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# CURRENT TRENDS IN AGRICULTURAL RESEARCH VOLUME II

Editors:
Ms. A. Jeevarathinam
Dr. Surendra Kadam
Dr. P. G. Paul
Ms. Shravani R. Wadekar

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# Current Trends in Agricultural Research Volume II

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## *PREFACE*

*Agriculture has always been the backbone of human civilization, supporting communities, economies, and global food security. Over the years, advancements in technology, biotechnology, and sustainable farming practices have significantly transformed agricultural research, leading to increased productivity, improved crop resilience, and enhanced environmental sustainability. In the face of climate change, population growth, and resource constraints, the need for innovative agricultural solutions has never been more pressing.*

*The book Current Trends in Agricultural Research aims to provide a comprehensive overview of contemporary developments in the field, encompassing a broad spectrum of topics including precision agriculture, genetic improvements, soil health management, sustainable farming techniques, and the application of artificial intelligence in agriculture. It brings together contributions from eminent researchers, academicians, and industry experts to explore cutting-edge methodologies and emerging trends that are shaping the future of agriculture.*

*One of the key aspects of modern agricultural research is the integration of interdisciplinary approaches, combining traditional knowledge with modern technological advancements. The application of biotechnology, remote sensing, nanotechnology, and climate-smart practices is redefining the way we cultivate crops and manage natural resources. This book highlights these transformative innovations and offers insights into their practical applications for achieving global food security and environmental conservation.*

*As the agricultural sector evolves, researchers, policymakers, and farmers must collaborate to implement strategies that enhance productivity while ensuring ecological balance. This book serves as a valuable resource for students, researchers, and professionals in agricultural sciences, providing a foundation for future studies and applications in sustainable agriculture.*

*We extend our sincere gratitude to all the contributors who have shared their knowledge and expertise to make this book a reality. Their dedication to advancing agricultural research is commendable and will undoubtedly inspire further innovations in the field. We hope that this book will stimulate discussions, encourage new research endeavors, and contribute to the ongoing efforts to build a resilient and sustainable agricultural system.*

**- Editors**

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# RECENT ADVANCES IN AGRONOMIC BIOFORTIFICATION WITH SPECIAL REFERENCE TO ZINC

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**Abstract:**

Adequate nutrition is crucial for human development, but issues like poverty, poor sanitation, and lack of dietary diversity contribute to widespread malnutrition. The World Health Organization (WHO) estimates that 2.5 billion people suffer from nutritional disorders. Zinc deficiency affects 17.3% of the global population, leading to weakened immune systems, stunted growth, and reduced productivity. These deficiencies are often unnoticed, earning the term "hidden hunger" (Wessells and Brown, 2012). In India, the National Family Health Survey (NFHS-4) reveals high anaemia rates of 58.6% among children, 53.1% among women, and 50.4% among pregnant women. Zinc deficiency affects 43.8% of children, 49.4% of adolescents, and 64.6% of pregnant women. The Indian Council of Medical Research (ICMR) recommends a daily intake of 12 mg of zinc for women and 10 mg for men. To address these deficiencies, micronutrient-fortified foods and biofortification, especially agronomic biofortification through mineral fertilizers, are essential. With 40% of Indian soils lacking zinc, applying chelated or conventional zinc fertilizers can enhance soil quality, crop growth, and the nutritional value of food grains, (Alloway, 2008).

**Keywords:** Biofortification, Malnutrition, Zinc, Fertilizers

**Introduction:**

Malnutrition results in enormous socio-economic costs to the individual, their community, and the nation's economy. The evidence suggests an overall negative impact of climate change on the agricultural productivity and nutritional quality of food crops. Producing more food with better nutritional quality, which is feasible, should be prioritized in crop improvement programs. Biofortification refers to developing micronutrient-dense cultivars through crossbreeding or genetic engineering. Over 400 minerals (Fe, Zn) and provitamin A-rich cultivars have been released in the Global South. Approximately 4.6

million households currently cultivate Zn-rich rice and wheat, while ~3 million households in sub-Saharan Africa and Latin America benefit from Fe-rich beans, and 2.6 million people in sub-Saharan Africa and Brazil eat provitamin A-rich cassava. Furthermore, nutrient profiles can be improved through genetic engineering in an agronomically acceptable genetic background. The development of "Golden Rice" and provitamin A-rich dessert bananas and subsequent transfer of this trait into locally adapted cultivars are evident, with no significant change in nutritional profile, except for the trait incorporated. A greater understanding of nutrient transport and absorption may lead to the development of diet therapy for the betterment of human health.

As per estimates from the World Health Organization (WHO) and the Food and Agriculture Organization (FAO) of the United Nations, 149 million children under 5 are stunted, 47 million are wasted, and 462 million are underweight. About 50% of child deaths under the age of 5 in developing countries are linked to undernutrition (FAO *et al.,* 2020). Therefore, malnutrition affects physical and mental development, immunity, and overall health, thereby hampering human life potential largely in low- and middle-income countries (LMICs). The magnitude of micronutrient deficiency is particularly alarming among children, women of reproductive age, and pregnant and nursing mothers. Increased availability, accessibility, and affordability of dietary diversity including animal and dairy products address this complex food-system-based health problem. Food production is meant for both food and nutrition security. This has been ignored in recent agricultural research for development undertakings. The agricultural sector gained momentum in producing high yields through the Green Revolution efforts, but ignoring crop-based essential nutrition. Alternative agriculture should emphasize the production of food crops with better nutritional quality to minimize the risk of malnutrition in developing countries.

Globally, tackling the burden of malnutrition in all its forms remains challenging. For instance, the staggering impact of malnutrition in developing countries, in terms of gross domestic product (GDP), is almost 11% in Asia and Africa. The World Bank (2020) estimated that loss in GDP due to hidden hunger is up to 12 billion for India alone. The highest nutrition priority for eradicating malnutrition and achieving optimum nutrition for all is embedded in the National Nutrition Policy (NNP) adopted in 1993 by the Government of India, which acknowledges high prevalence of malnutrition according to a national family health survey (NFHS-V, 2021). Improving nutrient levels in the edible parts of staple crops, by either crossbreeding, biotechnology, or agronomy, through the application of soil and leaf fertilizers, are cost-effective and sustainable approaches to reducing the burden of micronutrient deficiencies in the developing world (Garg *et al.,* 2018).

The CGIAR Harvest Plus Program has led nutrition research for development since 2003, by focusing on the top three nutrients with the highest deficiency among populations: iron (Fe), zinc (Zn), and vitamin A (Harvest Plus, 2022). Iron deficiency consequences are anemia, fatigue, weakness, and impaired cognition. Zinc deficiency leads to stunting in children, susceptibility to infections, and cell damage. Vitamin A deficiency contributes to impaired vision, night blindness, a higher risk of infection/death, and poor pregnancy outcomes. Nutrition is always given less priority in core crop improvement programs in national and international research and investments, except in a few time-bound bilateral projects. Thus, reducing the magnitude of malnutrition, especially in rural households, remains a big challenge. The prevalence of malnutrition after the COVID-19 pandemic is expected to significantly increase. The malnutrition prevalence levels are unacceptable in the Global South. The cost of addressing malnutrition is increasing in LMICs. An estimated 10 billion vitamin A capsules have been distributed to preschool children over two decades in LMICs (Tam *et al.,* 2020). The importance of food security and improved nutrition is highlighted in the Sustainable Development Goals (SDG 2), which aim to end all forms of hunger by 2030 (Jose *et al.,* 2020). The ongoing transition in CGIAR crop breeding and modernization investments highlight that improving nutrition traits is a priority to achieve SDG2.

**Global warming and elevated $CO_2$ reduce the nutritional quality of food crops**

Climate change and the quality of human diets are challenging issues and consequences for this century and upcoming ones. Increasing temperature and $CO_2$ affects crop productivity, resilience, and nutritious quality. Semba *et al.* (2022) argued that climate change will affect micronutrient malnutrition by restricting the accessibility to micronutrient-rich crops. Furthermore, stoichiometric theory suggests that high $CO_2$, as a rule, should alter the elemental plant composition (Loladze, 2002).

The flour from cereals that were grown under elevated $CO_2$ or using low nitrogen fertilizer amounts could lessen nutritional and processing quality and alter grain elemental composition (Erbs *et al.,* 2010). It has also been noted that climate may reduce proteins and micronutrients in food crops.

Likewise, iron and zinc content in wheat (*Triticum aestivum* L.) grains were reduced by ca. 32% and 6%, respectively, under heat stress (Panigrahi *et al.,* 2022). Loladze (2002) claimed that micronutrients may decline owing to "carbohydrate dilution" and reduce transpiration, thus affecting food quality and increasing micronutrient malnutrition, especially in the developing world.

Global warming lessens the uptake of micronutrients from the soil and the ensuing translocation within the plant (Maqbool *et al.,* 2020). In this regard, high temperature negatively affects zinc acquisition in plants, thus resulting in poor nutritional quality. Ahmad *et al.* (2022) indicated that poor soil fertility management may further decrease the dietary supplementary supply of micronutrients. Likewise, owing to the ongoing COVID-19 pandemic, malnutrition has risen particularly in South Asia and sub-Saharan Africa. Hence, when it comes to biofortification, it must consider the target population of environments where the nutrient-dense bred germplasm will be further grown. There are obvious interlinks between global warming, agri-food systems, and nutritional security. Both agri-food systems and nutrition security are highly affected by climate variability and long-term climate change.

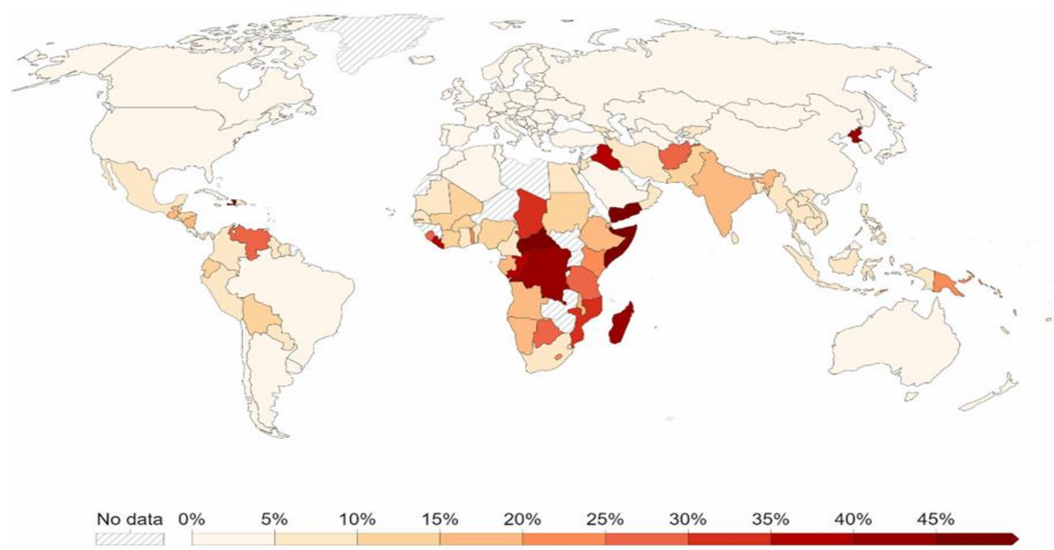



FIGURE 1
The prevalence of undernourishment (in percentage) in Global South (source: Asia, 2021; https://ourworldindata.org/hunger-and-undernourishment#long-term-decline-of-undernourishment).

**Fig. 1: The prevalence of undernourished population in world**

The different types of foods consumed vary in their released greenhouse gases (GHGs), such as $CO_2$ and NOx, and may promote change in land uses including an increase on clearing forests, draining wetlands, or tilling soil for agriculture, thereby contributing to climate change. This synergy steers different GHG emissions and distinct environmental footprints. A transdisciplinary approach should therefore be sought for developing an agri-food system that considers biofortification under rising temperatures, elevated $CO_2$, and water stress, with the aim of ensuring food and nutrition security. Biofortification should be included in agri-food system interventions to overcome micronutrient deficiency in rural households. The microbiome may also provide a path towards nutrient-rich crops because of the known role of rhizospheres on crop nutrient dynamics.

Micronutrient especially zinc (Zn) plays an important role in human growth, development, and maintenance of the immune system. Micronutrient malnutrition has always been considered a difficult task for humans because 2/3rd of the world's population may deficient one or more im portant mineral elements. Zinc is a crucial micronutrient that is involved in numerous biochemical paths (Alloway, 2009). All around the world, about 2.7 billion people suffer from Zn deficiency (WHO, 2012).

It is estimated that in humans 2800–3000 proteins contain Zn prosthetic group. Zn is the only metal to be involved in all six classes of enzymes: oxidoreductases, transferases, hydrolases, lysases, isomerases, and ligases. Further, Zn is required for the activation of over 300 enzymes. Zn ions are also neurotransmitters and are present in the cells of the salivary glands, prostrate, and immune system. Zn plays a key role in physical growth and development, the functioning of the immune system, reproductive health, sensory functions, and neurobehavioral development.

Zn is an integral component of zinc finger proteins that regulate DNA transcription. Zn is a "Type 2" nutrient, which means that its concentration in blood does not decrease in proportion of the degree of deficiency. As a result, physical growth slows down and excretion is reduced to conserve Zn. Thus, children suffering from Zn deficiency have reduced linear growth (stunting). Adverse health effects of Zn deficiency vary with age: low weight gain, diarrhea, aneroxia, and neurobehavioral disturbances are observed during infancy, whereas skin changes, blepharoconjunctivitis, and dwarfing are frequent among toddlers and school children. Common manifestations of Zn deficiency among the elderly include hypogeusia (impaired taste sensitivity), chronic nonhealing leg ulcers, recurrent infections, and adverse pregnancy outcomes. Zn is also essential for regulating intestinal absorption of Fe, and sufficient quantity of Zn along with Fe in human body is crucial for treating Fe deficiency anemia.

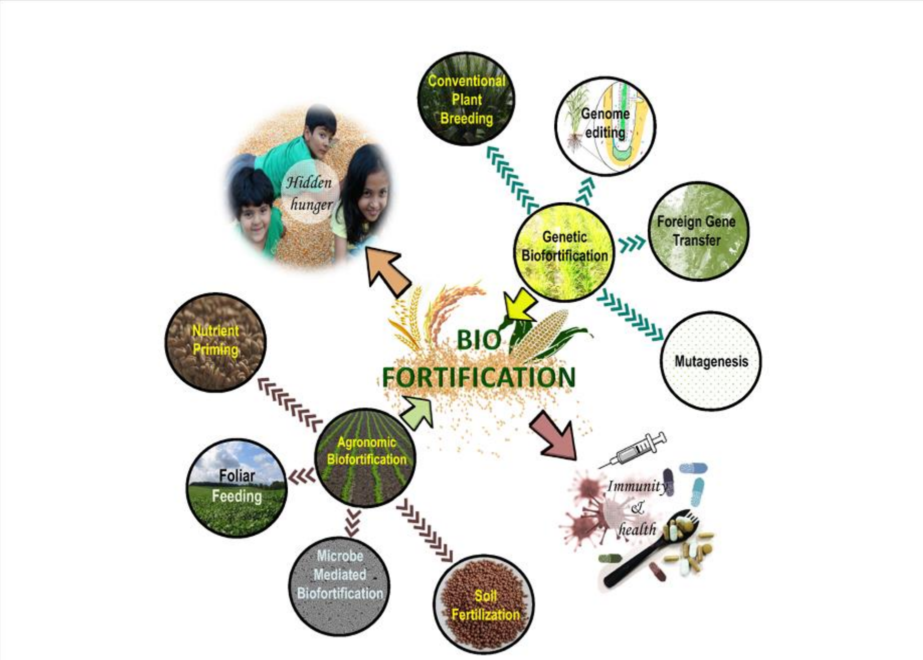



FIGURE 2
Conventional and advanced biofortification techniques used in crop production and improvement programs.

**1. Fortification:**

- **Definition:** Fortification is the process of adding essential vitamins and minerals (e.g., iron, zinc, vitamin A, iodine) to foods during processing to increase their nutritional value. This is often done in foods that are widely consumed, such as salt, flour, rice, and milk, to address specific nutrient deficiencies in a population.
- The nutrients are physically added to foods during the manufacturing or processing stage. For instance, iodized salt is produced by adding iodine to salt.
- **Objective:** The main goal of fortification is to enhance the nutrient profile of commonly consumed foods, particularly in regions or populations where dietary deficiencies are common. It is an external intervention aimed at improving the population's health.
- **Examples:**
    - Iodized salt (adding iodine to salt to prevent iodine deficiency and goiter).
    - Fortified milk (adding vitamin D to milk to prevent vitamin D deficiency and rickets).
    - Iron-fortified cereals (adding iron to prevent anemia).
- **Advantages:**
    - Can be implemented on a large scale to target specific nutrient deficiencies in the population.
    - Cost-effective and efficient in addressing micronutrient deficiencies.

- **Disadvantages:**
    - Relies on the food industry and proper regulations to ensure quality and consistency.
    - Not sustainable if the target population lacks access to the fortified foods.
    - May not reach rural or remote populations if fortified foods are not accessible.

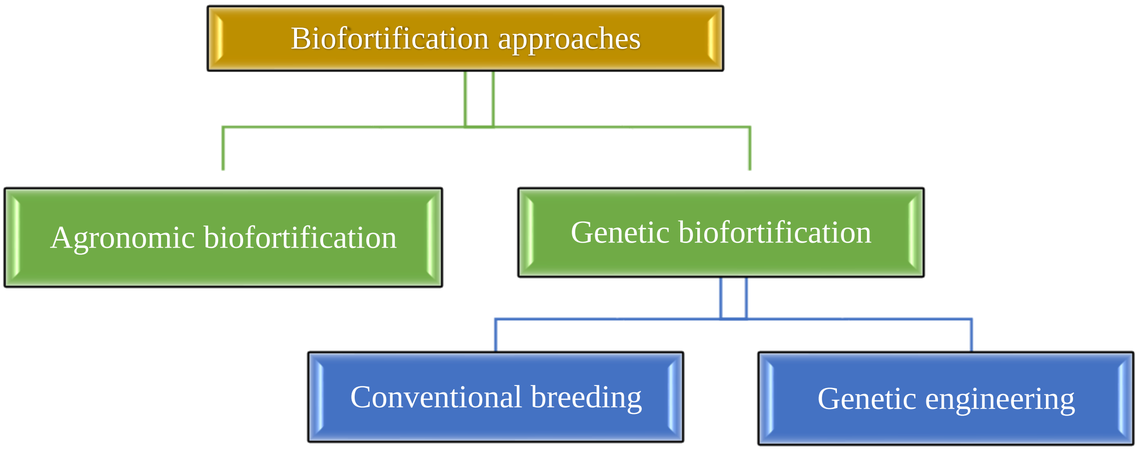
**2. Biofortification:**

- **Definition:** Biofortification is the process of increasing the nutrient content of crops during their growth, using either traditional breeding methods, genetic engineering, or agronomic practices (e.g., adding mineral fertilizers). This enhances the nutritional quality of food crops, making them richer in essential vitamins and minerals.
- Biofortification occurs through:
    - **Conventional Breeding:** Selecting and breeding plants that naturally have higher levels of a particular nutrient.
    - **Genetic Engineering:** Modifying the genetic makeup of crops to increase their nutrient content.
    - **Agronomic Biofortification:** Adding mineral fertilizers (e.g., zinc or selenium) to the soil where crops are grown.
- **Objective:** The aim is to provide sustainable, long-term solutions to malnutrition, particularly in developing regions where people rely on staple crops (like rice, wheat, maize) that may be low in essential nutrients.
- **Examples:**
    - Golden Rice (genetically modified to produce beta-carotene, a precursor to vitamin A).
    - Iron-rich beans (developed through conventional breeding).
    - Zinc-fortified wheat (achieved through soil enrichment techniques).
- **Advantages:**
    - Sustainable approach, as it focuses on improving the nutritional quality of food at the source.
    - Does not require continuous external inputs like in traditional fortification.
    - Can reach rural communities that rely on subsistence farming and have limited access to fortified foods.

- **Disadvantages:**
  - Takes time and resources to develop biofortified crops, especially when using traditional breeding techniques.
  - Acceptance by farmers and consumers can be challenging, especially with genetically modified crops.
  - May not provide sufficient nutrient levels for people with high nutritional needs.

**Differences Between Fortification and Biofortification:**

| Aspect | Fortification | Biofortification |
|---|---|---|
| **Process** | Adding nutrients during food processing. | Enhancing nutrient levels in crops during growth. |
| **Implementation** | Involves the food industry; external intervention. | Involves agricultural or breeding practices. |
| **Scope** | Limited to processed foods. | Applies to a wide range of crops, including staples. |
| **Target Population** | Urban and accessible rural areas where fortified foods are available. | Both rural and urban areas, especially where subsistence farming is common. |
| **Sustainability** | Relies on continuous addition of nutrients. | Provides long-term solutions through improved crops. |
| **Examples** | Iodized salt, fortified flour, vitamin D milk. | Golden rice, iron-rich beans, zinc-enriched wheat. |



**Biofortification:**

1. **Conventional Biofortification:**
    - This involves selecting and cross-breeding crop varieties that naturally have higher levels of a desired nutrient. Plant breeders use these varieties to develop crops that are richer in essential vitamins or minerals.
    - **Example:** Developing iron-rich beans through selective breeding of varieties with naturally higher iron content.
2. **Genetic Biofortification:**
    - This method uses biotechnology to introduce specific genes that enhance the nutritional profile of crops. Genetic engineering can be used to increase levels of vitamins, minerals, or other beneficial compounds that are not typically abundant in the crop.
    - **Example:** Golden rice, which is genetically engineered to produce beta-carotene.
3. **Agronomic Biofortification:**

- This technique involves applying mineral fertilizers or other soil treatments to crops to increase their uptake of essential nutrients. It does not alter the genetic makeup of the crops but enhances their nutrient absorption through improved soil conditions.
- **Example:** Adding zinc to soil to produce zinc-rich wheat.

Agronomic biofortification is done using micronutrient enriched fertilizers, and it is a simple and quick measure to increase the nutritional status of the crop, and consumption of such crops improves human nutrition status. Agronomic Biofortification generally relies on methods of fertilizer application, mineral element solubilization, and mobilization from source to sink (consumable parts of a plant). Nitrogen (N), phosphorus (P), and potassium (K) being macro minerals contribute toward higher yield goals. The increased drive to produce and use macronutrient fertilizers during the 1960s led to an immense increase in crop productivity and resulted in the green revolution which saved the world, particularly the developing countries, from starvation. In the present scenario, with a higher yield to feed around seven billion people focus is not only on producing more from limited resources but also to enrich consumable parts of the plant with micronutrients for good health. Micronutrients are found to varying degrees in different plant parts and are usually absorbed from the soil. The application of micronutrients as fertilizers can improve micronutrient status in the soil as well as correct their deficiency in plants and humans. Yet in many cases, micronutrients applied to the soil get immediately fixed and do not get readily translocated to the consumable plant parts. other means such as foliar sprays of soluble form is recommended then. If sufficient attention is given to some aspects, such as the fertilizer form, application method, and time of application, agronomic biofortification is a simple and inexpensive tool.

Agronomic biofortification using mineral fertilizers is feasible and can be exemplified by the success of Zn fertilization in Turkey, Se fertilization in Finland, fertilization in China. Agronomic biofortification has proved successful in many crops. The key advantage of agronomic biofortification over genetic biofortification is that the fertilizer forms and application techniques are crop non-specific. The fertilizer application rates and their mode of application can be quickly adapted from one crop to another while genetic and transgenic biofortification methods are crop specific, and therefore bringing more crops into the biofortified profile is highly time-consuming and resource exhaustive.

