2) compost organization, 3) crop sickness discovery, 4) observing (yield checking, quality checking, handling checking calculated monitoring), determining, and collecting, 5) environment conditions observing, and 6) fire recognition (Table 4). Moreover, this offers various sensors for farming that can recognize boundaries like soil NPK, dampness, nitrate, pH, electrical conductivity, $CO_2$, temperature, stickiness, light, weather conditions station, water level, domesticated animals, plant illness, smoke, fire, adaptable wearable (Morchid *et al.,* 2024).

**Table 4: Agricultural Sensors and their Applications (Morchid *et al.,* 2024).**

| Sensor Name | Sensor Application |
|---|---|
| Soil NPK Sensor | Fertilizer Administration |
| Temperature and Humidity Sensor | Quality Monitoring, Irrigation Monitoring Systems |
| Livestock Sensor | Logistics Monitoring |
| Smoke Sensor | Fire Detection |
| Flame Sensor | Fire Detection |
| Flexible Sensor | Yield Monitoring |

**(iii) Big Data Analytics.** Big data applications in farming are rapidly evolving as more expertise, apps, best practices, and computational capacity become available. actual answers to actual concerns are scarce. Massive information developments have accelerated as more expertise, calculations, best practices, and processing power become available (Oussous *et al.,* 2018). A few new Big Data and man-made reasoning applications for the rural area have been fostered everywhere, nonetheless: the large information qualities actually present significant difficulties, in any event, when superb mechanical offices and backing are accessible. Big data arrangements don't work out-of-the-container while changing application spaces, and extra innovation improvement is required for tending to the eccentricities of rural applications. The reception states of enormous scope, farming explicit huge information frameworks are arising, and frameworks thinking approach is expected to co-foster large information answers for tending to agricultural frameworks vulnerabilities and food security challenges (Osinga *et al.,* 2022).

**(iv) Machine Learning (ML).** Recent advancements including the Web of Things, sensors, mechanical technology, Artificial Intelligence, Machine Learning, Big Data, and Cloud Computing are driving agriculture towards the transformative Agriculture 4.0 paradigm. Machine Learning (ML), as a subset of artificial intelligence, has shown significant potential for improving various elements of Farming 4.0.

A computer software or system that can learn specific tasks without explicit programming can be defined as such. Araújo *et al.* (2023) define interaction as the process of utilizing a personal computer to make decisions informed by various information inputs.

**(v) Robotics.** The steady advances in agricultural mechanical technology plan to defeat the difficulties forced by populace development, sped up urbanization, high seriousness of excellent items, ecological conservation and an absence of qualified work. In this the really existing uses of farming mechanical frameworks for the execution of land readiness prior to planting, planting, planting, plant treatment, gathering, yield assessment and phenotyping. As a rule, all robots were assessed by the accompanying measures: its headway framework, what is the last application, in the event that it has sensors, mechanical arm as well as PC vision calculation, what is its improvement stage and which nation and landmass they have a place. In the wake of assessing every comparable trademark, to uncover the exploration patterns, normal entanglements and the attributes that thwart business improvement, and find which nations are putting into Innovative work (Research and development) in these advances for the future, four significant regions that need future examination work for upgrading the cutting edge in savvy agribusiness were featured: velocity frameworks, sensors, PC vision calculations and correspondence advancements. The after effects of this exploration propose that the interest in agricultural mechanical frameworks permits to accomplish short — reap observing — and long haul goals — yield assessment (Oliveira *et al.,* 2021).

**(vi) Blockchain Technology.** Blockchain innovation (BCT) to modify the farming business by giving a decentralized, straightforward, and unchangeable answer for meet the challenges it faces. BCT arises as a reasonable answer for address difficulties in the agricultural business, especially in the space of trust, viability, and recognizability, which have become more articulated because of late mechanical headways. BCT, as a protected and changeless information base utilizing cryptographic strategies, offers benefits like discernibility, unchanging nature, straightforwardness, and security. These properties are especially critical in the agricultural area, where trust and straightforwardness are fundamental for building a practical and secure food supply framework. The execution of BCT in farming can possibly advance certainty and straightforwardness all through the whole food store network. It can empower more productive observing and following of merchandise, limiting dangers related with food borne infections and food misrepresentation. The foundation of a framework for the exact following of the beginning, quality, and wellbeing of food things is urgent for customers, controllers, and industry partners, and BCT can give a more precise and solid answer for meet these necessities (Panwar *et al.,* 2023).

## CONCLUSIONS

Agri-bio innovations are transforming agriculture through the integration of sustainability and productivity. India's grassroots initiatives, such as Pusa Decomposer Powder and laser leveling, have enhanced the capabilities of small farmers. Technologies such as CRISPR and IoT are addressing significant agricultural challenges on a global scale. Policy Support: It is essential for governments to establish conducive policies that facilitate advancements in agri-bio innovations. Collaborative research fosters partnerships between Indian and global researchers, thereby accelerating innovation. Farmer Training: It is essential to ensure that farmers receive adequate training in the utilization of these technologies. Through the promotion of innovation, knowledge-sharing, and sustainability, agriculture can effectively address the increasing demands of humanity while ensuring the preservation of the planet.

## FUTURE SCOPE

This study expands the understanding of biotechnology's future in Indian agriculture by considering current research, strategic recommendations, and the potential for innovation to benefit smallholder farmers. The future of biotechnology in global agriculture is promising, with potential for significant advancement and dedication to the global economy. Plant biotechnology holds significant potential for enhancing agricultural productivity and well-being, addressing food security issues, and fulfilling global increasing need for food and nutrients. To address current issues and unlock the full potential of biotechnology in global agriculture, it is essential to integrate unique genetic resources, genomic modifications, and omics advancements, alongside the establishment of quantitative, objective, and automated screening methods. Biotechnology has profoundly influenced global agriculture through the application of genetically modified crops and advanced genetic control technologies. Tissue culture, an essential biotechnological technique, has significantly contributed to industry growth and market demands; nonetheless, its potential remains underutilized. Plant biotechnology has significantly contributed to enhancing crop health and yield, addressing the increasing demand for food and sustenance, especially in light of population growth. The agricultural biotechnology sector, especially regarding genetically modified crops, has experienced significant expansion, however it faces hurdles related to safety and environmental issues. Consequently, it is customary to recognize these challenges promptly. Borah underscores the significance of the Indian government's involvement in the region's development. McKinney examined the ethical, economic, and political dimensions of rural biotechnology, namely Bt cotton in Gujarat. It underscored the significance of natural resource management and economic advancements in global agriculture. These studies advocate for a significant governmental engagement in the fundamental reformation of biotechnology practices within global agriculture.

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