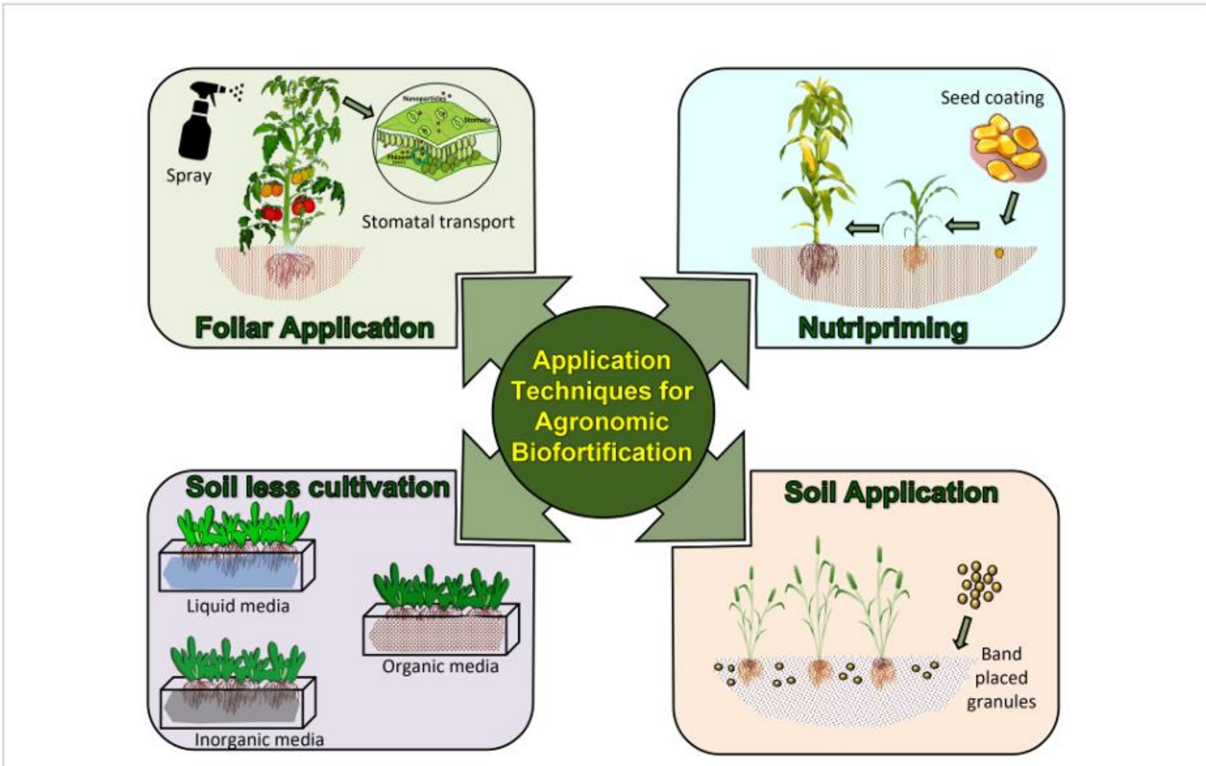
The Biofortification of crops and enhancing the bioavailability of nutrients in the edible component of the crop can help to prevent micronutrient deficiency. Biofortification of crops, whether agronomic or genetic, can be achieved with a little additional cost that is significantly less than the risk of hunger and malnutrition. Under the prevailing condition of the Covid-19 pandemic, micronutrient supplementation occupied center stage for providing an important role in providing resistance to respiratory virus infection (Calder, 2020).

Micronutrients support and influence each stage of an immune response. Micronutrient malnutrition can affect both innate and adaptive immunity, causing immune suppression and hence increasing susceptibility to infection (Gorji and Ghadiri, 2021). Inadequate nutritional status and infections have a synergistic relationship. An infection aggravates the nutritional deficiency status of the body and causes increased micronutrient demand (Al Sayah *et al.,* 2021). Viral infections are a major cause of morbidity and mortality throughout the world as demonstrated by seasonal influenza and the outbreak of the novel coronavirus (COVID-19).

Zinc being an essential micronutrient modulates the function of approximately 2000 enzymes and 750 transcription factors involved in different metabolic processes including immune response. Zinc also possesses a variety of antibacterial properties such as inhibition of RNA-dependant RNA polymerase enzyme that promotes replication of SARS-CoV-2 by pyrrolidine dithiocarbamate; a Zn ionophore, was found responsible for this inhibition. As the Zn cofactor functions in metalloenzyme, it also helps in maintaining the integrity of immune barriers. The cytotoxic nature of natural killer cells and cellular function, growth, and differentiation of innate immune cells is also influenced by the activity of Zn (Sheikh *et al.,* 2010;).

**Application techniques in agronomic biofortification:**

Several types of agronomic biofortification techniques have been tested for effectiveness worldwide. Of many, soil application of micronutrient fertilizer for plants to take up nutrients, foliar application using diluted fertilizer sprays, nutripriming, and soilless cultivation are the major techniques**.**




**1. Soil application:**

Soil application of micronutrients helps in replenishing the micronutrients in the soil on which a crop or plant is grown. This is a conventionally used technique. A higher application of micronutrients is recommended for crops that are quite sensitive to micronutrient deficiency. Soil application of micronutrients is a less efficient method of fertilizer application and increases the cost of production. The banding placement requires three times less micronutrient fertilizer as compared to broadcasting. Soil Zn fertilization may increase the yield of the crop but is comparatively less effective in increasing Zn content in grain as well as it has low fertilizer use efficiency. To address the micronutrient deficiency, adding Mo to the soil along with foliar treatments of $FeSO_4$-$7H_2O$ (0.5%) and $ZnSO_4$-$7H_2O$ (0.5%) significantly boosted cowpea production outcome, nodules plant$^{-1}$, root length, absorption, and nutrient concentration (Dhaliwal *et al.,* 2022).

It is claimed that soil application along with the foliar application is more effective and better to increase grain production compared to soil or foliar application alone. Several workers have demonstrated successful biofortification using soil application of micronutrient fertilizers. Though soil application is the most common method of micronutrient application to crops, it has mostly been tested for crop productivity improvement rather than biofortification. This method has low micronutrient use efficiency, less cost effectiveness, and pollutes soil over time due to excessive buildup of unused micronutrients.

**2. Foliar application**:

Foliar application is a preferred method over soil application for micronutrients due to minimal nutrient loss and direct absorption by plant tissues. It is particularly effective for increasing grain Zn content, with applications after flowering, during the early milk, and dough stages showing the most significant boost in grain Zn levels. Foliar Zn spraying also improves test weight and grain protein content in alkaline soils without affecting biological yield. Applying $FeSO_4$ during anthesis enhances grain protein and gluten content, especially with a seed rate of 125 kg ha$^{-1}$ in durum wheat. This approach is crucial in arid and semi-arid climates where water for irrigation and solubilizing soil-applied fertilizer is limited. Foliar Zn applications have been shown to increase grain Zn and Fe concentrations significantly and are more effective than soil applications in alkaline and calcareous soils. Studies indicate that foliar feeding can effectively biofortify wheat grains, reducing the phytic acid-to-Zn ratio while increasing Zn levels in flour. Additionally, applying a combination of Zn, Fe, B, and Cu through foliar sprays has been recommended for enhancing fruit quality and production in Mosambi orchards. Foliar application of nano-iron in soybean has also improved yield, seed quality, and drought tolerance. Overall, foliar feeding is a widely adopted, efficient, and straightforward method for micronutrient biofortification, requiring minimal infrastructure and technical expertise.

**3. Nutripriming**

- Nutripriming, or seed-priming, involves soaking seeds in a nutrient solution before planting to enhance germination, root development, seedling establishment, and yield. It has also been shown to improve grain nutrient content. For example, zinc nutripriming with $ZnSO_4$ can increase grain Zn content significantly in crops like chickpea and wheat. This method is cost-effective and environmentally friendly, as nutrients are applied directly to seeds before sowing.

- Various types of seed priming, such as hydro-priming and magneto-priming, have demonstrated benefits like stress relief and improved seedling growth. Zinc priming has been particularly effective, increasing yield and Zn content in grains. Nano-priming, which uses nanoparticles, is even more efficient due to its impact on seed cellular processes, such as activating enzymes that promote germination. Additionally, selenium priming has shown promise in reducing drought stress in crops like quinoa.
- The effectiveness of seed priming depends on factors such as crop type, priming duration, solution concentration, and environmental conditions. However, it may require technical knowledge and precise conditions, such as proper storage or immediate sowing, to maintain seed viability.

**4. Soilless cultivation**

Soilless cultivation uses inert media and nutrient solutions to grow crops, optimizing productivity by precisely controlling environmental factors like temperature, light, and nutrient concentration. This method includes hydroponics, aeroponics, and vertical farming, allowing year-round production without soil-related issues like fertility limitations and diseases. It also eliminates weeds, reduces labor, and enables easy harvesting and automation. Soilless systems are effective for enhancing plant nutrient content; for example, they have increased zinc and selenium levels in lettuce and cabbage. Microgreens grown in these systems are rich in micronutrients, helping combat deficiencies while enhancing flavor. Additionally, crops like cherry tomatoes and cucumbers have been successfully biofortified and cultivated efficiently with reduced resource use. Despite its efficiency and environmental benefits, soilless cultivation requires infrastructure that may not be accessible in all regions.

**Biofertilizers:**

Biofertilizers are microbial inoculants that promote plant growth and productivity by enhancing nutrient availability. These plant growth-promoting microorganisms are sustainable, cost-effective, and easy to produce. They aid in zinc biofortification in crops like corn, wheat, and soybeans, with species like *Azotobacter*, *Anabaena*, and *Bacillus aryabhattai* proving effective. Arbuscular mycorrhizal fungi, such as *Rhizophagus irregularis*, boost root development and nutrient uptake (e.g., P, N, Zn, Fe), while bacteria like *Pseudomonas spp.* enhance Fe uptake and overall plant growth. These microbes also secrete siderophores to increase Fe availability. However, challenges include identifying the right microorganisms for each crop and managing biofertilizer storage and application for consistent results across different agro-ecosystems.

**Nanofertilizers:**

Nanofertilizers, consisting of particles sized 1-100 nm, offer a targeted and efficient nutrient delivery system for crops, with high effectiveness due to their large surface area-to-volume ratio. They include materials like zinc oxide, silica, iron, and titanium dioxide, and can be engineered to address specific nutrient deficiencies. Studies have shown that nanofertilizers significantly enhance grain nutrient content and plant growth, such as zinc biofortification in wheat and manganese enrichment in soybean and *Vigna radiata*. For instance, zinc complexed chitosan nanoparticles (Zn-CNP) increased grain Zn levels even at lower concentrations compared to conventional fertilizers. Foliar applications of ZnO and Fe nanofertilizers have demonstrated increased nutrient content in plant tissues and grains. These fertilizers also enhance root growth and nutrient uptake efficiency without causing phytotoxicity, making them a promising, sustainable solution for agricultural nutrient management.

**Chelated fertilizers:**

Chelated fertilizers consist of nutrient ions surrounded by a macro-sized organic molecule (ligand) that protects the nutrients from immobilization, oxidation, and leaching. This makes them more efficient and environmentally friendly compared to inorganic fertilizers, ensuring higher nutrient uptake by plants. Chelated micronutrients like Zn-EDTA are particularly effective; for example, Zn-EDTA has shown better zinc biofortification in wheat than $ZnSO_4$ even at lower volumes. These fertilizers enhance plant growth, yield, and nutrient content, as seen with Zn chelates improving zinc and iron levels in wheat and lettuce. Chelates can also reduce heavy metal uptake, such as lowering cadmium levels while enriching zinc in contaminated soils. Studies have demonstrated that foliar applications of chelated nutrients at specific growth stages significantly improve crop development and yield compared to conventional fertilizers.

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# GREEN NANO PARTICLE SYNTHESIS FOR AGRICULTURAL ADVANCEMENT: APPLICATIONS AND IMPLICATIONS

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**Abstract:**

Nanotechnology holds significant potential for enhancing agricultural productivity through nano fertilizers, highly efficient herbicides and pesticides, wastewater management, and pathogen detection. However, conventional nanoparticle (NP) synthesis via physical and chemical methods is associated with high energy consumption, low yield, elevated costs, and environmental hazards. To mitigate these limitations, green or biosynthesis of nanoparticles using biological entities such as plants, animals, and microorganisms presents a more sustainable and eco-friendly alternative (Leon *et al.,* 2013). Green-synthesized nanoparticles have exhibited exceptional efficacy in agriculture by enhancing crop yield and quality, enabling targeted nutrient delivery, and facilitating early disease detection in plants. Therefore, advancing research on the green synthesis of nanoparticles and their agricultural applications is crucial for sustainable farming practices.

**Keywords:** Nano Technology, Green Synthesis, Nano Particles

**Introduction:**

The term "nano" originates from the Greek word *nanos*, meaning dwarf. In scientific and engineering contexts, "nano" is a prefix in the metric system denoting a factor of 0.000000001. One nanometer (1 nm) is equivalent to one billionth of a meter, approximately the distance a human fingernail grows in one second. A key characteristic of nanoparticles is their exceptionally high surface-area-to-volume ratio, which increases progressively as particle size decreases. This results in the dominance of surface atoms over interior atoms, significantly influencing both the intrinsic properties of the nanoparticle and its interactions with surrounding materials. The enhanced surface area imparts unique chemical, optical, mechanical, and magnetic properties to nanoparticles, distinguishing them from their bulk material counterparts.

## Terminologies

- **Nanotechnology**: The science and engineering of manipulating and structuring individual atoms and molecules to develop functional materials, devices, and systems with enhanced properties.
- **Nanoscience**: The study of fundamental interactions between physical properties and material dimensions at the nanometer scale, focusing on size-dependent phenomena.
- **Nanomaterials**: Materials with at least one dimension ranging from approximately 1 to 100 nanometers. The high surface-area-to-volume ratio of nanoparticles (NPs) imparts unique chemical, optical, mechanical, and magnetic properties, distinguishing them from bulk materials.

## Nano Pioneers

The origins of nanotechnology can be traced back to a lecture by American physicist Richard Feynman, titled *"There's Plenty of Room at the Bottom,"* delivered at an American Physical Society meeting at Caltech on December 29, 1959. This lecture is widely regarded as the conceptual foundation of nanotechnology. Feynman envisioned a process for manipulating individual atoms and molecules using progressively smaller tools at each stage, ultimately reaching the nanoscale. He also highlighted how scaling effects would alter physical phenomena, with gravity becoming less significant while surface tension and Van der Waals forces would gain prominence.

In 1974, Norio Taniguchi, a Japanese scientist from the Tokyo University of Science, was the first to formally use the term *"nanotechnology"* at a scientific conference. He described it in the context of semiconductor processes such as thin-film deposition and ion beam milling, which exhibited precision at the nanometer scale. Taniguchi defined nanotechnology as *"the processing, separation, consolidation, and deformation of materials by one atom or one molecule."*

Key milestones in nanotechnology include:

- **1986:** Gerd Binnig and Heinrich Rohrer invented the **Scanning Tunneling Microscope (STM)**, a breakthrough tool that enables the visualization and manipulation of matter at the nanometer scale.
- **2000:** Lucent Technologies and Bell Labs, in collaboration with Oxford University, developed the **DNA motor**, the first nano-biotechnological device.

**Nano Pioneers in India**

India has made significant strides in nanotechnology. The country's first dedicated nanotechnology magazine, "Nano Digest," is published from Hyderabad. Notably, Prof. C.N.R. Rao, regarded as the "Father of Indian Nanotechnology," has played a pioneering role in advancing the field.

Green Nanotechnology, a specialized branch of nanotechnology, focuses on developing environmentally sustainable technologies that minimize risks to human health and the ecosystem. Dr. Kattesh Katti, known as the "Father of Green Nanotechnology," pioneered the synthesis of gold nanoparticles using cinnamon and green tea. His research demonstrated that these nanoparticles are not only eco-friendly but also exhibit biological activity against cancer cells.

The two primary objectives of Green Nanotechnology are:

1. **Sustainable Nanomaterial Production** – Developing nanomaterials without adverse effects on human health.
2. **Eco-friendly Nano Products** – Creating nanotechnology-based solutions that address global challenges.

**What Matters at the Nanoscale**

Nanomaterials exhibit structural characteristics that lie between individual atoms and bulk materials. While most microstructured materials retain properties similar to their bulk counterparts, materials at the nanometer scale demonstrate significantly altered physical and chemical properties. This distinction arises primarily due to their nanoscale dimensions, which result in:

1. A large fraction of surface atoms
2. High surface energy
3. Spatial confinement
4. Reduced structural imperfections, absent in bulk materials

Due to their extremely small size, nanomaterials possess an exceptionally high surface-area-to-volume ratio. This means a significant portion of the atoms are located at or near the surface, leading to surface-dependent material properties. When nanomaterial dimensions approach critical length scales, surface properties begin to dominate, influencing the material's overall behavior. This can enhance or modify bulk properties; for instance, metallic nanoparticles serve as highly active catalysts, and chemical sensors based on nanoparticles or nanowires exhibit improved sensitivity and selectivity.

Additionally, the nanoscale dimensions introduce spatial confinement effects, leading to quantum phenomena. Nanomaterials also facilitate a self-purification process—impurities and intrinsic defects migrate toward the surface during thermal annealing. This improved structural perfection enhances various material properties, such as chemical stability and mechanical strength. For example, carbon nanotubes exhibit exceptional mechanical properties superior to those of bulk carbon-based materials. Due to their nanoscale size, nanomaterials possess unique properties, which have given rise to numerous novel applications.

**Nanoscale Fabrication Approaches**

Nanomaterials can be synthesized using two primary approaches:

**1. Bottom-Up Approach**

The bottom-up approach involves assembling materials from atomic or molecular building blocks to form nanostructures.

- Nanomaterials are constructed atom-by-atom or molecule-by-molecule through self-assembly.
- This method relies on chemical or physical forces at the nanoscale to arrange smaller units into larger, more complex structures.
- One key advantage is the ability to produce nanostructures with fewer defects and more uniform chemical compositions.

**Example:** The formation of carbon nanotubes through chemical vapor deposition.

**2. Top-Down Approach**

The top-down approach involves reducing the size of bulk materials through physical or chemical processes to obtain nanoscale structures.

- Larger materials are broken down into nanoscale components using mechanical, chemical, or lithographic techniques.
- Lithographic patterning, which employs short-wavelength optical sources, is a common top-down fabrication method.
- Mechanical attrition (milling) is a typical top-down method for producing nanoparticles.

However, a key limitation of the top-down approach is surface imperfections and significant crystallographic damage to processed patterns. The achievable nanostructure size through top-down techniques typically ranges from **10 to 100 nm**.

**Comparison of Approaches:**

| Approach | Methodology | Advantages | Examples |
|---|---|---|---|
| **Bottom-Up** | Assembly from atoms/molecules | Fewer defects, homogeneous composition | Carbon nanotube synthesis |
| **Top-Down** | Reduction of bulk material | Scalable but prone to defects | Lithography, milling |

Both approaches play essential roles in nanotechnology, with bottom-up methods favored for high-precision applications and top-down techniques used for scalable fabrication processes.

**Methods of Nanoparticle Synthesis**

Nanoparticles can be synthesized using three primary approaches:

1. **Physical Methods**
2. **Chemical Methods**
3. **Biological Methods**

**1. Physical Methods of Synthesis**

Physical techniques for nanoparticle synthesis involve mechanical or thermodynamic processes to produce nanoscale materials. These methods typically require sophisticated equipment and high energy input. Some key physical methods include:

- **Physical Vapor Deposition (PVD)**
- **Molecular Beam Epitaxy (MBE)**
- **Sputtering**
- **Laser Ablation**
- **Electric Arc Deposition**
- **Ion Implantation**
- **Etching**
- **Lithography**

While physical methods can yield high-purity nanoparticles, they often suffer from high operational costs and complex procedures.

**2. Chemical Methods of Synthesis**

Chemical synthesis involves controlled chemical reactions to form nanoparticles. Two widely used chemical synthesis techniques are:

**Sol-Gel Process**

- A widely used wet chemical method for producing ceramic and glass materials.
- This process involves the transformation of a colloidal solution (sol) into a semi-solid gel phase, followed by controlled drying and heat treatment.
- It enables the formation of various nanostructures, such as:
  - Ultra-fine powders
  - Thin-film coatings
  - Ceramic fibers
  - Microporous membranes
  - Aerogels

**Hydrothermal Method**

- A process that enables the growth of single crystals from mineral solutes dissolved in hot, pressurized water.
- Uses a **steel autoclave** with controlled temperature gradients to deposit solutes onto seed crystals, leading to nanoparticle formation.
- Operates under high temperatures (up to **500°C**) and pressures (**10–300 MPa**).

Chemical methods provide precise control over nanoparticle size and morphology but often involve hazardous chemicals and high energy requirements.

**3. Biological Synthesis of Nanoparticles**

Biological synthesis, also known as **green nanotechnology**, leverages biological agents to produce nanoparticles in an eco-friendly and cost-effective manner. It can be categorized into:

- **Use of plant extracts or enzymes**
- **Use of microorganisms (bacteria, fungi, algae, yeast)**
- **Use of biological templates (DNA, membranes, viruses, diatoms)**

**Plant-Based Nanoparticle Synthesis**

Conventional physical and chemical synthesis methods suffer from drawbacks such as high costs, energy consumption, and environmental hazards due to toxic chemicals. In contrast, plant-based synthesis offers a sustainable alternative, utilizing natural reducing and stabilizing agents present in plant extracts.

**Advantages of plant-mediated synthesis:**

- Low-cost cultivation
- Short production time

- Scalability for large-scale nanoparticle production
- Biodegradable and eco-friendly

Plant extracts contain diverse secondary metabolites such as **phenolic acids, flavonoids, alkaloids, and terpenoids**, which facilitate the reduction of metal ions into nanoparticles. These bioactive compounds also act as stabilizing agents, preventing aggregation and ensuring nanoparticle stability.

**Drawbacks of Physical and Chemical Methods**

Despite their effectiveness, traditional physical and chemical methods suffer from several limitations:

- High cost and labor-intensive procedures
- Significant energy consumption
- Time-consuming synthesis processes
- Use of hazardous chemicals and limited resource efficiency

**Advantages of Biological Nanoparticle Synthesis**

The biological synthesis of nanoparticles offers multiple benefits over conventional methods:

✅ Cost-effective and energy-efficient

✅ Environmentally friendly and non-toxic

✅ Biocompatible and safe for medical applications

✅ Rapid synthesis with high-yield production

By integrating biological synthesis techniques, researchers can develop nanomaterials that are sustainable, scalable, and suitable for diverse applications, including medicine, agriculture, and environmental remediation.

**Green Synthesis of Nanoparticles**:

Green synthesis is an environmentally friendly approach for the development of nanoparticles (NPs), utilizing natural resources such as plant extracts, microorganisms, and energy-conserving processes. This method is widely recognized for its sustainability, cost-effectiveness, and non-toxic nature, making it a superior alternative to traditional chemical and physical synthesis techniques. The principles of green nanotechnology emphasize energy efficiency, waste minimization, and the reduction of greenhouse gas emissions. Furthermore, the use of renewable biological materials significantly decreases environmental pollution and enhances the sustainability of nanoparticle production.

Green synthesis of nanoparticles leverages the biological molecules present in plant extracts and microorganisms to mediate the reduction of metal ions into their respective nanoparticles. The reaction rates for plant-mediated nanoparticle synthesis are considerably higher, typically occurring within a few minutes to hours, under mild conditions such as room temperature. Due to the simplicity of recovery and purification processes, plant-based synthesis has become a widely adopted method for producing high-quality nanoparticles. The process typically involves plant extraction, filtration, and the addition of metal NP salts, followed by continuous stirring, leading to the formation of nanoparticles that can be recovered from the resulting precipitate.

**Applications of Green-Synthesized Nanoparticles in Agriculture**

The integration of nanotechnology into agriculture has significantly contributed to sustainable development, enhancing agricultural productivity through the development of nano-fertilizers, nano-pesticides, and nano-herbicides. These nanoparticle-based formulations offer precise nutrient delivery, improving plant growth while minimizing environmental contamination. Additionally, nano-materials are extensively used for plant protection as nano-sensors, nano-herbicides, and nano-pesticides, which aid in detecting and mitigating plant diseases and pests efficiently. Nano-nutrients and nano-fertilizers have shown remarkable effects on germination rates, plant growth, and yield, while also reducing phytotoxicity in various crops and vegetables.

Despite their numerous advantages, nanoparticles pose potential risks to human health due to their ultra-small size, which allows them to enter the human body through inhalation or ingestion. Once inside, they may circulate in the bloodstream and accumulate in critical organs such as the heart, liver, and blood cells. While some nanoparticles exhibit non-toxic or beneficial effects, others may induce adverse biological responses, such as protein denaturation, reactive oxygen species (ROS) generation, impairment of phagocytic functions, and mitochondrial dysfunction. Chronic exposure to nanoparticles has also been linked to immune system disruptions, organ enlargement, and dysfunction.

**Biological Synthesis of Nanoparticles**

Green synthesis of nanoparticles can be broadly classified into three categories based on the biological source used: plant-mediated, animal-derived, and microbial-mediated synthesis. Each of these methods involves unique biochemical pathways that enable the reduction and stabilization of metal nanoparticles.

## 1. Plant-Based Synthesis of Nanoparticles

### Angiosperms

Angiosperms, being the most diverse and widely available plant group, are extensively utilized for the green synthesis of nanoparticles. Their abundant phytochemicals, including flavonoids, alkaloids, terpenoids, and polyphenols, facilitate the reduction of metal ions into nanoparticles. Angiosperm-derived nanoparticles are widely studied due to their accessibility, medicinal properties, and diverse applications. Several plant species have demonstrated remarkable efficiency in synthesizing metal nanoparticles, particularly gold (Au) and silver (Ag) nanoparticles, owing to their strong reducing capabilities.

- ***Camellia sinensis* (Green Tea):** Rich in catechins and theaflavins, which play a crucial role in the synthesis of Au NPs.
- ***Jatropha curcas* L.:** Contains cyclic peptide molecules that efficiently reduce metal cations, contributing to nanoparticle formation.

### Gymnosperms

Gymnosperms, as the first group of plants to develop seeds, possess unique metabolites responsible for the reduction of metal ions into nanoparticles. Research on gymnosperm-mediated green synthesis remains limited but has shown promising results.

- ***Thuja orientalis*:** This plant extract has been successfully used to synthesize gold nanoparticles with an impressive reaction efficiency of 90% within just 10 minutes. The nanoparticles produced were predominantly round in shape and crystalline in nature.

  **Algae-Based Synthesis**

  Algae are photoautotrophic organisms capable of synthesizing nanoparticles through bio-reduction mechanisms. The primary factors influencing the efficiency of algae-mediated nanoparticle synthesis include the presence of reducing agents, stabilizing capping agents, and solvent compatibility.

- ***Spirulina platensis* (Blue-Green Algae):** Used for the synthesis of gold and silver nanoparticles due to its rich bioactive compounds.
- ***Tetraselmis kochinensis*:** Effectively mediates gold nanoparticle formation through bio-reduction.

### 2. Animal-Derived Nanoparticles

**Silk Proteins**

Silk fibroin, a semi-crystalline polymer composed of amino acids such as glycine, alanine, and serine, is widely utilized in biomedical applications, including tissue engineering for bones, skin, muscles, and blood vessels. Due to its non-toxic and non-immunogenic properties, fibroin is employed in the synthesis of nanocomposites, such as fibroin-$TiO_2$ and nano-hydroxyapatite silk fibroin composites, which exhibit remarkable crystalline structures and stability.

Another silk-derived protein, sericin, which is found in the effluents of silk industries, has also been utilized for nanoparticle synthesis. Through ultrasonication, nano-sericin powder with significantly reduced particle size can be obtained.

**Chitosan**

Chitosan, derived from invertebrate chitin, has a wide range of applications in medicine, textiles, and environmental remediation. Nano-chitosan has been utilized in controlled drug release, vaccine delivery, and cancer therapy. It also plays a significant role in wastewater treatment due to its strong adsorption capabilities.

- **Magnetic chitosan:** Used for removing organic dyes from wastewater due to the presence of hydroxyl and amino groups that enhance adsorption rates when combined with $Fe_3O_4$ magnetic properties.
- **Bentonite-chitosan nanocomposites:** Effective in removing synthetic dyes from industrial wastewater.

### 3. Microbial-Based Nanoparticle Synthesis

Microbial synthesis of nanoparticles offers a sustainable and cost-effective alternative to chemical methods. The process occurs through intracellular or extracellular mechanisms:

- **Intracellular Mechanism:** Metal ions penetrate bacterial cell walls and are reduced by intracellular enzymes, leading to nanoparticle formation within the cell.
- **Extracellular Mechanism:** Fungal enzymes, such as nitrate reductase, catalyze the reduction of metal ions outside the cell, forming nanoparticles in the surrounding medium.

  Examples:
- **Fusarium oxysporum:** Produces silver and gold nanoparticles when exposed to tetrachloroaurate and silver nitrate solutions.

- **Aspergillus flavus:** Capable of synthesizing silver nanoparticles with an average size of approximately 8 nm.

**Procedure for Green Synthesis of Nanoparticles**

1. **Preparation of Plant Extract**
   - Collect fresh leaves, wash them thoroughly, and cut them into small pieces.
   - Take **25 g** of plant material and boil it in **100 mL** of deionized water at **80–90°C**.
   - Filter the extract to serve as a reducing and capping agent.
2. **Nanoparticle Formation**
   - Dissolve **20 mg of copper nitrate** in **50 mL** of deionized water at **60–70°C**.
   - Slowly add the plant extract dropwise, observing the color change to light green, indicating NP formation.
3. **Separation and Characterization**
   - Isolate the nanoparticles through precipitation and purify them.
   - Characterize them using **UV-Vis spectroscopy, TEM, SEM, and XRD**.

**Characterisation of nano particles**

Over the past few decades nano size and nano dimensional materials whose structures exhibit significantly novel and improved physical, chemical and biological properties, phenomena and functionality due to their nano scaled size, have drawn much attention. Nanotechnology is an emerging interdisciplinary area that is expected to have wide ranging implications in all the fields of science and technology such as material science, mechanics, electronics and also attracting a great deal of attention of the textile and polymer researchers and industrialists because of their potential applications for achieving specific processes and properties, especially for functional and high-performance textiles applications.

Nanoparticle characterisation methods are required to cover a range of requirements, from long term environmental monitoring campaigns over entire continents where only basic properties are measured, to one-off laboratory measurements on specially prepared samples where a full chemical and physical analysis is performed.

Characterisation techniques can be subdivided by both general measurand and the phase in which the nanoparticles reside. Measurements of each type present their own difficulties and often have subtly different interpretations. Moreover, comparison of results between phases is very difficult, and matrix effects can be significant due to the high surface area to mass ratio of nanoparticles. The techniques presented below give a general overview of common measurements made on nanoparticles for a range of applications.

**Scanning Electron Microscope:**

A scanning electron microscope (SEM) is a type of electron microscope that produces images of a sample by scanning the surface with a focused beam of electrons. The electrons interact with atoms in the sample, producing various signals that contain information about the surface topography and composition of the sample. The electron beam is scanned in a raster scan pattern, and the position of the beam is combined with the intensity of the detected signal to produce an image. In the most common SEM mode, secondary electrons emitted by atoms excited by the electron beam are detected using an Everhart-Thornley detector. The number of secondary electrons that can be detected, and thus the signal intensity, depends, among other things, on specimen topography. SEM can achieve resolution better than 1 nano meter.


**UV-Visible spectrophotometer:**

UV-Visible spectrophotometer refers to absorption spectrophotometer in the ultra- violet and visible spectral region of the electromagnetic spectrum, where molecules undergo electronic transition. When sample molecules are exposed to light having an energy, that matches a possible electronic transition within the molecule, some of the light energy will be absorbed as the electron is promoted to a higher energy orbit. An optical spectrophotometer records the wavelengths at which absorption occurs, together with the degree of absorption at each wavelength. The resulting spectrum was presented as a graph of absorbance (A) versus wavelength (λ). The optical properties of materials could be studied with the help of UV-Visible spectrophotometer.

**Conclusion:**

The advancement of nanotechnology has revolutionized various industries, with green synthesis emerging as a sustainable, eco-friendly, and cost-effective approach to nanoparticle production. Utilizing biological entities such as plants, microorganisms, and animal-derived materials, green synthesis minimizes environmental hazards, energy consumption, and toxic byproducts while enhancing biocompatibility and functionality. Its applications span across medicine, agriculture, and environmental remediation, improving drug delivery, crop productivity, and pollutant removal. However, challenges like large-scale production, reproducibility, stability, and potential toxicity require further research. The future of green nanotechnology lies in integrating artificial intelligence, machine learning, and computational modeling to optimize synthesis techniques and expand applications. By prioritizing safety, sustainability, and ethical considerations, green nanotechnology can drive innovation while ensuring minimal ecological and health risks.

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# EMERGING INNOVATIONS AND ECONOMIC DYNAMICS IN AGRICULTURAL RESEARCH

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## 1. Introduction:

Agriculture has been the backbone of human civilization, evolving over millennia to feed growing populations. Today, rapid advancements in research and economics are shaping the future of farming, with an emphasis on sustainability, productivity, and resilience. Agricultural economics plays a crucial role in ensuring food security, optimizing resource allocation, and improving farmers' livelihoods. This chapter explores the latest trends in agricultural research and their economic implications, providing a data-driven perspective on innovations that impact farming communities worldwide.

**Keywords:** Agricultural research, Agricultural economics, Climate-resilient crops, Organic farming, Regenerative agriculture, Precision agriculture, Cost efficiency in farming, Agroforestry, Sustainable pest management, Biopesticides, Soil microbiome research, Water conservation techniques, Drip irrigation, Farm income diversification, Market trends in agriculture, Food security, Sustainable farming practices, Economic impact of agriculture, Fertilizer cost reduction, Resource allocation in agriculture.

## 2. Climate-Resilient Crops and Economic Viability

With climate change posing significant challenges to global food security, researchers are focusing on developing crop varieties that can withstand extreme weather conditions. Drought-resistant wheat, flood-tolerant rice, and heat-resistant maize are among the innovations achieved through selective breeding and genetic refinement. These breakthroughs ensure stable yields despite erratic climate patterns, helping farmers adapt to environmental uncertainties.

### 2.1 Economic Impact

A study by the Indian Agricultural Research Institute (IARI) found that newly developed wheat varieties, such as HD 3226 and HD 3298, exhibit greater tolerance to drought conditions, leading to a 20% increase in yields. This results in an estimated increase in farm income by $200 per hectare annually (Sharma *et al.,* 2021). Globally, climate-resilient crop adoption has led to a reduction in crop failure rates by 35%, improving overall economic stability for farmers (FAO, 2022).]

**3. Organic and Regenerative Farming: Economic Sustainability**

The resurgence of organic and regenerative farming is a direct response to the detrimental effects of chemical-intensive agriculture. Researchers are exploring ways to improve soil health through natural fertilizers, crop rotation, and cover cropping. Organic farming can enhance farmers' incomes due to increasing consumer demand for chemical-free products.

**3.1 Market Analysis**

According to a study by the Rodale Institute (2020), organic farming methods result in 30% higher soil organic matter and a 20% increase in farm profits compared to conventional farming, driven by premium pricing and lower input costs. The global organic food market was valued at $188 billion in 2022 and is projected to grow at an annual rate of 10.5%, providing long-term economic benefits for farmers transitioning to organic practices (Market Research, 2023).

**4. Precision Agriculture and Cost Efficiency**

Precision agriculture has gained momentum in recent years, optimizing input usage and improving efficiency. Technologies such as soil sensors, remote sensing, and automated irrigation help farmers reduce costs while maintaining productivity.

**4.1 Cost-Benefit Analysis**

In Kenya, small-scale farmers utilizing precision techniques have reduced fertilizer costs by 25% and increased yields by 15%, leading to a net gain of $300 per hectare annually (FAO, 2021). In the United States, precision farming has contributed to a 50% reduction in water usage and a 20% increase in crop yields, demonstrating significant economic advantages (USDA, 2022).

**5. Agroforestry and Economic Diversification**

Agroforestry integrates trees within farming systems, promoting biodiversity while generating additional revenue streams. It offers long-term economic sustainability for farmers by providing timber, fruit, and medicinal plants alongside staple crops.

**5.1 Income Diversification**

India's National Agroforestry Policy has led to a 12% increase in farmer income while improving biodiversity conservation (Government of India, 2020). A global study found that agroforestry practices contribute to a 25% increase in annual farm income through diversified production streams (World Bank, 2022).

**6. Sustainable Pest and Disease Management: Reducing Costs**

Chemical pesticides and herbicides have caused severe environmental and health concerns. Researchers are now turning to biopesticides, companion planting, and integrated pest management (IPM) to combat infestations naturally.

**6.1 Financial Implications**

A study published in the Journal of Agricultural Sciences (2022) found that neem-based biopesticides reduced pest populations by 40% while lowering pesticide costs by 30%, enhancing farmers' net profit margins. The global biopesticide market was valued at $6.5 billion in 2021 and is projected to reach $12 billion by 2027, underscoring its growing economic potential (Agricultural Market Reports, 2023).

**7. Soil Microbiome Research and Fertilizer Cost Reduction**

Soil microbiome research highlights the role of beneficial microbes in enhancing soil fertility, improving nutrient uptake, and reducing the need for synthetic fertilizers.

**7.1 Economic Benefits**

Research shows that Rhizobium bacteria in leguminous crops enhance nitrogen fixation, reducing fertilizer expenses by 25%, saving farmers an average of $150 per hectare annually (Singh *et al.,* 2021). A recent analysis found that microbiome-enhanced soils lead to a 40% reduction in synthetic fertilizer dependency, translating to a $10 billion reduction in global agricultural input costs (FAO, 2023).

**8. Water Conservation Techniques and Economic Efficiency**

Given increasing water scarcity, agricultural research is focusing on efficient irrigation methods such as drip irrigation, rainwater harvesting, and conservation tillage.

**8.1 Cost-Effectiveness**

A report by the International Water Management Institute (2021) found that drip irrigation reduces water usage by 50% while increasing crop yields by 30%, translating to an annual cost saving of $400 per hectare for farmers in arid regions. The World Economic Forum (2023) estimates that widespread adoption of water conservation practices could reduce global agricultural water consumption by 20%, saving $50 billion annually in water management costs.

**Conclusion:**

Agricultural research continues to advance, driven by human expertise and economic considerations. The integration of research with agricultural economics ensures that new developments contribute not only to sustainability but also to farmers' profitability. The latest trends in agriculture underscore the importance of economic viability in decision-making, ensuring a resilient and prosperous food system for future generations.

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# CULTIVATION OF DRAGON FRUIT TOWARDS BOOSTING RURAL ECONOMY OF DAKSHIN DINAJPUR

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**Abstract:**

Dragon fruit, *Hylocereus costariensis* (pitaya roja) red fleshed with red skin, *H. undatus* (pitaya blanca) white fleshed with pink skin and *H.megalanthus* (pitaya amarilla) white fleshed with pink skin are major species cultivated by the farmers of India. Cultivation of Dragon fruit in Dakshin Dinajpur remarkably changed the economy of the area placing the district at the top of this perennial super fruit producer districts of West Bengal. The old alluvial soil, pH between 5.5 to 6.5, high temperature in summer (upto $42^0$ C), planting time being April to September is conducive of considerable high yield up to earn up to Rs.11,10,000 per annum bigha$^{-1}$, as observed in the study area. The stem cuttings mature to flower in 15 to 18 months, flowers are nocturnal, cream-white, showy, sweet smelling and crop cycle is from April to November with 25 to 100 fruits/plant in 4 to 6 flashes. Once planted, fruits can be up to 20 to 40 years. Present investigation is based on first hand interactive sessions with the cultivators for 4 years and thrust of knowledge on cultivation of this excellent immunity boosting nutritional fruit with immense medicinal as well as economical value.

**Keywords**: Dragon Fruit, Farmers, *Hylocereus*, Immunity, Medicinal, Pitaya

**Introduction:**

Fruit crops are crucial for raising land productivity and farmers' economic standing since they create jobs, boost income, and ensure nutritional security. India is the second largest fruit producing nation in the world. Cultivation of Dragon fruit has been observed to be suited for various agro-climatic regions of Southern, Western and North Eastern India that includes states like, Gujarat, Tamil Nadu, Maharashtra, Orissa, Andhra Pradesh, Karnataka, Andaman and Nicobar Islands, Punjab, Kerala, Assam and West Bengal. Due to its resilient nature, this fruit crop can withstand the harsh climate of arid and semi-arid regions of India (Perween *et al.,* 2018). Due to its steadily gaining demand, cultivation of Dragon fruit has become a viable commercial proposition. *Hylocereus undatus* (Haw.) Britt.

& Rose is the most widely cultivated species in India followed by *H. costaricensis*. In a few districts in West Bengal, like Nadia, Dakshin Dinajpur and others, farmers are opportunistic to become self reliant by cultivating this exotic immunity boosting fruit, commonly known as pitaya. But the most successful growers belong to Dakshin Dinajpur (N 25° 12' 27.1073", E 88° 46' 7.0975") district of West Bengal. This agri- based zone shares its border with Bangladesh. Until a few years back, there was hardly any awareness about the cultivability of Dragon Fruit in this area. Jb. Abdul Monim Miah, an Ex-Services personnel, from Bangshihari Block of the district pioneered the cultivation of Dragon Fruit in this locality in 2012, vocationally planting only 4 stem cuttings that he collected from a source across the border, in Bangladesh. His success encouraged many other farmers to follow suit. Now, the District, with all 8 blocks, can boast of being the only Dragon Fruit growing district in the northern part of the state. This long day flowing plant was originated in Central America. In twentieth century, dragon fruit started gaining popularity in South Asian country, Malaysia. It is largely cultivated in countries like Taiwan, South Florida, Thailand, Vietnam, China, Sri Lanka, Philippines, Australia, Bangladesh, Nicaragua and Israel.

Present investigation is based on first hand interactive sessions with the cultivators of Balurghat, Tapan, Kumarganj, Bangshihari, Gangarampur, Buniadpur, Kushumundi, Harirampur and Hili area of Dakshin Dinajpur over the last four years and thrust of knowledge on cultivation of this excellent immunity boosting nutritional fruit with immense medicinal as well as economical value.

**Nutritional and Medicinal Value**

Dragon Fruit or Pitaya is an exotic tropical plant that offers many benefits to human health due to its nutritious value and biologically active compounds containing powerful natural antioxidants.

The fruit looks and tastes very attractive with its bright red skin, seed-speckled interior and great natural sweetness. Health conscious food lovers are also attracted by its super food characters. The low calorie fruit packs a punch in high dietary fiber and content of essential minerals. Polyphenols, carotenoids, flavonoids, vitamin B1, B2, B3, calcium and phosphorus, fatty acid, vitamin C, beta-carotene, lycopene, betalain and betacyanins are amongst other added benefits delivered by this wonder package. Its high content of antioxidants is highly beneficial for the prevention of cell damage and chronic ailments. A matter that attracts special mention, in the current scenario arising out of the catastrophe Covid19 onslaught, is its high immunity boosting capability. Over and above, the prebiotic content of this fruit supports and augments the capacity of the gut health in humans, by aiding the growth of healthy bacteria. Being rich in iron, the fruit plays a vital role in the body's oxygen transportation. Dragon fruit is a rich source of magnesium as well. Consumers are overwhelmed by the exotic nature of Dragon fruit with its bright red skin and greenish scales. Proximate nutraceutical values in g or mg per 100 g edible portion of white-flesh dragon fruit are as follows: moisture (85.3 %), protein (1.1), fat (0.57), crude fiber (1.34), energy (Kcal) (67.7), ash (0.56), carbohydrates (11.2), glucose (5.7), fructose (3.2), sucrose (not detected), sorbitol (0.33); vitamin C (3.0), vitamin A (0.01), niacin (2.8), Ca (10.2), Fe (3.37), Mg (38.9), P (27.75), K (272.0), Na (8.9) and Zn (0.35) and for red-flesh fruit, moisture (82.5-83.0), protein (0.1590.229), fat (0.21-0.61), crude fiber (0.7-0.9) and ascorbic acid (8-9) (Jaafar *et al.,* 2009). In order to develop the nutritional composition data for dragon fruit and compare the differences between *H. undatus* and *H. polyrhizus*, the nutritional and biochemical composition of the two species of dragon fruit (*Hylocereus*)—*H. undatus*, which have white pulp and pink skin, and *H. polyrhizus*, which have red pulp and pink skin—was examined by Arivalagan *et al.* (2021).The contents of dietary fiber, protein, ash, moisture, pH, TSS, and total sugar ranged from 4.8 to 5.4, 8 to 12%, 5.13 to 7.06%, 82 to 85%, 0.7 to 0.85%, 0.90 to 1.1%, and 0.8 to 1.0%, respectively.

The content of flavonoids and total phenolics ranges from 15–35 mg CE and 25–55 mg GAE per 100 g, respectively. Compared to *H. undatus*, *H. polyrhizus* has a substantially higher quantity of phenolics and antioxidant potential. About 120–200 mg K, 3045 mg Mg, 20–45 mg Ca, and 0.70-1.5 mg Fe, 0.20-0.40 mg Zn, and 20-35 mg P.A maximum of 6 mg/100 g of vitamin C was detected, followed by 150 µg of vitamin E, 50 µg of pantothenic acid, and 25 µg of vitamin K1 were present in 100 g of fruit. It is possible to extract the phytoconstituents from the fruit's seeds, peel, and flesh. The fruit is well-known for being high in lycopene, vitamin C, and betacyanin. The treatment of many illnesses and the enhancement of human health in general depend heavily on phytoconstituents. Dragon fruit is believed to have anti-cancer, anti-microbial, anti-diabetic, and antioxidant properties. Additionally, the fruit can be used as a nutraceutical, or functional food (Joshi and Prabhakar 2020). According to Nishikito (2023) pitaya's bioactive compounds—which may include vitamins, potassium, betacyanin, p-coumaric acid, vanillic acid, and gallic acid can help treat a number of illnesses, including diabetes, dyslipidemia, metabolic syndrome, cardiovascular diseases, and cancer. Due to its low calorie content, it is the perfect fruit for preserving health. Because of its incredibly appealing fruit colour, nutritional value, and enormous bioactive potential, pitaya (*Hylocereus* spp.) is found to lower blood sugar, cholesterol, and prevents liver damage, cancer, and other negative effects. To create nutritionally rich value-added products and simultaneously lessen the problems brought on by waste generation and spoiling, it is crucial to process both the edible and non-edible portions (Tarte 2023).

This plant's main bioactive components were phenolic compounds like α-amyrin (15.87%) and β-amyrin (13.90%). There are also anti-inflammatory, antifungal, antibacterial, hypolipidemic, antiviral, thrombolytic, antiplasmodial, anticancer, hepatoprotective, antidiabetic, cardioprotective and antioxidant properties in *H. polyrhizus*. (Chowdhury *et al.,* 2024).

In healthy individuals, endothelial function and arterial stiffness were improved by acute and brief consumption of dragon fruit in dietaryly achievable amounts. This suggests that because dragon fruit has a high betalain content, regular consumption may have a significant effect on the risk of cardiovascular disease (Cheok *et al.,* 2022). Its remarkable antioxidant capacity, which is essential for reducing the risk of developing chronic illnesses.

Numerous phytochemicals, which act as antioxidants and combat harmful free radicals, are found in the fruit. The body is protected from the effects of oxidative stress by this protective action. Interestingly, the dragon fruit's bark has an even greater concentration of bioactive substances with strong antioxidant qualities. From a pharmacological and nutritional perspective, this unique characteristic is highly intriguing as it may provide a natural source of antioxidants for a range of medicinal uses (Rathi *et al.,* 2023).

According to Ho *et al.,* (2024) obesity is one of the main risk factors for metabolic syndrome (MetS), which greatly increases the risk of premature death. Dragon fruit, which is grown all over the world, shows bioactivity in reducing disorders linked to obesity. Conventional research employing organic solvents for extraction is inconsistent with real-world usage trends. The agricultural economic worth of red dragon fruit is increased by these discoveries, which support the use of entire fruits in the creation of functional products.

Stems, flowers, peeling, dragon fruit pulp extracts are useful not only for diseases such as diabetes, obesity, hyperlipidemia, cancer, but also for pathogenic microorganisms such as bacteria, fungi, viruses, etc. In addition, dragon fruit extracts have cardiovascular and hepato protection properties, as well as prebiotic potential (Luu *et al.,* 2021). The fruits from both origins, Israel and Thailand, were analyzed by Paśko *et al.,* (2021), exhibited strong cytotoxic activity against prostate and colon cancer cells, but no anti-inflammatory or toxic effect on healthy cells. Moreover, water extracts of dragon fruits showed a high binding ability to HSA. All of these predestined dragon fruits are potential additions to a daily diet that are both aesthetically pleasing and chemopreventive.

The fruit's (*Hylocereus* spp.) antioxidant, anti-inflammatory, and anti-microbial qualities are attributed to its abundance of bioactive phytochemical components, such as flavonoids, phenolic acids, and pigments like betalains and anthocyanins. In order to develop best practices for producers, future research must prioritise understanding how environmental conditions and production practices affect the bioactive composition of dragon fruit (Chen *et al.,* 2024).

**Classification**

The plant belongs to Kingdom- Plantae, Sub kingdom- Tracheobionta, Division-Tracheophyta, Super Division- Spermatophyta, Division-Magnoliophyta, Class-Magnoliopsida, Order- Caryophyllales, Family- Cactaceae, Tribe- Hylocereeae, Genus *Hylocereus* (A. Berger) Britton & Rose, Species *H. undatus* (Haw.) Britton & Rose. The plant is a spiny succulent with photosynthetic, triangular glaucous stem, freely branched, jointed, hanging epiphytic, apparently leafless with areal roots, flowers large, nocturnal, showy, solitary, hermaphrodite, epigynous, stamens indefinite, carpels syncarpous, unilocular inferior ovary with parietal placentation, fruit is a berry. Fruit is red and covered with spiky growth. According to Fournet (2002), the primary characteristic of this genus is its climbing vine nature with aerial roots that contain a glabrous, attractive berry with numerous scales. According to the classification of Britton and Rose (1963). *H. purpusii* (Weing.) Britton and Rose - bears scarlet, oblong fruit covered with large scales (length: 10–15 cm; weight: 150– 400 g); red flesh with many small black seeds; pleasant flesh texture, but not very pronounced. *H. polyrhizus* (Web.) Britton and Rose - bears scarlet oblong fruit (length:10– 12cm; weight:130–350g) covered with scales that vary in size; it has a red flesh with many small black seeds, pleasant flesh texture and good taste. *H. costaricensis* (Web.) Britton and Rose – vigorous vines, perhaps the stoutest of this genus. Stems are waxy white and flowers are nearly the same as *H. polyrhizus*; *H. undatus* (Haw.) Britton and Rose - has rosy-red oblong fruit (length: 15–22 cm; weight: 300–800 g) is covered with large and long scales, red and green at the tips; it has a white flesh with many small black seeds, pleasant flesh texture and a good taste. *H. trigonus* (Haw.) Saff – bears red fruit (diameter: 7–9 cm; weight: 120– 250 g) is ovoid or oblong, nearly smooth; the white flesh has many small black seeds and pleasant flesh texture, but not a very pronounced flavor.

A study by Abhirami *et al.* (2021) using morphological (34 quantitative and 26 qualitative features), biochemical (5 attributes), and molecular (14 ISSR primers) characterisation to identify three dragon fruit species that are well suited to Andaman & Nicobar Island. According to morphological characterisation, there are a significant number of genetic variants among them, particularly with regard to fruit characteristics like peel and pulp colour. Three *Hylocereus* species under investigation may be identified using cladode characteristics, such as the number of spines (3-5), the length of the areoles (mm) as 1-4, the convex or concave edge ribs of the cladode, and its waxiness (weak or strong white waxy or light waxy). The pulp weight had the highest coefficient of variation (%) at 88.7%, while the anther distance below the stigma had the lowest (3.3). Dragon fruit varieties can be identified using metabolite profiles. Secondary metabolites differ both qualitatively and quantitatively amongst species. By-products of dragon fruit production are a natural source of a number of glycosylated flavonoids. Depending on the type, dragon fruit plants can contain a variety of flavonoids. (Kamikawachi *et al.,* 2023).

**Planting and Planting Pit Material**

Soil and weather for cultivation of *Hylocereus* spp. in Dakshin Dinajpur district of West Bengal is favorable for a considerably high yield. The old alluvial soil, pH between 5.5 to 6.5, high temperature in summer (up to $42^0$ C), planting time being April to September is conducive for vegetative and reproductive growth.

The planting pit material comprises of 40 Kg vermi compost (or equal quantity of dried cow dung) mixed with 750g single super phosphate, lime 400g, Neem oil cake 300g (pre decomposed), Mustard oil cake 500g (pre decomposed), Sterameal (or any suitable micro nutrient mixture) 200g. This mixture will fill one pit accommodating four saplings around each supporting pillar. The growers also apply maintenance manure in split doses three to four times per year. Zinc and Boron is applied during flowering and fruit setting. It is also observed that Boron combined with phyto- hormone increases the fruit size noticeably. When seeds are used as propagation material, it takes 3 years to come to bearing. The hardiness of the crop is the key to its survival under field condition.

Uniquely to this crop, it can be planted perennially; however, it is best done between April and September. Each planting pit can accommodate up to 4 saplings which are tied around a centrally placed concrete pole of approximately 8 ft in height. Ideally, for commercial cultivation from each bigha of land growers of this area accommodate 150 concrete poles with 600 saplings. The diameter of horizontal support on the top of the vertical support ranges from 1 to 1.5 meter which facilitates crop management providing support to hold the inclined branches.

**Irrigation**

Heavy rain and over irrigation causes rotting of stem and flower and fruit drop. Water logging is detrimental for the growth of the plant, hence, high land with dry or semi arid soil is preferred for cultivation. It is seen that this plant can be grown on wide range of soils from sandy loam to clay loam. Sandy soils with good organic matter and appropriate internal drainage are best for cultivation of Dragon fruit.

**Flowering**

The large, showy, hermaphrodite, nocturnal flowers with fragrance are the characteristic feature of this shrub. Depending upon the species the size and color of margin and perianth varies from white to scarlet. In Dakshin Dinajpur a full grown plant starts to flower from end of April and extended up to end of November with four to six flowering cycles. Since the inter flush lull stretches between 3 to 4 weeks, a single vine is often observed bearing floral buds, flowers, young fruits and mature fruits simultaneously (Barbeau 1990; Le Bellec 2004). The number of flowering episodes or flushes depends on the species seven to eight for *H. costaricensis* (Anon 2017) and five to six for *H. undatus.*

The duration between floral bud's appearance (lifting of the areole) and flowering and also between flower anthesis and fruit harvest are very short. It is around 15 to 20 days for the first stage and 30 days for the second stage. Dehiscence occurs a few hours prior to the blooming. Pollen is abundant, heavy and not powdery and yellow in color. The position of encourages allogamy as the stigma dominates the stamens. Flowers bloom only for the night and after anthesis it closes whether fertilized or not latest by 6 am in the morning next day, petals soften and then slowly dry. The lower part of a unfertilized flower becomes yellowish and the whole flower drops off within a week. The lower part of a fertilized flower remains greenish and increases enormously in volume, indicating that the fruit has set (Anon 2017).

**Vegetative Propagation**

Stem cutting is the prime method of propagation in Dragon fruit plants in Dakshin Dinajpur. Nursery condition is maintained with high land soil mixed with organic manure in somewhat shady place. Generally 20-25cm long stem cuttings are used for planting. The cutting is prepared in one–two days prior to planting and the latex oozing out of cut is allowed to dry. After the fruiting season, healthy mother plant is selected to have 20-25cm long stem cuttings, kept for drying of latex for some hours, treated with fungicides and planted in 12×30 cm (lay flat) size polyethylene bags, filled with 1:1:1 ratio of soil, organic manure and sand. Excess moisture should be avoided for prevention of rotting of cutting. These cutting roots profusely when watered regularly and become ready for planting with 5-6 months (Tripathi *et al.,* 2014). The farmers of Dakshin Dinajpur are raising stem cuttings to mitigate their own demand for planting material. Some generate additional revenue by selling saplings.

**Pruning**

Being a fast growing semi epiphytic succulent it can through over 30 branches in one year. The plant starts fruiting within 15 to 18 months depending on the climatic condition. However, it is observed that the plant takes almost 5years to attain peak commercial productivity in this district. The branches are trimmed adequately succeeding a harvest. Following every pruning a round of fungicide (n-Carbendazim, Copper oxy chloride) spraying is essential.

**Pest and disease**

Incidence of pest and disease is not frequent in this zone. Sucking pests e.g. mealy bugs, and ants reported from some places are successfully controlled by spraying Malathion@ 2ml liter$^{-1}$ of water. Ants often come hunting for nectar and bore through the flowers. Mealy bugs follow the trail, hunting for ants. Water is sprayed to drive away the ants. Besides pests, birds peck at the ripe fruits, thereby damaging the crop.

**Fruit harvesting**

The plants bear fruits from August to December. On maturation, the skin colors of the fruit change from green to red or rosy-pink (25 or 27) days (depending on the species) after anthesis (Nerd *et al.,* 1999). Using hand or sickle or siketer the fruits are harvested within 5 to7 days of color transition and can be kept for 4 to 7 days at room temperature before packaging or marketing or export. Organic acids present in the fruit influence the organoleptic properties such as flavor, color, aroma, taste and play vital role in the post-harvest management of fruits since they increase the stability, microbial safety and shelf life (Al-Farsi *et al.,* 2005; Nour *et al.,* 2010).

**Yield**

Agriculture forms the backbone of India's economy and 46% of which is contributed by rural economy. The farmers of Dakshin Dinajpur district cropped up to 400 Kg bigha$^{-1}$ from a fully matured plantation. The plant continues to bear fruit up to 40 years. The harvest is marketed in adjacent areas and other districts of West Bengal fetching prices of up to rupees 200/- to 250/- Kg$^{-1}$ for the grower**.** An inspiring interview with the pioneer grower unveiled the encouraging statistics where he claims to earn up to Rs.11,10,000 per annum from 1 bigha of land with 222 pillars accommodating 888 plants. Each pillar yields an average of 25 Kg fruit in a year which fetches Rs.200/-as grower's price Kg $^{-1}$ and total amount of fruit is 222×25 = 5550kg from this fast return perennial fruit crop.

**Conclusion:**

Ever increasing unemployment, fear of migration for livelihood as well as poor economic background has compelled the youth and existing cultivators of Dakshin Dinajpur of West Bengal to diversify into innovative options, such as this quick return exotic fruit crop. Apart from this, the growers also raise grapes, amaranthus, turmeric, zinger, onion (both winter and rainy type), cucumber, pumpkin, malta, pine apple etc. as companion crop which augment their revenue generation. Interactive sessions with the growers inculcates a firm belief that the Dragon fruit bears the potential to emerge as the crop of the future.

Field visits are indicative of the fact that the cultivar, with a red colored epicarp along with white and pink sub-sweet juicy pulp matrix, is emerging as the one of choice amongst practicing farmers. Commercial cultivation of this super fruit is steadily gaining pace with more and more farmers joining in the fray to be self reliant by its cultivation and marketing. Although the market for Dragon fruit is not saturated yet, an advance and innovative thinking could open the gates of value addition by way of processing and packaging hygienically, so that any future surplus crop will be absorbed by the consumers. It is opined that the cultivation of this crop will have to be backed by scientific research with the aim to improve quantity and quality of Dragon fruit.

**Figure 1: Vegetative propagation nursery of *Hylocereus* sp.**

**Figure 2: Bee pollinating a flower of *Hylocereus* sp.**

**Figure 3: A plant bearing flowers and fruits of *Hylocereus* sp.**

**Figure 4: Immature fruits of *Hylocereus* sp.**

**Figure 5: Onion grown as companion crop**

**Figure 6: Grapes grown as companion crop**

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# GREEN ACCOUNTING FOR SUSTAINABLE DEVELOPMENT: A STATISTICAL STUDY OF SANGLI MIRAJ & KUPWAD CITY OF MAHARASHTRA STATE

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**Abstract:**

Green accounting is a lane for development. It is a well-liked expression for environmental and natural source accounting. It is an accounting scheme that procedures the presently economic losses that are knowledgeable by renewable and nonrenewable resources in the environment. By integrating these losses into all stages of economic accounting, all elements of the economic divisions can make well-versed conclusions that bear long term sustainable development and facilitate reinforce human rights exaggerated. This paper's core point is to comprehend what green accounting or green reporting means and also its magnitude. Through primary data collection in this study, we also try to understand people's perspectives towards green accounting. It also aspires to locate out how imperative it is for a company to execute green accounting and keep a roadway of what is getting from the environment and what it is giving back in return. This would assist in the well-organized utilize of resources and it would also assist in dropping pollution to a point. Green accounting plays a chief position in the corporate social responsibility (CSR) of a firm. The government must take strict actions is the environmental norms are not followed and also penalties must be compulsory for it. The accountability towards the environment has become one of the majority significant factors in the corporate social responsibility of a firm.

**Keywords:** Green Accounting, Environmental Impact, Social Responsibility, Environment Protection, Environmental Sustainability

**Introduction:**

Green accounting which is furthermore called as environmental environment was pioneered by an economist and Professor Peter Wood in the year 1980.It plays an essential responsibility in today's Corporate Social Responsibity. The mounting countries like India are facing the double dilemma of defensive the environment and encouraging economic improvement. A tradeoff among environmental shelter and improvement is mandatory.

The espousal of Green accounting depicts the assurance an enterprise has towards the environment. It compacts with three mainly imperative aspects people, profitability and the planet and also more or less aspects with the expenses and the compensation or remuneration an environment brings to a business concern. The System of Environmental-Economic Accounting (SEEA) is used in green accounting. It spotlights to avert the reduction of inadequate natural resources and averting the environmental degradation. The green accounting has two reasons out of which one is to recover the financial environmental performance in the business and the other is to check how the maneuvers of the organization have a consequence on the environmental system. Execution of green accounting in the management system of the association is imperative for the improvement of environmental and economic performance of the association.

Green accounting is an alley way to a sustainable prospect when the companies are making their final accounts or their balance sheets; they usually believe the internal costs such as the labour cost and material cost which directly concern the balance sheet of the organization (The European Commission, 2011). External costs such as the environmental cost, social cost, and the economic cost are often unnoticed. The company must construct sure to take external factors also into deliberation so that the inadequate funds can be watchfully and competently used. It can be used as a implement by the company to keep a footpath of all the activities through which the company is gaining from the environment, keep an account of what it has been doing to give impressive reverse to the environment in revisit of what it has conventional and also assess the data as to what procedures have to be in use to save the environment which is sooner or later receiving exhausted. Green accounting gets nearer up with diverse objectives as well as viewpoints which seldom comprises safeguard environmental assets as well as it accounts for the transform in interests because of the consequence on the environment (Salah El Serafy, 1997). It plays a extremely imperative position in the corporate social responsibility (CSR) of a firm and also plays a imperative position in decision making of the firm concerning the methods or procedure used and also the profitability of the firm.

**Review of Literature:**

Nasir Zameer Qureshi *et al.* (2012) in their research paper, environmental accounting and reporting: an essential component of business strategy, describes the environmental component of the business strategy, producing the required performance reports and recognizing the multiple skills required to measure, compile and analyze the requisite data. Special emphasis of the research is on generation of reports and their standards, for the range of business and regulatory purposes. They also identified the major obstacles for environmental accounting and reporting and concluded that for sustainable development of country, a well-defined environmental policy as well as proper follow up and proper accounting procedure is a must. Unless common people of India are not made aware about environmental damages and safety, development of accounting in this regard is really becomes difficult.

In this study, the author explains about IAR (interpretive accounting research). The main objective of IAR is to understand how the accounting discipline like management accounting might help in overcoming or suppressing issues related to global warming and sustainability considerations. The author also depicts how interpretive accounting research allows people to re-think the structure and strategies towards the natural world (Lehmann, 2011).

Heba Y M & Yousuf (2010 by observing the concepts based on the environmental accounting, explored techniques which can be used in environmental reporting. Environmental reporting helps the companies become more aware of their corporate responsibility as well as the government could use the environmental report to keep track of the acts of the companies towards the environment. The author also observed that there is a parallel increase in measuring the environmental performance as the need for environmental accounting increases.

Malarvizhi P (2008) in a study corporate environmental reporting on the internet: an insight into Indian practices tried to establish the approach and scope of environmental accounting and reporting, as it exists today. The study was based on a sample of 24 documents comprising annual reports, environmental or sustainability reports and other relevant reports of past years. Initially companies in the sample were classified as manufacturing and nonmanufacturing sectors. Since some companies operate in both sectors analyzed, the assignment to a specific one was determined on the basis of main activity carried out by the company. A structured data analysis sheet has been used for capturing corporate environmental reporting practices on the internet. The data collection and analysis sheet were framed to gather data on, key environmental indicator areas, as identified by the World Business Council for Sustainable Development and by the Global Reporting Initiative. The most relevant types of environmental information, as identified by them are: Environmental policy; Environmental impacts; Environmental management systems; Environmental targets and Environmental performance disclosure.

Gray Otte, (2008) in his article 'GHG emissions accounting' mentioned that there are certain internal as well as external benefits to the company if they adopted green accounting. The GHG (greenhouse gas) emission accounting involves keeping a track of the emissions, accounting and later reporting them. By implementing the GHG process, there would be development in the communication process between the firms and the suppliers which would, in turn, lead to reductions in the costs. Also, green accounting does have limitations and barriers as well. But the author mentions certain ways through which the company can overcome these barriers.

Yajhou and Doreweiler (2004) in this study, we can observe that the business policy, as well as the policy of the environment, have been combined and taken into consideration to a large extent. The government led incentive-based regulation and public's consideration has been the two major objectives of this study. This study also talks about the environmental policy along with the strategy of the business. The companies whether big or small, have to soon come up with a framework within which it would operate its business strategies towards environmental accounting.

**Need For Study**

Many companies do not provide much magnitude towards environmental accounting when contrasted to its financial accounts. The natural resources are diminishing speedily and consequently maintenance an account of the environmental costs would assist in via the resources competently and stand by the environmental policies. The need for this study was to create people comprehend and awake regarding the significance of environmental accounting/environmental reporting in companies so that there would be better sustainability as well as to understand the corporate social responsibility of the companies towards the environment.

- Green accounting is used to enhance the quantity of significant for those who require it or can utilize it.
- Relevant data depends on the extent and range of exposure
- To enhance the sustainable development
- It determines environmental social and economic force of business
- It incorporates the environmental sources and assets into corporate accounts

**Objectives of the Study**

- ✓ To enlighten the impression of green accounting.
- ✓ To identify what are the variety of forms of environmental accounting.
- ✓ To enlighten the diverse applications conditions and procedure of environmental accounting.
- ✓ To enlighten the legal structure espoused in India for environmental practices
- ✓ To identify what are the international inventiveness in environmental accounting.
- ✓ To create consciousness about environmental accounting.

- ✓ To comprehend the need and import of green accounting.
- ✓ To create an effort to make green accounting an ingredient of the company's accounts.

**Research Methodology**

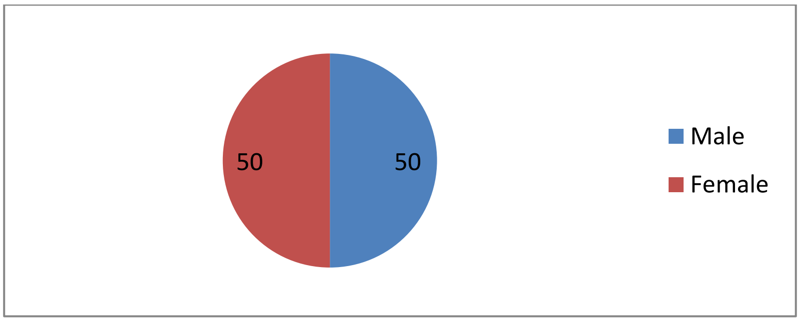
Primary data was composed and an exploratory study using a survey method was mannered to comprehend people's opinion towards environmental accounting and its insinuation. This research study was conducted in Sangli, Miraj & Kupwad city of Maharashtra state and the sample of 80 respondents was selected for the study. The research study was targeted to students and working professionals. The primary data was composed and managed using a well – structured questionnaire. Likert's scale of agreement (Strongly agree, Agree, Neutral, Disagree and strongly disagree) was used. The score of 5 was used to correspond to "Strongly agree" while the score 1 correspond to "strongly disagree" on the scale. The data collected was classified and tabulated for analysis in accordance with the objectives of the study.

**Analysis and Interpretation**

The primary data composed with the help of a questionnaire and investigation and elucidation was done with the aid of final results. In the first part of the analysis, the percentage analysis was used to study the general profile of the respondents. The google forms were used and the percentage investigation was done which represented the approach of people towards green accounting.

**Table 1: Gender of Respondents**

| Gender | N | Percentage |
|---|---|---|
| **Male** | 40 | 50.00 |
| **Female** | 40 | 50.00 |
| **Total** | **80** | **100** |

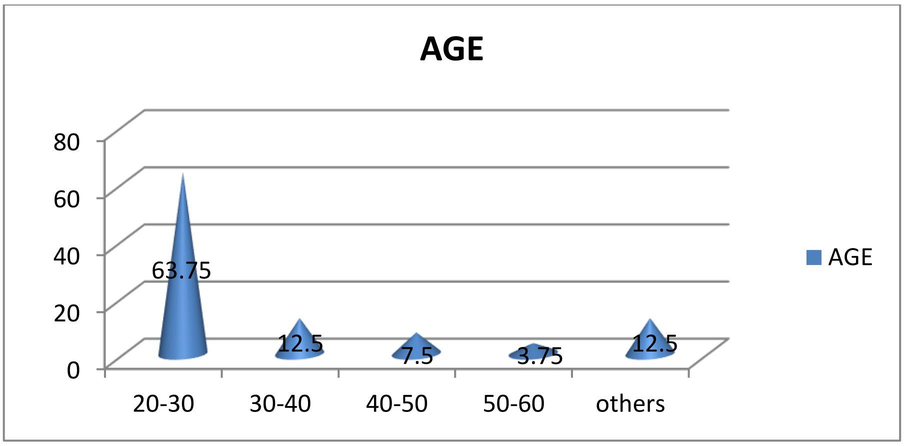



The primary data was collected with the help of 80 respondents. The above table shows that out of 80 respondents, 40(50%) respondents were males and 40(50%) were females.

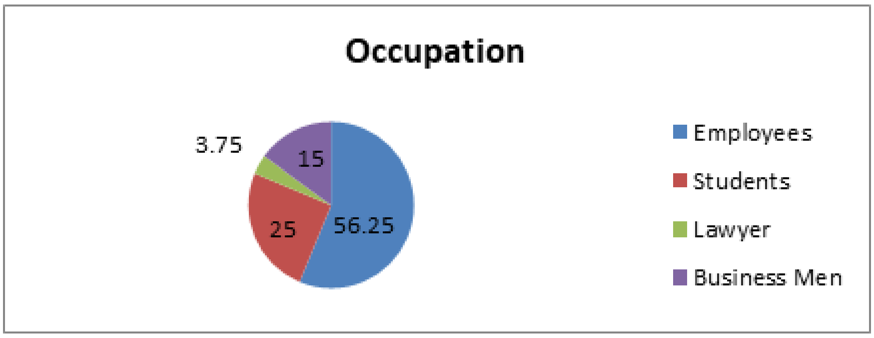
**Table 2: Age wise Classification Respondents**

| Age Group | Frequency | Percentage |
|---|---|---|
| 20-30 | 51 | 63.75 |
| 30-40 | 10 | 12.5 |
| 40-50 | 6 | 7.5 |
| 50-60 | 3 | 3.75 |
| others | 10 | 12.5 |
| Total | 80 | 100 |

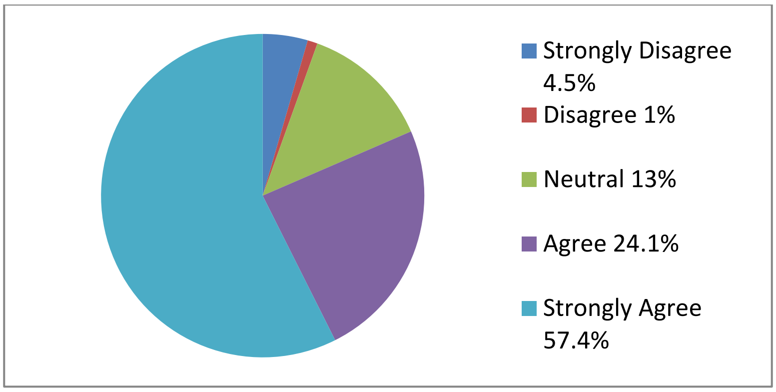
51(63.75%) respondents were in the age group of 20-30 years, 10(12.5%) was the age group of 30-40 years, 6(7.5%) respondents came under 40-50 age group, 3(3.75%) were in the age group of 50-60 years and 10(12.5%) belonged to another age group excluding the above-mentioned age group.




| Occupation | Frequency | Percentage |
|---|---|---|
| Employees | 45 | 56.25 |
| Students | 20 | 25.00 |
| Lawyer | 3 | 3.75 |
| Business Men | 12 | 15.00 |
| Total | 80 | 100 |

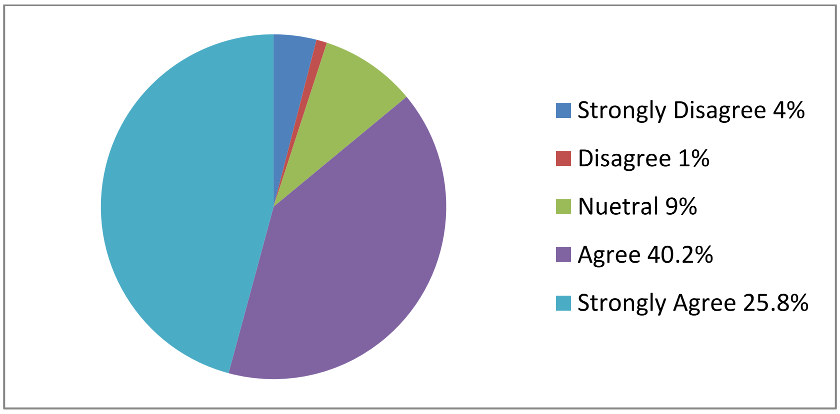


Out of which, 45(56.25%) respondents were employees, 20(25.00%) of them were students, 3(3.75%) were lawyers and 12(15.00%) of them were businessmen.



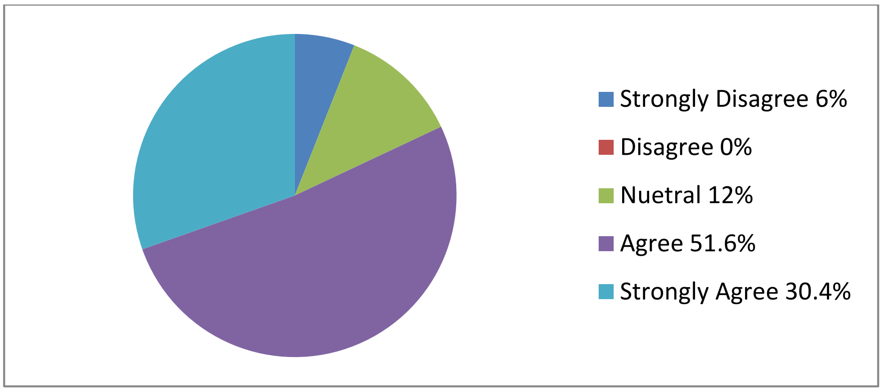

**Graph showing response of "Should environmental accounting be implicated in all companies?"**

When 80 respondents were asked if environmental accounting has to be implicated in all the companies, 57.4% of the people strongly agreed and 24.1 agreed that it has to be implicated in all the companies and 13% of them were neutral about it, 1% of the disagree and also, 4.5% of the people disagreed to it. All the way through this response we can conclude that, even though very less number of people disagree about environmental accounting being implicated in all the companies, mainstream of the people think that environmental accounting has to be implicated in all of the companies as it helps the companies to keep track of what it is taking from the environment and what it is giving back in return.




**Graph showing response of there must be more awareness created about environmental accounting**

Next, the respondents were asked if more awareness has to be created for environmental accounting and the response was as follows; Here, in the second graph, we can see that 4% of the respondents strongly disagree & 1% disagree about more awareness being created about environmental accounting whereas majority of the respondents which constitute 40.2% of the people, agreed and25.8% strongly agreed to the fact that there has to be awareness created everywhere among people and companies regarding environmental accounting since not many of the people know what it actually means and how it actually helps the company as well as the environment and how benefiting it actually is.




**Graph showing responses for there must be strict actions to be taken by the government if environmental reporting is not followed**

Further, when a statement was put up for the respondents if strict actions must be taken by the government if environmental reporting is not followed, 6% of them disagreed& strongly disagreed with it. Moreover, the majority of them, 51.6% of the respondents agreed and 30.4% strongly agreed with the statement that yes, strict actions must be taken by the government if environmental reporting is not followed. And also 12% of them were neutral about it.

**Conclusion:**

Through this study, we can come to a wrapping up that statistical conclusion of Green accounting assists the company as well as the environment in different ways and also, this study assists us to know what green accounting or green reporting means and what are its characteristics and how it works. If it is rigorously executed in all the levels of the organizations, there can be foremost modifies brought towards the betterment of the environment. In view of the fact that there is exhaustion of natural resources, green accounting assists us to keep a roadway of it and how it can be used and what can be done for greatest utilization of it. It also tries to elucidate how important it is for companies to associate green accounting for better consumption of resources and also for the sustainability of the environment. Through the data collected through the primary source, we can come to a conclusion that the employees are more aware and Lawyers are least aware of green accounting. Most of the people are in the support of green accounting and its implication in the company and about government being exacting about its rules and regulations towards it.

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# IoT (INTERNET OF THINGS) IN AGRICULTURE

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## Introduction:

The Internet of Things (IoT) is transforming agriculture by enhancing sustainability, efficiency, and productivity through the incorporation of smart technology. Through the use of data analytics, automated systems, and interconnected sensors, IoT enables the real-time monitoring and management of various agricultural activities. The shift to smart farming boosts crop yields, reduces environmental impact, and optimizes resource efficiency. Conventional agricultural practices are being revolutionized by the integration of the Internet of Things (IoT) into farming, resulting in smarter and data-driven methods. With the world's population increasing and agricultural resources becoming scarcer, the IoT is vital for optimizing resource use, enhancing productivity, and ensuring food security. The IoT addresses major challenges such as climate change, water scarcity, labor shortages, and unpredictable crop diseases through real-time monitoring, automation, and predictive analytics. It is essential for modernizing agricultural practices and improving their efficiency, sustainability, and profitability. Modern agriculture is undergoing a change thanks to the Internet of Things (IoT), which makes data-driven decisions possible while also increasing productivity and efficiency. IoT technology combines cloud computing, drones, smart sensors, and automated irrigation systems to track weather patterns, crop health, soil conditions, and animal management in real time. By giving farmers useful insights, these networked gadgets enable precision farming, minimize resource waste, and maximize productivity. By reducing the excessive use of water, fertilizer, and pesticides, IoT-based smart farming promotes environmentally friendly agricultural practices and improves sustainability. Furthermore, IoT-powered predictive analytics can lessen the dangers of pest infestations and climate change. The use of IoT in agriculture is examined in this research along with its advantages and disadvantages, emphasizing how it can help make conventional farming more sustainable and effective.

Conventional farming is confronted with a multitude of challenges, such as suboptimal resource utilization, erratic climate patterns, shortages of labor, and losses occurring after harvest. These problems often lead to diminished productivity, higher expenses, and harm to the environment. With the incorporation of the Internet of Things (IoT) into agriculture, these challenges can be met through data-driven decision-making, automation, and real-time monitoring. This ultimately enhances efficiency and sustainability.

**Components of IoT in Agriculture:**

**A. Sensors**: IoT in agriculture depends on a range of components to gather, analyze, and apply real-time data for effective farming. Among these, sensors are essential as they keep track of various environmental and soil parameters. Farmers can make well-informed choices about irrigation, fertilization, and crop protection thanks to these sensors. This results in enhanced productivity and better resource management.

**Types of Sensors in IoT-Based Agriculture:** In the realm of IoT-based agriculture, sensors are essential for collecting real-time data to enhance farming methods, boost crop production, and reduce resource consumption. Here's a short summary of every sensor you referred to:

**i. Soil Moisture Sensors:** In IoT-based agriculture, soil moisture sensors track water content to optimize irrigation and save water. These sensors use capacitive or resistive methods to deliver real-time data for automated systems, guaranteeing that crops get the appropriate amount of water. When combined with other IoT devices, they cut down on water waste, improve yields, and foster sustainable agriculture.

**ii. Temperature Sensors:** Temperature sensors measure the temperature of the environment or surroundings. They are of different types i.e. thermistors, thermocouples, resistance temperature detectors, infrared sensors, semiconductor sensors. In agriculture they measure the temperature variants in a field (Kour and Arora, 2020). Mahan *et al.,* designed an optimal temperature based field monitoring system by using a low-cost infrared sensor (Mahan *et al.,* 2010).

**iii. Humidity Sensors:** They are small in size, power consummation is low upto-20 meter indicator transmission make it the greatest option for different applications, This DHT11 Humidity sensor have the features humidity sensor difficult through calibrated digital signal output (Saini and Saini, 2021).

**iv. pH Sensors:** In IoT-based agriculture, pH sensors gauge the acidity or alkalinity of the soil, which affects nutrient availability and plant growth. They assist farmers in real-time monitoring of soil conditions, optimizing fertilization strategies, and initiating corrective

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measures for imbalances. These sensors contribute to soil quality enhancement, crop productivity increase, and reduction in the reliance on excessive chemical inputs.

**v. Nutrient Sensors:** In IoT-driven agriculture, nutrient sensors track the levels of essential soil nutrients like nitrogen, phosphorus, and potassium to guarantee ideal plant growth. They offer real-time information for accurate fertilizer management, which minimizes waste and environmental effects. These sensors automate the application of nutrients, enhance crop yields, lower expenses, and foster sustainable agricultural practices.

**vi. Weather Sensors:** In IoT-based agriculture, weather sensors track environmental factors such as temperature, humidity, and precipitation. This allows for accurate forecasting and improved decision-making. They assist in optimizing irrigation, pest management, and preparation for severe weather events. When integrated into IoT systems, they enhance efficiency, minimize resource waste, and foster sustainable and resilient farming practices.

**vii. $CO_2$ Sensors:** In IoT-based agriculture, $CO_2$ sensors keep track of carbon dioxide levels to enhance photosynthesis and plant development. They offer instantaneous data for the regulation of $CO_2$ levels, productivity enhancement, and inefficiency prevention. When incorporated into IoT systems, these sensors facilitate automated climate regulation, enhance resource efficiency, and foster sustainable and economical farming practices.

In IoT-based agriculture, seamless communication between sensors, devices, and centralized systems relies on connectivity technologies such as Wi-Fi, LoRa, Bluetooth, and 5G. While Wi-Fi and Bluetooth facilitate short-distance communication within localized systems, LoRa provides a long-range, low-power option ideal for extensive agricultural fields. 5G improves real-time data transmission, facilitating remote monitoring and aiding advanced agricultural applications. These connectivity options facilitate an efficient data flow, aiding farmers in making informed decisions and optimizing their agricultural operations.

In sensor data-heavy IoT-based agriculture, data processing and cloud computing are crucial for analysis and storage. Farmers can utilize cloud platforms to access and analyze data from a distance, facilitating data-informed choices regarding irrigation, fertilization, and pest management. Farmers can enhance operational efficiency, increase yields, and adopt more sustainable farming practices by utilizing cloud computing.


**Iot in Agriculture (Bouni, *et al.,* 2024)**

Automation and intelligent devices are crucial as well, taking care of duties like watering, fertilizing, and pest management. These devices, activated by IoT sensors, modify their operations according to environmental conditions, leading to reduced labor costs, minimized waste, and enhanced crop yields.

**Applications of IoT in Agriculture:** The introduction of advanced solutions through IoT has led to significant changes in agriculture, allowing for resource optimization, efficiency enhancements, and productivity improvements. Below is an elucidation of the application of IoT in different domains of agriculture:

**1. Precision Farming (Real-time Monitoring, Yield Prediction)**

- ❖ Real-Time Monitoring: With IoT sensors gathering data on soil moisture, temperature, humidity, and various environmental factors, farmers can monitor crop conditions in real time. This assists farmers in making informed choices about when to irrigate, fertilize, or harvest.

**2. Smart Irrigation (Automated Water Management)**

- ❖ Automated Irrigation Systems: Systems based on the IoT track soil moisture levels and weather parameters to ascertain the optimal quantity of water required for crops. These systems can automatically modify irrigation schedules and quantities, which minimizes water waste and guarantees that crops receive the appropriate amount of water at the correct time.

- Water Conservation: Smart irrigation utilizes sensors to monitor soil moisture and weather forecasts, leading to reduced water consumption. This contributes to sustainable farming practices and helps conserve water resources.

**3. Livestock Monitoring (Health Tracking, Geofencing)**

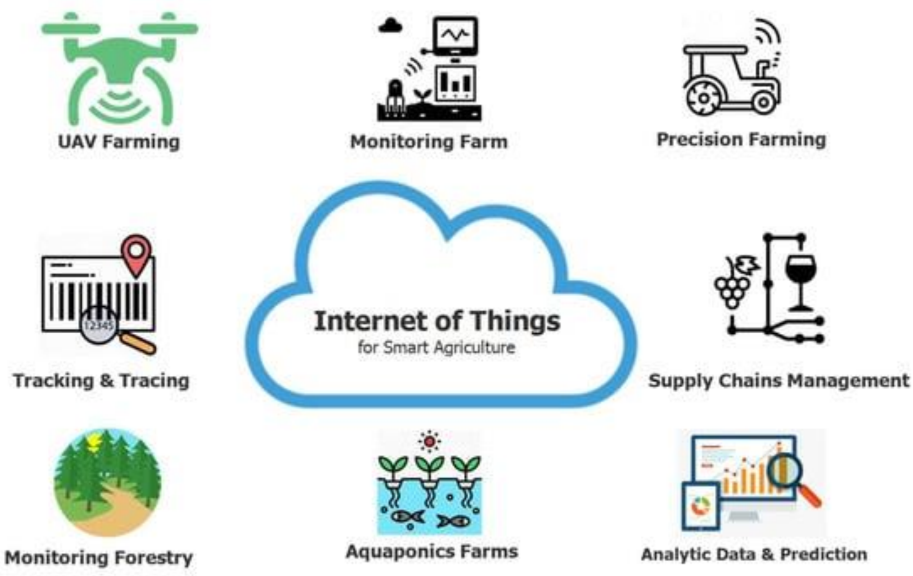
- Health Monitoring: IoT devices, including wearables and RFID tags, oversee the health of livestock by tracking vital signs (like heart rate and body temperature) and movement patterns. When irregularities are found, farmers receive alerts. This allows for early action in the event of illness or injury.
- Geofencing: GPS systems with IoT capabilities establish virtual boundaries (geofences) around farms or pastures. If livestock crosses these boundaries, farmers receive alerts, which helps keep animals within designated areas and minimizes the risk of theft or injury.

**4. Greenhouse Automation (Climate Control, Lighting Optimization)**

- Climate Control: In greenhouses, IoT systems keep track of temperature, humidity, $CO_2$ levels, and light intensity. Automated systems regulate ventilation, heating, cooling, and irrigation according to real-time data, establishing ideal plant-growing conditions throughout the year.
- Lighting Optimization: Greenhouse smart lighting systems leverage IoT to modify light intensity according to plant requirements, guaranteeing energy efficiency and creating ideal growth conditions. This can be particularly beneficial in places where natural light is scarce or during the winter months.

**5. Supply Chain and Logistics (Cold Storage Monitoring, Traceability)**

- Cold Storage Monitoring: IoT sensors monitor temperature and humidity in cold storage units while perishable goods are being transported and stored. It guarantees that food items like meat, fruits, and vegetables are stored at the appropriate temperature, which diminishes waste and spoilage.
- Traceability: The journey of agricultural products from farm to market can be tracked with the help of IoT technology. By embedding sensors in packaging or on equipment, farmers and consumers can trace the entire supply chain, ensuring food safety, transparency, and quality control. Furthermore, this traceability aids in recognizing and dealing with any problems that occur during transport or storage.




**An illustration of IoT applications for smart agriculture (Quy, *et al.,* 2022)**

**Benefits of IoT in Agriculture:** In agriculture, the Internet of Things (IoT) offers considerable advantages by converting conventional methods into systems that are more efficient, productive, and sustainable. Here's a detailed enumeration of the benefits:

**a. Enhanced efficiency and productivity:** By automating tasks like irrigation, fertilization, and pest management, IoT greatly minimizes the requirement for manual work. Precision farming involves the use of sensors and IoT devices to gather data on soil conditions, weather, and crop health. This enables farmers to implement targeted interventions that improve both the quality and quantity of their yields. Moreover, IoT systems allow for real-time surveillance of crop growth, guaranteeing ideal growth conditions and the enhancement of total productivity.

**b. Cost Reduction and Resource Optimization:** Smart irrigation systems powered by IoT utilize soil moisture sensors and weather data to water crops efficiently, leading to reduced water consumption and cost savings. In a like manner, sensors keep track of the exact requirements of crops, thereby optimizing the application of fertilizers and pesticides and reducing waste as well as environmental effects. Moreover, the use of automation and real-time data collection diminishes the reliance on manual work. This results in considerable savings on labor costs and a reduction in total operational expenses.

**c. Real-time Monitoring and Decision-making:** Farmers can utilize IoT to remotely keep track of different facets of their operations—like the health of their crops, the functioning of their equipment, the moisture content of their soil, and climatic conditions—thanks to connected devices. The IoT offers farmers real-time, data-driven insights that facilitate informed decision-making about planting, harvesting, and resource management. Furthermore, predictive analytics driven by IoT systems can foresee potential challenges like pest infestations or plant diseases before they escalate, enabling proactive measures and more effective farm management.

**d. Reduced Environmental Impact:** By optimizing the use of water, energy, and fertilizers, cutting down on waste, and lessening environmental harm, IoT technologies are essential in advancing sustainable resource use. These innovations result in more efficient farming practices that reduce emissions and prevent the overexploitation of valuable resources, thus lowering the overall carbon footprint. Moreover, IoT solutions aid in improved waste management by facilitating real-time observation and efficient management of agricultural waste, guaranteeing its environmentally responsible handling.

**Challenges and Limitations:** The adoption of IoT in agriculture presents several challenges and limitations that need to be addressed for successful integration:

a. **High Initial Investment Costs**: To implement IoT systems, a considerable initial investment in devices, sensors, software, and infrastructure is necessary. This can pose a considerable obstacle, particularly for smallholder farmers or individuals in developing areas, as the expenses may exceed the perceived short-term advantages. Although it is possible to achieve long-term savings and productivity improvements, the initial financial burden can serve as a deterrent.

b. **Connectivity and Infrastructure Issues**: Many rural regions, particularly in developing nations, may not have dependable internet connectivity or the required infrastructure for IoT systems to work at their best. IoT devices require stable network connections for real-time data transmission, and without reliable connectivity, these systems may not function efficiently. This can pose challenges for farmers in remote areas to reap the full benefits of IoT technology.

c. **Data Security and Privacy Concerns**: In agriculture, the utilization of IoT produces extensive data sets that encompass sensitive details regarding farming activities, yield performance, and soil states. This gives rise to worries regarding privacy and data security, since these data streams could be aimed at by hackers. While it is essential that data is encrypted and safeguarded against unauthorized access, many farmers may lack the necessary resources or knowledge to ensure their data is adequately secured.

d. **Farmers' Adaptability and Technical Knowledge**: Farmers must adapt to new methods of farm management with the advent of new technologies, which can pose a challenge. A lot of farmers might lack the required technical expertise to run and maintain IoT systems competently. Farmers may find it challenging to incorporate these technologies into their daily routines due to a lack of familiarity with digital tools and the complexities involved in managing IoT-based solutions. Farmers' adaptability and their ability to leverage IoT innovations depend on adequate training and support.

**Future Trends and Innovations:** The future of IoT in agriculture holds exciting trends and innovations that can revolutionize farming practices and increase efficiency. These advancements include:

a. **AI and Machine Learning Integration**: To improve decision-making, Artificial Intelligence (AI) and machine learning (ML) are being more and more incorporated into IoT systems. AI and ML can assess extensive datasets collected from IoT devices to forecast crop yields, identify diseases, enhance irrigation practices, and tailor fertilization schedules. With these technologies, farmers can respond to challenges with greater precision and automation, leading to enhanced efficiency, reduced waste, and increased productivity.

b. **Blockchain for Transparent Supply Chains**: Blockchain technology is being investigated for the development of agricultural supply chains that are transparent and secure. Blockchain guarantees that data remains unaltered-enhancing accountability and traceability-by monitoring every phase of production, storage, and distribution. This can assist in fraud reduction, guarantee food safety, and furnish consumers with verifiable details regarding the source of their food, thereby bolstering trust in the supply chain.

c. **5G and Edge Computing for Faster Data Processing**: The launch of 5G networks and the expansion of edge computing will greatly improve agricultural IoT applications. 5G will offer ultra-low latency, accelerated data transfer, and more dependable connections—critical for real-time monitoring and management of IoT devices on extensive farms. By processing data near its source instead of routing it to a central cloud, edge computing will enable quicker and more efficient data processing. This will facilitate rapid action on insights without the delays associated with long-distance data travel.

d. **Autonomous Farming Systems**: It is expected that autonomous farming systems will have a major impact on the future of agriculture. The systems consist of self-operating tractors, drones for planting and monitoring crops, and automated harvesters that perform tasks with minimal human involvement. These innovations will reduce labor costs, improve precision, and enable farmers to manage larger operations more efficiently. Due to their ability to run non-stop, autonomous systems can boost productivity and ensure timely task completion, even in challenging conditions.

**Conclusion:**

The introduction of IoT technology into agriculture has significantly transformed the industry, enabling smarter and more efficient farming practices. The IoT facilitates farmers in making decisions based on data, maximizing resource use, and improving crop yields while minimizing waste by allowing for the real-time observation of crops, soil, and weather conditions. Smart irrigation, precision farming, and automation have led to reductions in labor costs and environmental impact. Looking ahead, the IoT in agriculture holds great promise, with innovations like AI, machine learning, blockchain, 5G, and autonomous systems set to enhance productivity and sustainability. To fully leverage these benefits, ongoing investment in infrastructure, data security, and farmer education will be crucial. This will ensure that IoT technologies are accessible, secure, and fully utilized by the agricultural community.

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**Introduction:**

The Laser Land Leveller is a cutting-edge precision agriculture instrument that uses laser-guided technology to increase land levelling efficiency. Conventional land levelling techniques frequently produce uneven fields, which increase weed infestation, reduce crop growth, and waste water. Laser land levelling, on the other hand, guarantees a field that is consistently graded, improving crop productivity and water distribution. A laser transmitter, a receiver fixed to a levelling blade, and a control system that automatically modifies the blade's height in response to laser signals make up this system. By guaranteeing consistent nutrient distribution, the technique increases fertilizer efficiency, lowers fuel and labour expenses, and drastically cuts water usage by up to 30%. It also promotes improved seed germination and reduces soil erosion, both of which increase crop yields. The advantages of laser land levelling, including improved farm profitability, resource conservation, and environmental sustainability, outweigh the initial investment cost, making it an essential breakthrough in contemporary agriculture. Using such precision tools is crucial for sustainable farming as climate change exacerbates water constraint. Its widespread adoption will probably be fuelled by additional automation and cost improvements that make it more accessible to smallholder farmers.

A precision farming method called laser land levelling employs laser-guided machinery to produce a level, consistent field surface. By guaranteeing uniform water distribution, it increases agricultural yields, decreases soil erosion, and improves water efficiency. A controlled leveller mounted on a tractor, a laser transmitter, and a receiver are all involved in the procedure. Water waste is reduced, fertilizer effectiveness is increased, and labour costs are decreased with laser land levelling. Because it maximizes irrigation techniques, it is especially advantageous in areas with limited water resources. Long-term advantages include higher production, fuel savings, and sustainable land use, despite the high initial cost. This technology is a vital component of contemporary sustainable agriculture since it encourages effective resource use and enhances soil health, which supports climate-resilient farming.

In contemporary agriculture, laser land levelling is essential for increasing sustainability, water efficiency, and production. It maximizes irrigation, lowering water waste by up to 30% and enhancing soil moisture retention by guaranteeing a level field surface. By reducing runoff and soil erosion, this precision technology improves fertilizer management and increases crop yields. Additionally, it lowers input, labour, and fuel expenses, increasing farming's efficiency. By preserving resources and enhancing land usage, laser levelling promotes sustainable agriculture in areas with water scarcity and climate change issues. Improved weed control, consistent seed germination, and automation efficiency are all facilitated by the technology. Laser land levelling is a crucial technique in contemporary, climate-smart farming because of the long-term financial and environmental advantages, despite the high initial cost.

**Components and Working Principle:**

A laser land leveller is an advanced agricultural tool designed to create a uniformly levelled field, enhancing water efficiency and crop yield. Its primary components include:

1. **Laser Transmitter:** The laser transmitter is mounted on a tripod, enabling the laser beam to cover the field. Multiple tractors equipped with a laser unit and drag bucket can operate from a single transmitter, guided by a laser receiver (Sarma and Borah, 2024).
2. **Laser Receiver:** Attached to the levelling equipment, it detects the laser beams position and transmits this information to the control box.
3. **Control Box:** The control box receives and processes signals from the machine-mounted receiver. It shows these signals to indicate the drag bucket's position in relation to the finished grade. When the control box is set to automatic, it generates electrical power to drive the hydraulic valve. The control box is conveniently mounted on the tractor for easy access for the operator. The three control box switches are ON/OFF, Auto/Manual, and Manual Raise/Lower (which allows the operator to manually raise and lower the drag bucket) (Jat, *et al.,* 2006)
4. **Hydraulic System**: Utilizes the tractor's hydraulics to raise or lower the levelling blade based on inputs from the control box.
5. **Drag Scraper/Bucket:** Connected to the tractor, it redistributes soil to achieve the desired field level.

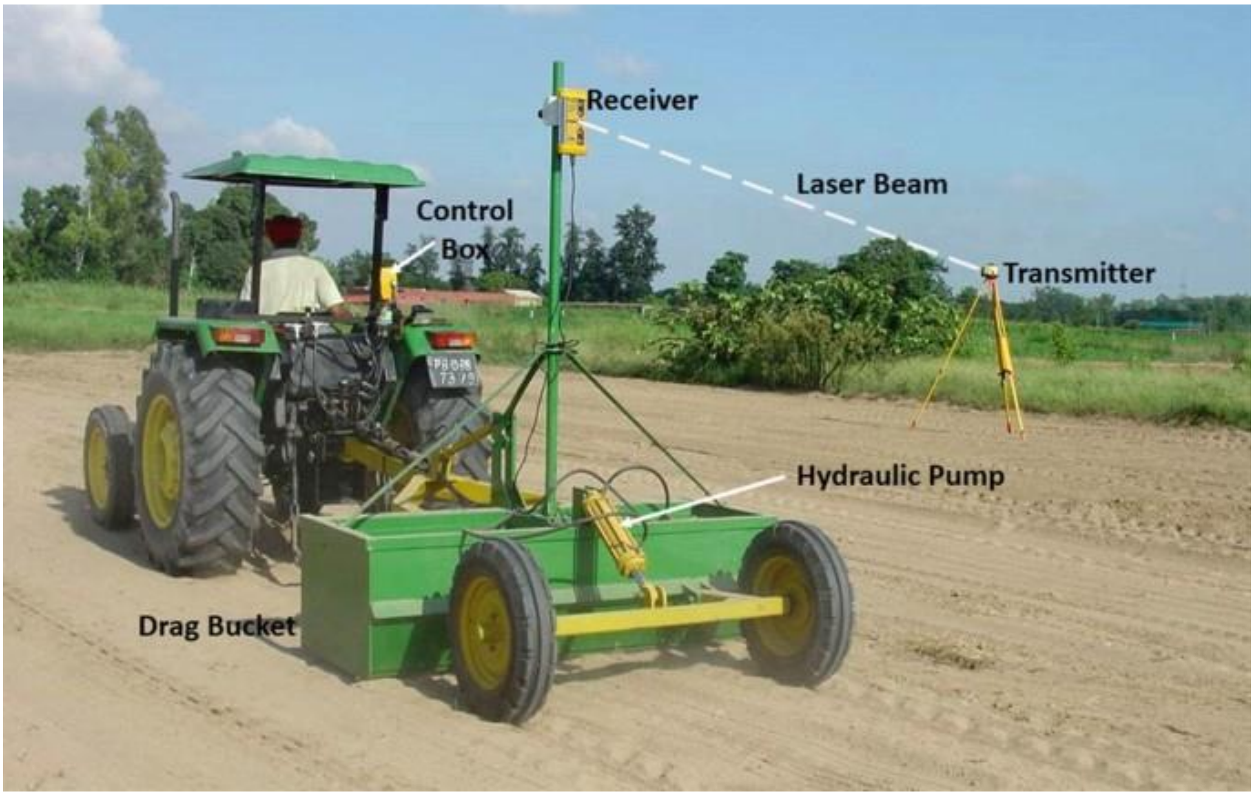


**Fig. 1: Components of laser land leveller** (Brye, *et al.,* 2006)

These components work in unison to ensure a level field surface, promoting efficient water distribution and optimal crop growth.

By using a laser-guided device to create an evenly sloped area, laser land levelling improves crop performance and water distribution. To create a reference plane across the field, a laser transmitter that is fixed on a tripod starts the procedure by launching a revolving laser beam. This beam is detected by a laser receiver that is mounted on a tractor-connected drag scraper and connects to a control box. In order to transfer soil from higher to lower locations, the control box interprets these signals and instructs the tractor's hydraulic system to raise or lower the scraper's blade. Precise field levelling is guaranteed by this automated adjustment, which encourages effective watering and consistent crop development.

**Benefits of Laser Land Leveling**

A precise agricultural method called laser land levelling has several advantages, such as increased crop output, decreased weed infestation, equal fertilizer distribution, and better water use efficiency.

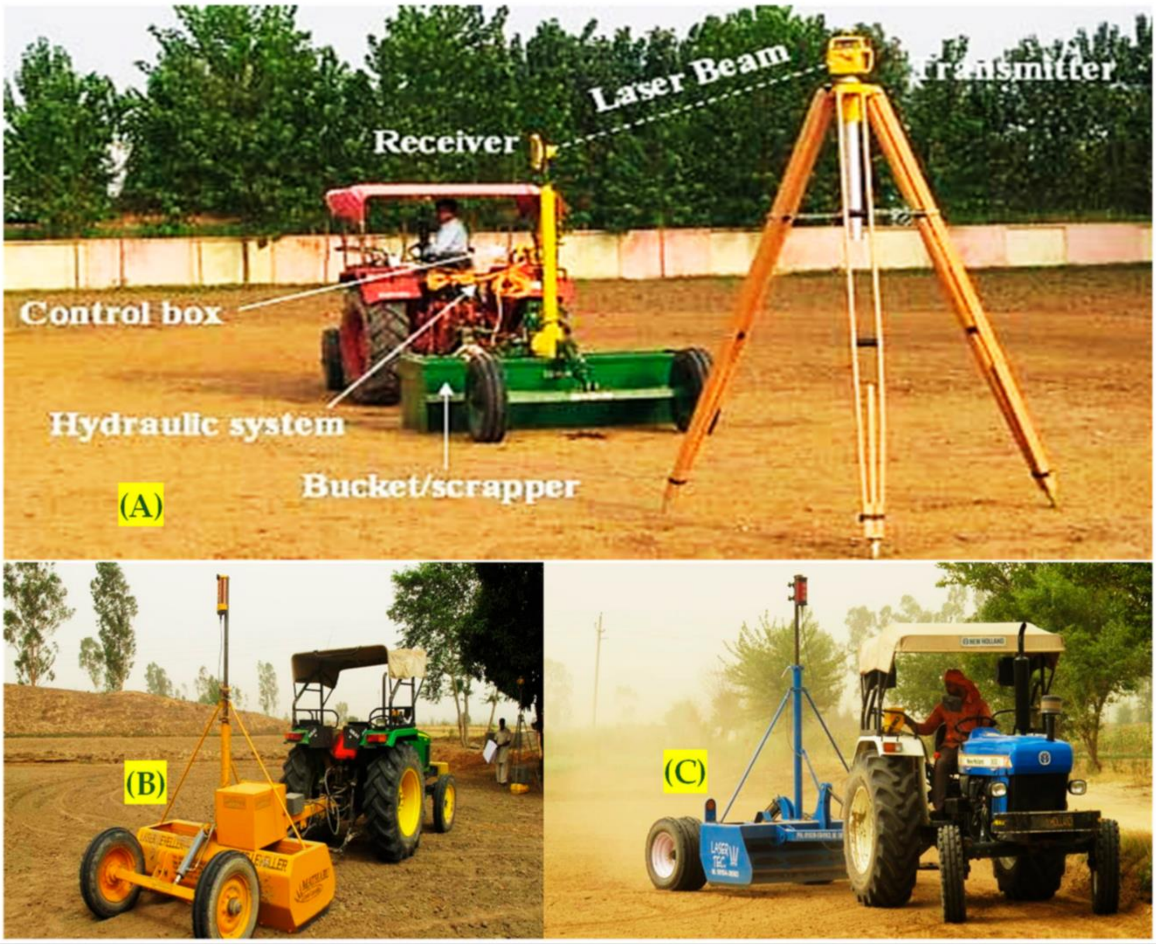


**Fig. 2: Precision laser land leveling (PLL) in field conditions, (A) showing the function of different components; (B,C) PLL in operation levelling a field (Naresh *et al.*, 2021)**

**1. Increased Efficiency in Water Use:** Laser land levelling maximizes water distribution during irrigation by producing a field that is consistently level. This consistency guarantees that every part of the field receives enough moisture and minimizes water waste. According to studies, by reducing the amount of time needed for irrigation, laser levelling can result in water savings of up to 20–25%.

**2. Increased Productivity of Crops:** A level field encourages consistent crop development and seed germination, which raises yields. According to research, yield benefits from laser land levelling can be substantial. For example, it has been demonstrated that using laser levelling technology in the cotton-wheat cropping system increases crop productivity.

**3. Decrease in Infestation of Weeds:** Water stagnation from uneven fields frequently fosters the growth of weeds. These low-lying areas are removed by laser levelling, which lowers the growth of weeds. According to a study, laser land levelling reduced the number of weeds in pearl millet production by 27.81%.

**4. Even Distribution of Fertilizer**: Fertilizers are dispersed uniformly throughout the field on a level, smooth surface, which maximizes crop nutrient availability. This consistency improves fertilizer use efficiency by preventing over- or under-application in certain locations. According to the International Rice Research Institute, levelling the soil improves crop stands and yields by increasing the efficiency of water and fertilizer nutrient utilization.

**Environmental and Economic Impact**

Laser land levelling (LLL) is a precision agricultural technique that offers significant environmental and economic benefits.

**Environmental Impact**

**a. Water Conservation:** By levelling the land, Laser land levelling improves irrigation water distribution. This consistency guarantees that every part of the field receives enough moisture and minimizes water waste. According to studies, by reducing the amount of time needed for irrigation, laser levelling can result in water savings of up to 20–25%.

**b. Less Soil Erosion:** Laser land leveling reduces soil erosion by removing uneven surfaces, which also lessens water runoff and soil displacement. By maintaining soil fertility and structure, topsoil preservation aids in sustainable land management.

**Environmental and Economic Impact**

Laser land levelling (LLL) is a precision agricultural technique that offers significant environmental and economic benefits.

**Economic Impact**

**a. Lower Fuel and Labor expenses:** Because Laser land levelling is more precise, fewer irrigation events and field activities take place, which results in lower fuel and labor expenses. According to research, it can save a substantial amount of diesel fuel by reducing groundwater pumping by 24%.

**b. Enhanced Farm Profitability:** Higher yields and higher-quality food are a result of more efficient use of water and consistent crop growth. Despite the somewhat high initial cost of Laser land leveling equipment, increased crop output and lower input costs frequently result in higher net farm profitability.

**Challenges and Limitations of Laser land leveling**

While laser land levelling (LLL) offers numerous agricultural benefits, its adoption is hindered by several challenges and limitations:

**a. High Initial Investment Cost**

The acquisition of laser levelling equipment entails substantial financial outlay, encompassing expenses for the laser transmitter, receiver, control systems, and compatible tractors. This significant capital requirement can be prohibitive, especially for smallholder farmers with limited financial resources. The Food and Agriculture Organization (FAO) notes that laser-controlled precision is often unfeasible for most irrigated agriculture due to the high cost of such equipment, unless a large number of farmers form a cooperative or a government program is initiated to subsidize land levelling efforts.

**b. Technical Expertise Requirement**

Operating Laser land leveling equipment demands specialized knowledge and skills. Operators must be proficient in setting up and calibrating laser systems, as well as managing the machinery during the levelling process. A lack of trained personnel can impede the effective utilization of this technology. A publication highlights the necessity for skilled operators to set and adjust laser settings and operate the tractor efficiently.

**c. Accessibility for Smallholder Farmers**

Smallholder farmers often face compounded challenges in adopting Laser land leveling due to financial constraints and limited access to information. A study identifies several barriers, including a lack of awareness about the technology, inability to afford the initial investment, and difficulties in financing the necessary labor and inputs. Additionally, small-scale farmers may be risk-averse, concerned about the time lag between investing in the technology and realizing returns.

## Potential Mitigation Strategies

To overcome these challenges, collaborative approaches such as forming cooperatives or utilizing custom hiring services can be effective. By sharing resources, farmers can collectively invest in Laser land leveling equipment, thereby reducing individual financial burdens. Furthermore, enhancing farmers' knowledge through extension services and training programs can facilitate the broader adoption of Laser land leveling technology.

## Future Prospects and Technological Advancements

Laser land levelling (LLL) is evolving with technological advancements that promise to enhance its efficiency, accessibility, and integration into modern agricultural practices. Key areas of development include:

**1. Integration with Automation and Artificial Intelligence (AI)**

The incorporation of AI and automation into Laser land leveling systems is set to revolutionize land preparation. AI can analyze data from drones, soil samples, and other sources to create precise land models, facilitating more efficient planning and execution of levelling projects. This reduces manual labor and minimizes errors. Automation enables real-time adjustments during the levelling process, enhancing accuracy and consistency. Such integration not only streamlines operations but also allows for predictive maintenance and optimization, leading to better resource utilization.

**2. Cost Reduction and Improved Accessibility**

Technological advancements are driving down the costs of Laser land levelling equipment, making it more accessible to a broader range of farmers, including smallholders. The development of modular and mobile land levelling systems offers scalable solutions that can be tailored to different farm sizes and terrains. Additionally, the emergence of cooperative ownership models and government support programs can alleviate the financial burden on individual farmers, promoting wider adoption of Laser land leveling practices.

**3. Adoption in Precision Farming**

Laser land leveling is becoming an integral component of precision agriculture, which emphasizes the use of technology to optimize field-level management. By ensuring a uniformly level field, Laser land leveling enhances the effectiveness of precision irrigation systems, leading to significant water savings and improved crop yields. The synergy between Laser land leveling and other precision farming technologies, such as GPS-guided machinery and variable rate application systems, contributes to more sustainable and efficient farming practices.

**Conclusion:**

Laser land leveling (LLL) is a transformative technology that enhances agricultural productivity and resource efficiency by improving water use efficiency, ensuring uniform crop growth, reducing weed infestation, optimizing fertilizer distribution, and increasing farm profitability. By creating a level field, Laser land leveling minimizes water runoff, soil erosion, and uneven irrigation, leading to higher yields and better resource utilization. Studies indicate that Laser land leveling can reduce water usage by up to 25% and improve crop productivity by 10–15% (FAO, 2023). Its role in sustainable agriculture is crucial, as it conserves water, limits soil degradation, and reduces excessive fertilizer application, helping to mitigate climate change impacts by improving water retention and reducing reliance on groundwater, especially in drought-prone areas. Research also highlights that Laser land leveling technology can lead to a 27.8% reduction in weed growth and significantly lower fuel consumption. However, widespread adoption faces challenges, including high initial costs, technical expertise requirements, and limited accessibility for smallholder farmers. To overcome these barriers, governments, research institutions, and private sectors must collaborate to promote affordable leasing models, training programs, and subsidies. The integration of AI and automation can further enhance precision and reduce operational costs, making Laser land leveling more feasible for farmers worldwide. Encouraging cooperatives and public-private partnerships can scale up this technology and maximize its benefits across diverse agricultural landscapes (Just Agriculture, 2022). In conclusion, Laser land leveling represents a major step toward modernizing agriculture, improving resource efficiency, and ensuring environmental sustainability. Proactive efforts are essential to make this technology accessible and affordable, as its global adoption is key to achieving food security, conserving natural resources, and advancing sustainable farming practices.

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# NANOPARTICLE SYNTHESIS OF ENTOMOPATHOGENIC FUNGI (EPFs)

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**Abstract:**

An expanding field of study called nanotechnology deals with the fine tuning of nanoparticles. The micro molecular size allows for a substantial difference in characteristics, resulting in superior particles. Nanotechnology offers a revolutionary approach to sustainable pest management, particularly through the biosynthesis of Nanoparticle using entomopathogenic fungi (EPFs). The EPFs, such as *Beauveria bassiana* and *Metarhizium anisopliae*, not only act as natural biocontrol agents but also facilitate the eco-friendly synthesis of silver nanoparticles (AgNPs). These nanoparticles have demonstrated strong antimicrobial and insecticidal properties, making them highly effective against pests like aphids, whiteflies, and other insect pest affecting agricultural crops. EPF-synthesized nanoparticles disrupt insect physiology through oxidative stress, cuticle penetration, and metabolic interference. Their advantages over chemical pesticides include biodegradability, reduced resistance development, and minimal environmental impact. However, challenges such as scalability, environmental sensitivity, and limited field trials hinder widespread application. Advancing EPF-based nanoparticle synthesis can lead to more reliable, rational and sustainable pest control strategies, reducing dependence on harmful and toxic chemical pesticides.

**Keywords:** Nanoparticle, EPFs as Biopesticides, Synthesis of Nanoparticle, Green Synthesis, Intracellular and Extracellular Synthesis, Mode of action of mycosynthesized nanoparticle.

## Introduction:

Agricultural productivity is heavily impacted by pest infestations, leading to significant crop losses and economic damage worldwide. Traditional pest control relies on chemical pesticides, which, although effective, have led to serious environmental and health concerns. The excessive use of synthetic pesticides has resulted in soil and water contamination, impact on beneficial organisms, and the emergence of pesticide-resistant pest populations. As a result, there is an urgent need for sustainable alternatives that provide effective pest management while minimizing ecological harm (Bihal *et al.,* 2023). Nanotechnology has emerged as a revolutionary approach to pest management by improving pesticide efficiency, reducing environmental impact, and offering new solutions for controlling insect pests. Nanoparticles, especially silver nanoparticles (AgNPs), exhibit unique characteristics such as high surface-area-to-volume ratio, potent antimicrobial activity, and enhanced penetration into biological tissues. These characteristics make them highly effective against various agricultural pests. However, conventional nanoparticle synthesis often involves toxic chemical reagents, limiting their large-scale agricultural application due to potential environmental and health risks (Santos *et al.,* 2021). Using biological agents, particularly entomopathogenic fungi (EPFs) offers a promising alternative to chemical-based nanoparticle synthesis. EPFs such as *Beauveria bassiana* and *Metarhizium anisopliae* are well-known for their ability to infect and kill insect pests. Recent research has shown that these fungi can also mediate the synthesis of nanoparticles through the secretion of extracellular enzymes and metabolites. This green synthesis approach is not only eco-friendly but also cost-effective, eliminating the need for hazardous chemicals. EPF-synthesized nanoparticles, especially AgNPs, have demonstrated strong insecticidal properties by disrupting insect physiology through oxidative stress, membrane damage, and metabolic interference (Gouda and Ashwini, 2023). Integrating nanotechnology with biological pest management opens new avenues for sustainable agriculture. EPF-mediated nanoparticle synthesis provides a dual advantage: enhancing fungal pathogenicity while ensuring efficient pest control. However, challenges such as optimizing synthesis conditions, ensuring nanoparticle stability, and conducting large-scale field trials need to be considered before widespread adoption. Future research should emphasize on improving synthesis techniques, evaluating environmental safety, and developing commercial formulations for agricultural use (Rai *et al.,* 2009).

In this book chapter, the synthesis of nanoparticles, their use in pest management, and their application in sustainable agriculture have been explored. Utilizing the inherent potential of EPFs and the developments in nanotechnology, safer and more efficient methods of managing pests, lowering the need for chemical pesticides and fostering environmental sustainability can be developed.

**Role of EPFs as Biopesticides**

Entomopathogenic fungi (EPFs) are natural biological control agents that infect and kill insect pests, making them an effective alternative to chemical pesticides. Fungal species like *Beauveria bassiana, Metarhizium anisopliae,* and *Isaria fumosorosea*, infect insects by attaching to their exoskeletons, penetrating through enzymatic degradation, and proliferating inside their bodies. The fungi grow internally, disrupt physiological functions, and eventually kill the insect. The fungi then emerge from the cadaver, producing spores that spread to other pests, continuing the cycle (Mukherjee and Patra, 2017).

EPFs provide several advantages over traditional chemical pesticides. They are environmentally friendly, biodegradable, and highly specific to target pests while being safe for beneficial insects like bees and natural predators. Unlike chemical pesticides, which often lead to resistance, EPFs utilize multiple pathways to attack pests, making resistance development less likely. Additionally, they do not leave harmful residues in soil or water, reducing environmental pollution (Sundaravadivelan and Padmanabhan, 2014). However, some challenges hinder their large-scale application. EPFs have a slower mode of action compared to chemical pesticides, requiring days or weeks to kill pests. They are also sensitive to environmental conditions such as exposure to UV radiation, humidity, and temperature changes, which affect their effectiveness. Furthermore, their short shelf life and difficulties in large-scale production limit their commercial adoption (Dantas *et al.,* 2021).

**Nanoparticles**

Nanotechnology has emerged as a transformative tool in agriculture, particularly in pest management. Nanoparticles, which range from 1-100 nm in size, have unique properties that enhance their effectiveness against pests. Due to their high surface area, nanoparticles interact efficiently with biological systems, allowing for better penetration into insect cuticles and plant tissues (Bihal *et al.,* 2023). Silver nanoparticles (AgNPs) have been widely studied for their strong antimicrobial and insecticidal properties. They work by producing reactive oxygen species (ROS), which lead to oxidative stress, disrupt cellular membranes, and interfere with enzyme functions. This results in cell damage and ultimately leads to insect mortality (Santos *et al.,* 2021). AgNPs are highly stable, effective at low concentrations, and have broad-spectrum activity against various pests, including mosquitoes, aphids, and beetles. Despite their advantages, concerns exist regarding the toxicity and environmental accumulation of chemically synthesized nanoparticles. High concentrations of AgNPs may pose risks to beneficial organisms, soil microbiota, and aquatic life. This has led researchers to explore eco-friendly methods for nanoparticle synthesis, such as using biological agents like EPFs (Gouda and Ashwini, 2023).

**Synthesis of Nanoparticle**

Two approaches are generally followed for synthesis of Nanoparticle:

- Top down approach
- Bottom up approach

1. **Top down approach**

This involves the formation of nonmaterial's from larger substrates. Depending on the type of base matter, it entails cutting, etching, and grinding through mechanical, chemical, or electrochemical methods. This can be the result of numerous contaminants and structural flaws in the lithography-synthesised nanoparticles. It encompasses sputtering, thermal or laser ablation, chemical etching, mechanical or ball milling, and other methods of creating nanoparticles (Baig *et al.,* 2021).

2. **Bottom Up Approach**

The bottom-up method in comparison to the top-down method, the bottom-up approach involves constructing structures through self-assembly or positional assembly into crystals or tubes, then synthesizing particles with nanoscale dimensions. The aggregation of substrates into atoms or molecules, followed by assembly into nanostructures such as nanorods, nanotubes, nanowires, or quantum dots facilitates this process. The bottom-up synthesis method produces a wide variety of nanoparticles with greater homogeneity and fewer flaws. According to Baig *et al.,* (2021), the bottom-up approach to nanoparticle synthesis also includes the green or bio-based synthesis of nanoparticles from fungi, bacteria, and plant extracts.

**Green synthesis /Biological synthesis of nanoparticles by EPFs**

The green synthesis of nanoparticles using entomopathogenic fungi (EPFs) is an emerging field that provides an environmentally friendly alternative to chemical synthesis. EPFs generate extracellular enzymes and metabolites that facilitate metal ion reduction, leading to nanoparticles formation without the need for toxic chemicals (Mukherjee and Patra, 2017). Green synthesis is the process of nanoparticles synthesis using organic materials, bacteria, fungi, algae, and plant components. Plant metabolites themselves serve as both a stabilizing and a reducing agent, hence no additional stabilizing agent is required. Green-synthesised nanoparticles typically have higher antibacterial activity than those made by physical or chemical methods because they are coated with different pharmacologically active biomolecules, which enables the conjugation of the nanoparticle with receptors on bacterial membranes using multiple ligands. The majority of these biomolecules are amides, polysaccharides, quinones, aldehydes, ketones, organic acids, and flavones (Sundarajan *et al.,* 2015).

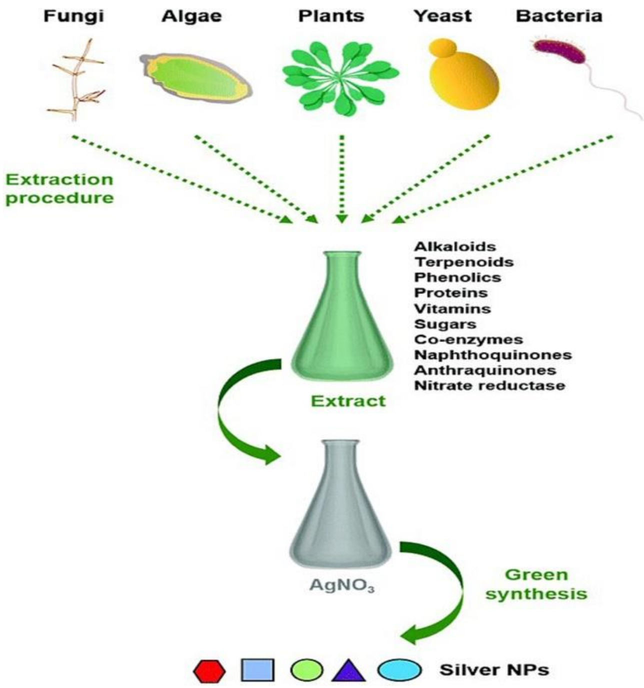


**Fig. 1: Green synthesis of AgNPs (Roy *et al.,* 2019)**

There are mainly two main pathways for EPF-mediated nanoparticle synthesis

1. **Intracellular Synthesis**: In intracellular synthesis, the microorganisms must come into close interaction with the silver ions which will be absorbed and digested inside the cells in order for the nanoparticles to develop. Small and stable nanoparticles are typically produced by the microbes capable of this synthesis, but other procedures are needed to extract the nanoparticles from the cellular structures, which may not be beneficial (de Souza*et al.,* 2015).

**2. Extracellular Synthesis**: Microbial biomass that comes into direct exposure with silver or extracts from microbes can both be involved in extracellular synthesis. Because of the negative charges on the cell wall surface resulting from the presence of carboxyl or amine groups, proteins on the outside of the microorganisms' cell wall interact with silver ions to facilitate extracellular production, which is mediated by microbial biomass (Figure 3). Because the resultant nanoparticles stick to the microbes' surface, separation methods are required to separate them, much like in intracellular synthesis (Moghaddam B. *et al.,* 2015).

**Mechanism of action of mycosynthesized nanoparticles**

Nanoparticles are extremely tiny particles capable of entering insects through their spiracles. They travel via the trachea and tracheoles, reaching different tissues and cells, where they induce toxicity. This eventually results in apoptosis and tissue destruction.

Through the endocytic pathway, these nanoparticles are taken up by lysosomes, leading to membrane disruption. This process releases lysosomal enzymes, allowing nanoparticles to reach organelles like mitochondria, nuclei, and even nearby cells. When nanoparticles enter the nucleus, they cause irreversible DNA damage. Within mitochondria, nanoparticles induce the formation of reactive oxygen species (ROS). Excess ROS triggers apoptosis by increasing cytochrome c levels, disrupting the balance between bax and bcl-2 proteins, and activating caspase 3. Ultimately, this cascade results in cell and tissue death, which negatively impacts physiological and biological functions.

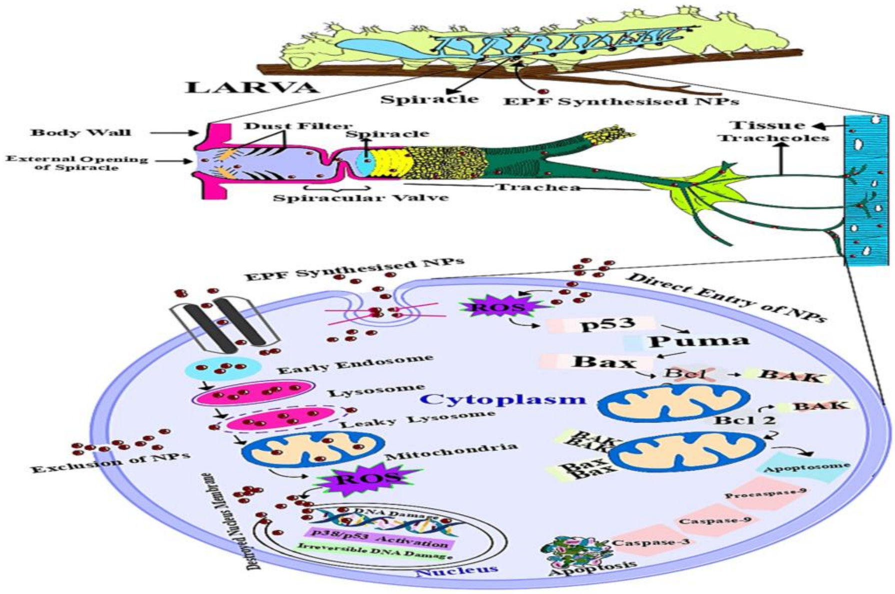


**Fig. 2: Mode of action of nanoparticles (Bihal *et al.,* 2023)**

**Challenges and future prospects**

Despite their promising potential, EPF-synthesized nanoparticles face several challenges that must be addressed before large-scale implementation. One major issue is their short shelf life i.e. fungal formulations tend to degrade over time, making long-term storage difficult. Additionally, environmental factors such as UV radiation and humidity can weaken nanoparticle effectiveness; limiting field application (Rai *et al.,* 2009). Another challenge is scalability i.e. producing bio-nanoparticles in large quantities requires optimized fermentation and synthesis processes. Also, there is no conclusive evidence confirming whether these nanotechnologies are entirely safe or harmful to health. Commercialization remains difficult due to high processing costs, particularly at the farmer level and there is a lack of comprehensive understanding of their mode of action, as well as how insects uptake and transport these nanoparticles.

To overcome these barriers, research efforts should focus on:

1. Enhancing formulation stability to prolong shelf life and effectiveness.

2. Improving large-scale production through optimized growth conditions and bioreactor technologies.
3. Conducting toxicological studies to assess the environmental impact and safety of bio-nanopesticides.
4. Integrating EPF-synthesized nanoparticles into sustainable agriculture, combining them with organic farming practices and integrated pest management (IPM) approaches (Mukherjee &Patra, 2017).

The development of EPF-mediated nanoparticles and their use can help agriculture move toward safer, more environmentally friendly pest management techniques. Food security and environmental health will improve as well as biodiversity protection if reliance on chemical pesticides is reduced.

**Conclusion:**

The synthesis of nanoparticles using entomopathogenic fungi (EPFs) offers a sustainable and eco-friendly approach to pest management. EPF-synthesized nanoparticles, particularly silver nanoparticles (AgNPs), have demonstrated strong insecticidal properties by inducing oxidative stress, disrupting insect cuticles, and interfering with metabolic processes. Their biodegradability, target specificity, and reduced risk of resistance make them a promising alternative to chemical pesticides. Despite their potential, challenges such as short shelf life, environmental sensitivity, and scalability challenges need to be tackled. Future research should prioritize optimizing synthesis conditions, improving nanoparticle stability, and conducting toxicological studies to ensure environmental safety. Integrating EPF-synthesized nanoparticles into sustainable agricultural practices could significantly reduce chemical pesticide dependency while promoting long-term ecological balance. By leveraging nanotechnology and biological pest control, EPFs can revolutionize agricultural pest management, ensuring safer and more efficient solutions for crop protection.

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# OPPORTUNITIES AND OBSTACLES FOR THE RICE GROWING SYSTEMS SUSTAINABILITY AND PRODUCTIVITY

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**Abstract:**

The rice-wheat cropping system, which is widely used in the Indo-Gangetic Plains (IGP), played a significant role in meeting the growing demand for food grains from South Asia's growing population. However, in the northern Indian plains, some practices, such as long-term intensive rice cultivation using traditional methods, have been linked to severe degradation of natural resources, declining factor productivity, multiple nutrient deficiencies, groundwater depletion, labour shortages, and higher cultivation costs, raising concerns about agricultural sustainability. Varietal development, soil and water management, and the adoption of resource conservation technologies in rice cultivation are the main areas for policy interventions to address these issues. When growing rice in medium-to-heavy-textured soils, direct seeding of short-duration, high-yielding, and stress-tolerant rice cultivars with water-saving technology can be an effective way to increase input usage efficiency. Furthermore, given the current situation, a viable strategy for a sustainable rice production system may involve the integrated use of appropriate cultivars for conservation agriculture, mechanized transplanting on zero-tilled/unpuddled fields, and need-based use of pesticides, fertilizer, and water. Numerous issues pertaining to the sustainability and productivity of the rice growing system, as well as potential remedies and alternatives, are covered in detail in this extensive study.

**Introduction:**

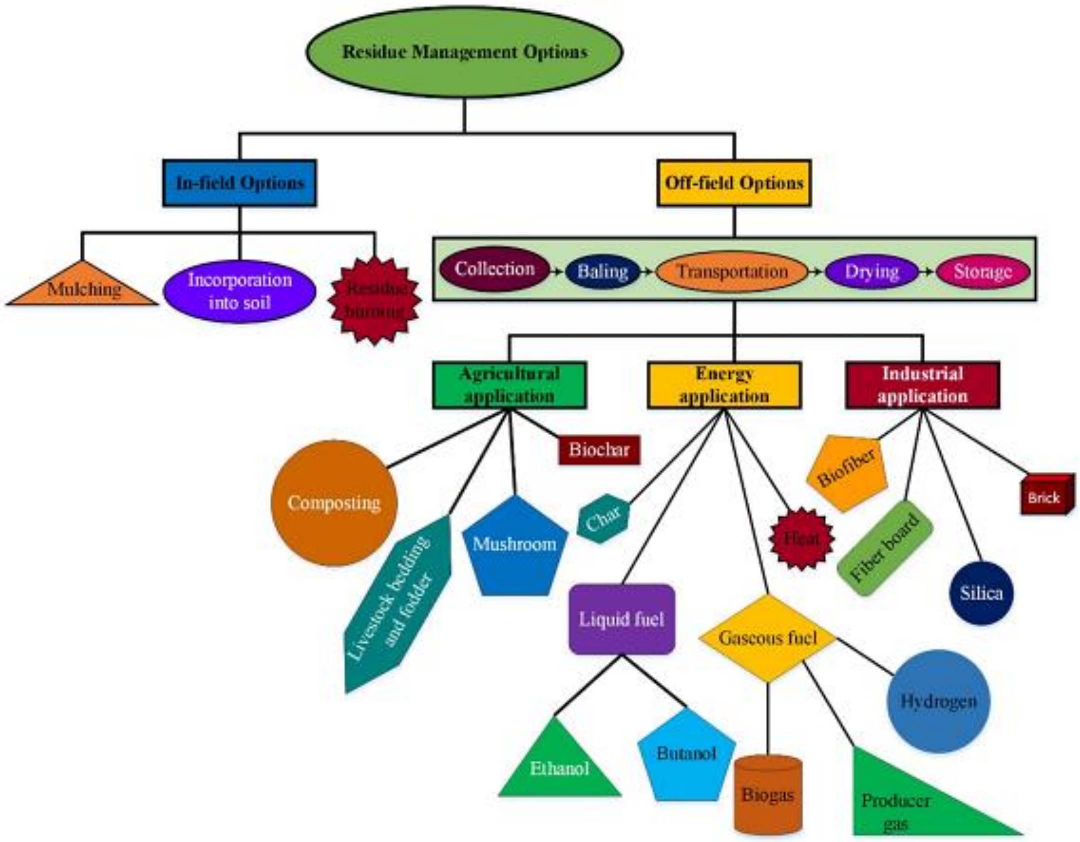
The most common farming system in South Asian nations is rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) (Nawaz *et al.,* 2019). The Indo-Gangetic Plains (IGP), which span an area of approximately 13.5 million hectares (mha), are home to about 85% of this farming system. About 76% of IGP is covered by India alone, which is divided over the states of West Bengal, Punjab, Haryana, Uttar Pradesh, and Bihar. Rice and wheat, the nation's primary crops, were essential in reducing the discrepancy between the demand and supply of food grains. Through an integrated strategy of high-yielding cultivars, disease and pest management, nutrition management, irrigation water management, and improved mechanization, the nation has recently seen the production of excess food grains. India, with 17.7% of the global population, is the largest consumer of water, requiring 3000 billion cubic meters yearly (Vyas *et al.,* 2019). India is the greatest consumer of groundwater, using approximately 230 km3 year. India receives around 4000 billion cubic meters of precipitation per year. Only 48% of water is stored in surface and groundwater bodies due to losses from hydrological processes such runoff, river discharge to seas, evaporation, and evapotranspiration. Approximately 88-90 percent of groundwater extracted is used for irrigation in agricultural fields. Rice crops require significantly more water than other cereal crops, consuming approximately 3000-5000 L of water to produce 1 kilograms of rice (Geethalakshmi *et al.,* 2011). Approximately 75% of global rice production involves nurturing seedlings in a nursery and transplanting them in a puddled field. Rice farming is linked to soil degradation and ecosystem loss, as well as high water, capital, and energy demands. It is estimated that India needs to produce 130 mt of rice by 2030 to meet the demand of the growing population (Gujja and Thiyagarajan 2009). To achieve the projected demand, use of high-yielding varieties, expansion of rice cultivation area, and wet tillage would be required; however, these two practices would further increase the irrigation water demand and greenhouse gas emissions. In the current scenario, degradation of soil structure, declining soil health, residue handling issues. A comprehensive examination of the prospects and difficulties in the productivity and sustainability of the rice growing system from an Indian viewpoint has been attempted, taking into account all of these factors. Additionally, efforts were undertaken to draw attention to potential substitutes and fixes for the current problems with the rice cultivation system. The following sections provide a detailed discussion of the main obstacles and areas of intervention in the rice cultivation system:

**Soil health deterioration and degradation of soil**

The intensive tillage, puddling operation and excessively cultivation of rice–wheat cropping system deteriorated health, structure and nutrient balance of the soils in north-western India. Killebrew and Wolf (2010) reported that long-term intensive rice cultivation system led to soil salinization, nutrient deficiencies, soil toxicities and reduced capacity of the soil to supply the nitrogen to the plant roots. Such changes can lead to reduced yield and abandonment of paddy felds in long-term. In other studies, it is observed that long-term water submergence and mineral fertilization practices in conventional rice cultivation resulted in degraded soil quality in terms of disintegration of stable aggregates and reduced soil organic matter. The concerns have been expressed on the sustainability of high yield of crops due to intensive rice cultivation system and multiple harvests of crops in a year. The sustainability of rice production under rice–wheat cropping system in Punjab has been reported at risk due to soil degradation and declining water table along with inadequate crop residue recycling and lack of organic fertilization. These changes in soil–water environment led to micro-nutrients deficiencies and yield stagnation.

**Uncontrollable weeds**

Weeds are the major problem in rice cultivation. Effective weed management plays an important role in the overall profitability of any cropping system. The destruction of weeds with puddling is the main reason for ongoing traditional practice in rice cultivation. However, intensive rice cultivation over the years confined the eco-biodiversity and weed spectrum, and therefore, specific weeds develop more resistance against herbicides and compete with crop plants for water, nutrient and energy. Crop diversification can effectively change the weed spectrum and reduce weed infestation and resistance. *Echinochloa crus-galli* and *Echinochloa colona* are the major weeds found in different rice ecologies (aerobic as well as anaerobic rice) in Asian countries. There are many weeds such as *Dactyloctenium aegyptium, Digitaria sanguinalis, Digera arvensis, Trianthema portulacastrum* and *Cyperus rotundus*, which do not infest puddle transplanted rice but found in abundance in DSR and cause huge yield reductions (Chhokar *et al.,* 2014). In DSR, single pre- or post-application of herbicide fails to control the diverse weed fora and combination of herbi - cides either in tank mixture or in sequence is required to have efective control of broad-spectrum weeds. The application of pre-emergence pendimethalin or oxadiargyl followed by either bispyribac or penoxsulam in combination with eth - oxysulfuron or pyrazosulfuron controls the diverse weed fora in DSR. Fenoxaprop +safener (Rice Star) efectively controls the problematic weeds, Dactyloctenium aegyptium and Digitaria sanguinalis. Also, the ready mixture of tria - famone +ethoxysulfuron as well as penoxsulam +cyhalo - fop can be utilized for diverse weed fora control. The sole dependency on herbicide is not desirable due to the risk of evolution and spread of herbicide resistant weeds. Weedy rice or red rice (O. sativa f. spontanea) has turned out as a major challenge in rice cultivation where PTR has been replaced with DSR. For effective weed management with multiple non-chemical weed control strategies such as stale seed bed, competitive cultivars, crop rotation, use of weed free seed and mechanical weeding to remove the weeds before seed setting. In addition, the development and large-scale adoption of herbicide-tolerant rice in future will simplify and provide cost-effective diverse weed flora control in DSR.

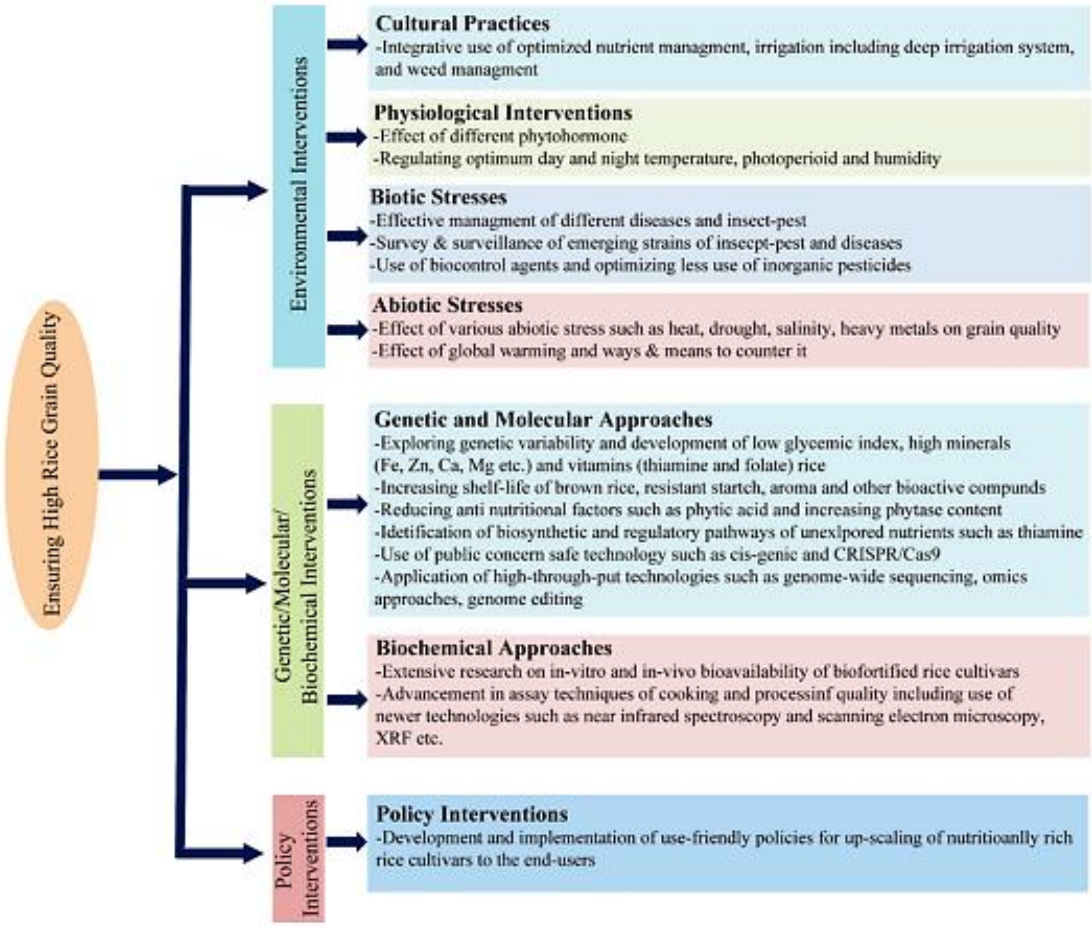



## Residue management challenges

These challenges force the farmers of north-western India to adopt the injudicious practice of residue burning as an economical option for timely sowing of wheat into combine harvested rice felds. Such unfair practices degrade the environment by contaminating the air with carbon monoxide (CO), carbon dioxide (CO2), methane (CH4) and particulate matter. In fact, air quality index of National Capital Region of India falls sever to emergency level during the rice-harvest and wheat-sowing season (APRC 2018). Crop residue burning is also associated with other problems such as loss of nutrients retained in the residue, global warming and soil health deterioration. Hence, the farmers have been suggested to use the rice residue for manure, energy production, biogas production, ethanol generation, gasifcation, biochar and mushroom cultivation according to easily accessible option to them. Despite multiple benefts, the adoption of these technologies is not very impressive at farmers' feld. Therefore, more eforts on the development of suitable seeding machines for multi-cropping systems under conventional and CA and their popularization are required for efective in-situ residue management on large scale at farmers' feld. Custom hiring service needs to be promoted at block and village level to overcome the issue of costly residue handling and seedling machines for farmers belonging to small- and medium-land holdings.

**Genetic tools and molecular approaches of rice improvement**

Rice is one of the most widely adapted crops due to the vast genetic diversity and its wild relatives (Singh *et al.,* 2018). There are 22 wild and 2 cultivated species (*Oryza sativa* and *Oryza glaberrima*) under the genus *Oryza*. The *O. sativa* covers most of the area under rice cultivation and has been classifed into five major groups: *indica, aromatic japonica, tropical japonica, temperate japonica* and *aus* (Garris *et al.,* 2005). These genomic resources conserved by national and international organizations have been used in crop improvement programs and also for basic research. A total of 132,000 accessions of rice were maintained by International Rice Genebank Collection Information System (IRGCIS) of International Rice Research Institute (IRRI). A large number of indigenous, exotic and wild rice accessions are also maintained by National gene bank of India of National Bureau of Plant Genetic Resources (NBPGR), New Delhi. Among the crops, rice is the frst to have complete genome sequence, which helped in developing genetic resources for gene discovery, molecular markers and crop improvement. Genomic information of 3,010 diverse Asian cultivated rice including 3000 rice accessions of 3 K rice genome project was used to identify 29 million SNPs, 2.4 million small indels, 10,000 novel full-length protein-coding genes andmore than 90 thousand structural variations, which will serve as an extremely important genetic resource for breeding and biotechnology research (Wang *et al.,* 2018). Several databases and genomic resources of rice are available in public domain for gene/allele discovery, molecular marker designing and basic studies (Kamboj *et al.,* 2020). These resources have facilitated the QTL discovery and gene cloning for marker-assisted breeding programs and transgenic research. Novel resources such as gene activation mutants, EMS mutants and T-DNA-tagged rice mutant populations are powerful genetic resources for functional genomics and crop improvement. Marker-assisted selection and introgression have been used for developing biotic and abiotic stress-tolerant rice genotypes (Das *et al.,* 2017). Three major bacterial blight resistance genes (Xa21, xa13 and xa5) were introduced through marker-assisted breeding to produce a bacterial blight resistant rice cultivar, Improved Samba Mahsuri. Transgenic rice lines for various traits have been developed using a number of genes and genetic elements. Recently, genome editing is projected as the potential breeding technique due to its precision and efciency. Several traits and genes of rice are being targeted and improved using the CRISPR/Cas technology of genome editing.




**Conclusion:**

Continuous rice growing using traditional methods poses major concerns to natural resources and agricultural sustainability. In a scenario with diminishing production, crop response, water level, and increasing air. To reduce pollution and produce more rice with less water in a sustainable manner, researchers and policymakers should take a systematic and coordinated strategy. Encourage the development of water-saving crops in places with light-textured soils and rainfed conditions through incentives and minimum support prices. To ensure sustainable rice production in medium-to-heavy soils, a multi-dimensional strategy to varietal development, soil and water management, resource-conserving machinery, and need-based fertiliser and chemical application is necessary. To conserve resources, consider delaying direct seeding of short-duration, high-yielding, and stress-tolerant rice varieties with a zero-till seeder or transplanting them with a zero-till transplanter under drip irrigation. Be encouraged to cultivate rice. More research and analysis are needed to determine the yield and profitability of a new rice cultivation system and persuade farmers to switch from PTR.

Policy reforms are necessary to eliminate subsidies for methods and systems that lead to low water productivity on a system level. Reforms on water security to users, the decentralization and privatization of water management functions to suitable levels, water pricing, markets in tradable property rights and introducing water conserving technologies.

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# MANAGING THE FLOW: TECHNIQUES FOR ECOLOGICAL WATER RESOURCES

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**Abstract:**

The article provides a detailed exploration of water management, emphasizing its importance for sustainable development in the face of challenges like water scarcity, pollution, and climate change. It highlights Integrated Water Resources Management (IWRM) as a key framework that balances environmental, social, and economic needs. Techniques to minimize waste and pollution include water-efficient household and industrial practices, sustainable agriculture, advanced wastewater treatment, and green infrastructure. Effective water storage during floods and cyclones involves rainwater harvesting, reservoirs, groundwater recharge systems, and both traditional and modern storage solutions. Mathematical models, such as hydrological, groundwater flow, and optimization models, play a crucial role in water management, enabling informed decision-making and efficient resource allocation. Specific models also address floodwater cleanup through quality assessments, sediment transport analysis, and biological or chemical treatments. The article reviews key literature on water challenges, urban sustainability, and policy innovations, underscoring the need for collaboration among communities, governments, and international organizations. By integrating technology, policy, and ecological restoration, water management ensures resilience and equitable resource access for future generations.

**Introduction:**

The process of organizing, creating, allocating, and overseeing the best possible use of water resources is known as water management. It includes a variety of actions meant to guarantee the long-term supply and quality of water for environmental, industrial, agricultural, and residential purposes. Since water is a limited and vital resource, managing it effectively is crucial to balancing conflicting demands and tackling issues like population expansion, climate change, and environmental degradation.

Fundamentally, water management entails the appropriate disposal or recycling of wastewater in addition to the collection, storage, treatment, and distribution of water. The process consists of both non-technical strategies like putting laws, rules, and public awareness campaigns into place and technical ones like constructing reservoirs, canals, and wastewater treatment facilities.

Addressing water shortage, a worldwide problem brought on by overexploitation, pollution, and unequal distribution of freshwater resources, is a crucial component of water management. The widely used strategy known as Integrated Water Resources Management (IWRM) encourages the integrated development and management of land, water, and related resources in order to optimize social and economic well-being while maintaining environmental sustainability.

The goals of sustainable water management techniques are to reduce pollution and waste, save ecosystems, and guarantee fair access. These methods include protecting wetlands, reusing treated wastewater, rainwater collection, and water-efficient devices. For example, to control runoff and lessen urban flooding, urban regions frequently use green infrastructure solutions like permeable pavements and green roofs.

Water management in agriculture, which uses around 70% of all freshwater worldwide, is centered on increasing irrigation effectiveness and implementing drought-tolerant crop varieties. Industries are also urged to limit wastewater output and adopt water-saving technologies.

Managing water resources effectively is a social and political issue in addition to a technical one. Governments, communities, corporations, and international organizations must work together. Water management can be crucial to guaranteeing water security for future generations and advancing sustainable development goals by using comprehensive and progressive approaches.

**Literature survey:**

California's water supply, which is largely dependent on snowmelt from the Sierra Nevada Mountains and little rainfall, is covered in the book [1]. Droughts and the increasing demand from cities, industry, and agriculture make the state's water supply uncertain. The problem is made more difficult by climate change, which results in altered precipitation patterns and higher rates of evaporation. In many areas of California, pollution from industrial waste, urban wastewater, and agricultural runoff has caused the quality of the water to decline. The ecosystem and public health are at risk from contaminants such heavy metals, fertilizers, and pesticides. Lassiter draws attention to the difficulties in purifying and preserving the quality of water in such a complicated and interconnected water system.

An extensive analysis of the past, present and future of water management and infrastructure may be found in the book [2]. Sedlak takes readers on a tour of the development of water systems, showing them how societies have come up with ever-more-advanced ways to get, purify, and distribute water as well as how these systems need to change to meet the demands of the contemporary world.

An extensive examination of the IWRM framework is given in the Book [3], which highlights its significance for sustainable water management. A comprehensive approach to managing water resources in a way that balances environmental, social, and economic needs is provided by the book, which includes the theoretical underpinnings, research advancements, and practical implementations of IWRM.

The special difficulties and approaches needed to manage water resources in quickly expanding urban areas are the main emphasis of Sustainable Water Management in Urban Environments [4]. The book looks at how water supply systems, wastewater management, and the general sustainability of urban environments are under a lot of strain due to urbanization, population increase, and climate change. In order for cities to meet the needs for clean water while preserving ecological balance, it emphasizes the necessity of creative solutions such water conservation methods, rainfall collecting, wastewater recycling, and green infrastructure. In order to handle urban water concerns more comprehensively, it also highlights the significance of integrated water management systems that take into account the interdependencies of storm water, wastewater, and water supply.

The book highlights the importance of governance, policy, and community involvement in developing sustainable water management practices in addition to these technical solutions. Government organizations, businesses, and local communities must work together to manage water resources effectively in metropolitan areas. Smart technology must also be implemented to effectively monitor and control water consumption. The book promotes a move toward more decentralized and flexible water systems that can adjust to shifting environmental conditions and population expansion, stresses the significance of sustainable urban design, and asks for long-term planning that incorporates climate resilience.

Cynthia Barnett's book Blue Revolution: Unmaking America's Water issue[5] examines the serious water issue the US is currently facing and suggests a radical change to sustainable water management techniques. Barnett contends that a "blue revolution" that rethinks the connection between humans and water is necessary in light of the nation's persistent water shortages, contamination, and poor management. The book looks at how America's water policy, which has traditionally prioritized technological solutions like reservoirs, dams, and irrigation systems, has resulted in water scarcity, unequal access, and environmental degradation. Barnett challenges these conventional approaches and advocates for a new way of thinking that puts ecosystem health, water conservation, and fair distribution first.

The book explores the numerous water issues that various U.S. areas face, ranging from the Midwest and South's contaminated water supplies to the West's excessive groundwater exploitation. Barnett draws attention to the concerning trend of deteriorating water quality brought on by urban sprawl, agricultural runoff, and industrial pollution, which endangers aquatic ecosystems as well as human health. She also talks about how underprivileged areas frequently suffer the most from the problem due to differences in access to water. The effects of climate change, which worsen water scarcity, increase the frequency of extreme weather events, and affect hydrological cycles, are highlighted in the book. These changes make it even more challenging to manage water resources efficiently.

Barnett ends by outlining his vision for the future, which calls for a water revolution involving technical innovation, policy reform, and grassroots initiatives. Through institutional and personal initiatives like investing in water recycling, enhancing irrigation methods, and minimizing water waste, she highlights the significance of water conservation. With a focus on ecosystem restoration, sustainable water management, and the deployment of green infrastructure, the book also emphasizes the necessity of extensive legislative changes at the municipal, state, and federal levels. In order to guarantee a sustainable future for everybody, Blue Revolution ultimately advocates for a culture change that views water as a shared, limited resource that needs to be managed carefully.

A thorough examination of water resources with an emphasis on their historical development, management, and policy frameworks can be found in Principles of Water Resources: History, Development, Management, and Policy [5]. Beginning with early civilizations that created rudimentary water infrastructure to sustain agricultural and urban settlements, the book charts the development of water management systems up to the current global issues of pollution, climate change, and water scarcity. It looks at how many societies have handled water distribution and management, emphasizing the conflicts between maintaining natural water systems and meeting human demands for water.

The book also explores current methods to water policy and management, highlighting the significance of multidisciplinary solutions and integrated water resources management (IWRM). It talks about how urbanization, environmental deterioration, and growing population pressures have affected water governance and policies. In addition to outlining tactics for enhancing water security, resolving water conflicts, and encouraging sustainable behaviors, the authors emphasize the importance of both governmental and non-governmental organizations in managing water resources. The book provides insightful information about the intricacies of managing water resources and the regulations required to guarantee sustainable water use for future generations by tying historical background to contemporary issues.

Thomas V. Cech [6] *Principles of Water Resources* provides a comprehensive foundation on water resource history, policy, and management, offering a broad perspective vital for understanding global challenges. Ahmadov[2020] study on Azerbaijan highlights how sustainable development hinges on effective water management, focusing on region-specific strategies that resonate globally. Dinar[2020] article delves into economic and modeling approaches, addressing the complexities of water resource challenges and emphasizing interdisciplinary solutions. Khadse et al[2012] offer insights from an Indian perspective, showcasing local water management issues and practices, which can inform broader applications. Zhang *et al.,* [2024]research advances the technical dimension, demonstrating innovative soil moisture retrieval methods using dual-polarization SAR, which can enhance agricultural water management. Together, these studies underscore the interplay of policy, sustainability, technology, and localized strategies in achieving effective water resource management.

**Ways to Minimize Waste and Pollution in Water**

Pollution and water waste are major worldwide issues that endanger human health, ecosystems, and water security. Protecting water resources requires implementing sustainable methods to cut waste and stop pollution. The following are important tactics to reduce pollution and water waste:

**1. Improving Water Efficiency**

- **Household Measures**: Simple actions like fixing leaks, installing low-flow fixtures, and using water-efficient appliances can significantly reduce water wastage in homes.
- **Industrial Solutions**: Industries can implement water recycling and reuse processes, such as treating wastewater for non-potable purposes like cooling or cleaning.

**2. Adopting Sustainable Agricultural Practices**

- **Efficient Irrigation**: Techniques like drip irrigation and sprinkler systems deliver water directly to plant roots, minimizing evaporation and runoff.
- **Precision Agriculture**: Using data-driven approaches to monitor soil moisture and optimize water usage reduces overwatering.
- **Reducing Runoff**: Planting cover crops and building buffer zones prevent fertilizers and pesticides from contaminating nearby water bodies.

**3. Proper Wastewater Treatment**

- Upgrading wastewater treatment facilities ensures that harmful pollutants, such as chemicals, heavy metals, and pathogens, are removed before water is discharged back into the environment. Treated wastewater can also be reused for irrigation or industrial processes.

**4. Preventing Plastic and Litter Pollution**

- Preventing litter, especially plastics, from entering water systems is crucial. Proper waste disposal, recycling, and community cleanup initiatives can help reduce marine pollution. Banning single-use plastics also reduces waste that clogs waterways.

**5. Reducing Chemical Use**

- Using environmentally friendly household cleaners, pesticides, and fertilizers minimizes chemical runoff into water bodies. Industries can adopt green manufacturing processes to reduce harmful discharges.

**6. Implementing Green Infrastructure**

- Urban areas can reduce pollution and manage stormwater effectively through solutions like green roofs, rain gardens, and permeable pavements. These systems filter and absorb pollutants while replenishing groundwater.

**7. Public Awareness and Education**

- Educating individuals and communities about the importance of conserving water and reducing pollution empowers them to adopt sustainable practices. Awareness campaigns can highlight the impacts of water pollution and ways to prevent it.

**8. Strengthening Regulations and Policies**

- Governments play a crucial role by enforcing regulations on industrial discharges, agricultural runoff, and plastic waste management. Providing incentives for adopting water-efficient technologies further supports conservation efforts.

**Ways to Store Water During Floods and Cyclones**

Floods and cyclones often lead to an abundance of water that can be effectively stored for future use. Proper water storage systems not only help mitigate the impact of these disasters but also contribute to sustainable water management. Here are some effective ways to store water during floods and cyclones:

**1. Rainwater Harvesting Systems**

- **Rooftop Rainwater Harvesting**: Collecting rainwater from rooftops and channeling it into storage tanks or underground reservoirs ensures the water is saved for later use.
- **Surface Runoff Harvesting**: Capturing runoff water from paved areas and open spaces during heavy rains helps reduce flood risks and stores excess water.

**2. Floodwater Reservoirs**

- Constructing large reservoirs in flood-prone areas helps store floodwater. These reservoirs can be multipurpose, providing water for irrigation, drinking, or industrial use.
- Temporary floodwater storage basins can also be created in open areas to hold surplus water during emergencies.

**3. Groundwater Recharge Systems**

- **Recharge Wells**: Directing floodwater into recharge wells helps replenish depleted groundwater reserves. This method is particularly effective in urban and semi-urban areas.
- **Infiltration Pits**: These shallow pits allow excess water to seep into the ground, naturally filtering it while recharging aquifers.

**4. Check Dams and Embankments**

- **Check Dams**: Small barriers across streams or rivers can temporarily hold floodwater, allowing controlled release and infiltration.
- **Raised Embankments**: Constructing embankments with gates allows the controlled storage of water from rivers during floods.

**5. Storage Tanks and Cisterns**

- Large storage tanks, both above ground and underground, can be used to collect and store rainwater or floodwater. Cisterns can also be equipped with filtration systems for potable water storage.

**6. Constructing Wetlands and Retention Ponds**

- Wetlands act as natural sponges, absorbing floodwaters and gradually releasing them into the environment while filtering pollutants.
- Retention ponds store excess rainwater and floodwater, preventing downstream flooding and preserving water for later use.

**7. Using Modular Water Storage Systems**

- Modern modular systems, such as collapsible tanks and water bladders, can be quickly deployed in flood-prone areas to capture and store water. These systems are portable and ideal for emergency response during cyclones.

**8. Reviving Traditional Water Systems**

- Traditional systems like step wells, village tanks, and kunds (circular underground storage) can be revived to collect and store water during heavy rains.

**9. Desilting and Strengthening Water Bodies**

- Natural lakes, ponds, and reservoirs can be desilted and strengthened to hold larger volumes of water during floods.

**10. Community-Level Solutions**

- Encouraging communities to build water storage structures such as farm ponds or shared reservoirs increases local resilience to cyclones and floods.

By implementing these strategies, floodwaters can be transformed from a hazard into a valuable resource, enhancing water security and reducing the adverse impacts of natural disasters

**Mathematics models in water management**

Mathematical models are essential tools in water management, helping to analyze, predict, and optimize the use and distribution of water resources. These models provide quantitative frameworks for understanding hydrological processes, designing infrastructure, and making informed decisions under varying environmental, social, and economic conditions. Here are some common mathematical models and their applications in water management:

**1. Hydrological Models**

- **Purpose**: Simulate the movement, distribution, and quality of water within natural and built systems.
- **Examples**:
  - **Rainfall-Runoff Models**: Estimate runoff from precipitation (e.g., SCS-CN method, HEC-HMS).
  - **Flood Prediction Models**: Predict flood levels and extents using rainfall and topography data.
- **Applications**: Flood control, reservoir operation, and stormwater management.

**2. Groundwater Flow Models**

- **Purpose**: Simulate the behavior of groundwater, including flow, recharge, and interaction with surface water.
- **Examples**:
  - **MODFLOW**: A widely used numerical model to simulate groundwater flow.
  - **Analytical Models**: Solve specific problems like well drawdown (e.g., Theis solution).
- **Applications**: Groundwater resource management, contamination studies, and aquifer recharge planning.

**3. Water Quality Models**

- **Purpose**: Analyze and predict changes in water quality due to natural and human-induced factors.
- **Examples**:
  - **QUAL2K**: Simulates the flow and quality of rivers and streams.
  - **SWAT (Soil and Water Assessment Tool)**: Models water quality in watersheds.
- **Applications**: Pollution control, wastewater treatment planning, and ecosystem protection.

**4. Optimization Models**

- **Purpose**: Optimize the allocation and management of water resources based on competing demands and constraints.
- **Techniques Used**:
    - Linear Programming (LP): For optimizing water distribution.
    - Dynamic Programming (DP): Used in reservoir operation and flood management.
    - Genetic Algorithms: Solve complex, nonlinear optimization problems.
- **Applications**: Irrigation planning, reservoir operation, and urban water supply management.

**5. Hydraulic Models**

- **Purpose**: Simulate the behavior of water in pipes, channels, and rivers.
- **Examples**:
    - **EPANET**: Models water distribution networks.
    - **MIKE 11**: Simulates river and open channel flows.
- **Applications**: Urban water supply design, floodplain management, and irrigation system design.

**6. Climate and Weather Models**

- **Purpose**: Predict the impact of climate variability and change on water resources.
- **Examples**:
    - General Circulation Models (GCMs): Simulate long-term climate patterns.
    - Regional Climate Models (RCMs): Provide detailed climate predictions at smaller scales.
- **Applications**: Drought risk management, flood forecasting, and long-term water resource planning.

**7. Decision Support Systems (DSS)**

- **Purpose**: Integrate multiple models and data sources to support decision-making.
- **Examples**: Water Evaluation and Planning (WEAP) system combines supply, demand, and quality models.
- **Applications**: Balancing water allocation between agriculture, industry, and households.

**8. Economic Models in Water Management**

- **Purpose**: Evaluate the economic efficiency of water management strategies.

- **Techniques Used**: Cost-benefit analysis, econometric modeling, and game theory.
- **Applications**: Pricing water, evaluating infrastructure investments, and resolving conflicts over shared resources.

**Mathematical Models for Cleaning Flood Water**

Mathematical models for cleaning flood water focus on simulating and optimizing processes to remove pollutants, restore water quality, and facilitate water reuse. These models integrate hydrological, chemical, and biological parameters to design efficient water treatment systems and manage large-scale floodwater cleanup. Here are key models and approaches:

**1. Water Quality Assessment Models**

- **Purpose**: Evaluate pollutant levels in floodwaters and predict the effectiveness of cleaning strategies.
- **Examples**:
  - **QUAL2K**: Models water quality in streams and rivers, simulating processes like oxygen balance and pollutant removal.
  - **SWAT (Soil and Water Assessment Tool)**: Assesses pollutant loads in floodwaters from agricultural or urban runoff.
- **Applications**: Identifying hotspots of contamination and prioritizing treatment zones.

**2. Sediment Transport Models**

- **Purpose**: Analyze sediment deposition and transport during floods, which often carry pollutants like heavy metals.
- **Examples**:
  - **HEC-RAS (River Analysis System)**: Simulates sediment transport and its impact on floodwater quality.
  - **MIKE 21**: Models sediment dynamics in floodplains and coastal regions.
- **Applications**: Designing sediment removal processes in floodwater treatment.

**3. Adsorption and Filtration Models**

- **Purpose**: Simulate processes for removing contaminants from floodwater using filtration and adsorption techniques.

- **Mathematical Frameworks**:
  - **Langmuir and Freundlich Isotherms**: Used to model adsorption of pollutants like heavy metals and organic compounds onto cleaning materials (e.g., activated carbon).
  - **Darcy's Law**: Applied to filtration systems to model water flow and contaminant removal through porous media.
- **Applications**: Optimizing treatment plants for large-scale floodwater filtration.

**4. Biological Treatment Models**

- **Purpose**: Simulate the use of biological processes, such as wetlands or microbial treatment, for cleaning floodwater.
- **Examples**:
  - **Activated Sludge Models (ASM)**: Model microbial degradation of organic pollutants in wastewater, applicable to floodwater treatment.
  - **Constructed Wetlands Models**: Simulate nutrient and pollutant removal by plants and microorganisms in wetland systems.
- **Applications**: Designing eco-friendly floodwater treatment systems.

**5. Chemical Treatment Models**

- **Purpose**: Simulate chemical dosing and reactions for disinfecting and removing harmful substances from floodwater.
- **Examples**:
  - **Chemical Kinetics Models**: Predict the behavior of reactions (e.g., chlorine disinfection or coagulation).
  - **Mixing and Transport Models**: Simulate the distribution of treatment chemicals in large floodwater bodies.
- **Applications**: Scaling chemical treatment systems for large volumes of floodwater.

**6. Hydrodynamic and Contaminant Transport Models**

- **Purpose**: Simulate the flow and dispersion of pollutants in floodwaters.
- **Examples**:
  - **Delft3D**: Models water movement and pollutant dispersion in flood scenarios.
  - **ADVECTION-Diffusion Models**: Predict how contaminants spread and settle over time.

- **Applications**: Designing containment and cleanup strategies for polluted floodwaters.

**7. Optimization Models for Resource Allocation**

- **Purpose**: Optimize the deployment of cleaning technologies and resources during floodwater treatment.
- **Examples**:
  - **Linear Programming Models**: Minimize costs or energy while maximizing pollutant removal efficiency.
  - **Dynamic Programming**: Optimize sequential decisions in multi-stage floodwater treatment.
- **Applications**: Allocating cleaning resources (e.g., mobile treatment units) to prioritize the most affected areas.

**8. Decision Support Systems (DSS)**

- **Purpose**: Integrate various models to support decision-making for large-scale floodwater cleanup.
- **Examples**:
  - Combining hydrological, water quality, and treatment models into a single framework.
- **Applications**: Real-time floodwater cleanup management and disaster response.

**Mathematical Formulations in Action**

- **Mass Balance Equations**: Used to track pollutant levels during floodwater treatment.
- **Reactor Models**: Simulate processes in treatment tanks, such as coagulation, sedimentation, and aeration.
- **Flow Models**: Predict water flow through treatment systems to optimize throughput.

**Benefits of Mathematical Models**

- **Precision**: Quantifies pollutant levels and treatment efficiency.
- **Cost Optimization**: Reduces costs by optimizing treatment processes and resource allocation.
- **Scalability**: Adapts to large-scale flood events and varying water quality conditions.
- **Sustainability**: Helps design eco-friendly and energy-efficient water treatment systems.

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# EMERGING TECHNOLOGIES IN PRECISION AGRICULTURE: THE ROLE OF IOT, AI, AND DRONES

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## Introduction to Precision Farming:

Precision agriculture, also known as site-specific crop management (SSCM), is a rapidly evolving farming approach that leverages advanced technologies to optimize agricultural productivity while minimizing environmental impact. It enables farmers to address a wide range of challenges by using data-driven insights and real-time monitoring to make informed decisions (Zhang & Kovacs, 2022).

The term "precision farming" was first highlighted in March 1994 during the Second International Conference on Site-Specific Management for Agricultural Systems in Minneapolis, Minnesota, USA. This concept involves the development of agricultural management systems that account for spatial and temporal variability within a field, allowing for more efficient resource allocation (Tsouros *et al.,* 2022). Over time, precision agriculture has been referred to by various names, including spatially prescriptive farming, computer-assisted farming, site-specific farming, high-tech sustainable agriculture, and soil-specific crop management (Yang *et al.,* 2021).

## Definition and Key Concepts

Precision farming is broadly defined as "an information and technology-based agricultural management system that identifies, analyses, and manages soil and crop conditions with respect to spatial and temporal variability to maximize profitability, sustainability, and environmental protection" (NIST, 2023). It integrates technologies such as remote sensing, IoT-based monitoring systems, artificial intelligence (AI), and drones to enhance decision-making and operational efficiency (Sharma *et al.,* 2020).

In a more applied sense, precision farming focuses on the precise evaluation of soil and crop management practices to address varying field conditions effectively. By implementing SSCM, farmers can optimize their input use, including fertilizers, pesticides, and water, ensuring sustainable and climate-smart agricultural practices (EASA, 2023).

## Technological Advancements in Precision Agriculture

Recent advancements in satellite imagery, machine learning, and UAV (unmanned aerial vehicle) technology have further revolutionized precision agriculture. Emerging innovations such as real-time soil health monitoring, AI-driven predictive analytics, and LiDAR-based mapping have significantly improved agricultural productivity (Mohanty *et al.,* 2016; Kamilaris & Prenafeta-Boldú, 2018). The integration of Internet of Things (IoT) sensors, AI-powered data analytics, and autonomous drones has made it possible to detect crop diseases, monitor irrigation efficiency, and enhance yield predictions with greater accuracy (Yang *et al.,* 2021).

With ongoing research and technological advancements, precision farming is expected to play a crucial role in climate-smart agriculture, reducing resource wastage, and ensuring food security for a growing global population (Zhang and Kovacs (2022).

**Why precision farming**

- To increase agriculture productivity
- Prevents soil degradation
- Reduction of chemical application in crop production
- Efficient use of water resources
- Dissemination of modern farm practices to improve quality, quantity and reduced cost of production
- Developing favourable attitudes
- Precision farming changing the socio-economic status of farmers

## Importance of Technology in Modern Agriculture

India, with over 155 million hectares of arable land, ranks among the world's largest agricultural producers. However, the sector faces significant structural challenges, including low productivity, uneconomical landholding sizes, sub-optimal input efficiency, high biotic losses, and limited mechanization (Gokulam Seek IAS, 2023). Additionally, pressing concerns such as climate change, depletion of natural resources, and food security threats necessitate a transition from traditional farming methods to precision agriculture. This shift is further supported by global market projections, indicating that the precision farming sector is expected to reach USD 14.6 billion by 2026.

To address these challenges and improve agricultural efficiency, the integration of Internet of Things (IoT), Artificial Intelligence (AI), and Unmanned Aerial Vehicles (UAVs or drones) has become crucial. These technologies have transformed traditional farming into a data-driven and highly efficient industry, enabling farmers to make informed decisions based on real-time insights (Kamilaris & Prenafeta-Boldú, 2018). The adoption of automation, digital tools, and advanced analytics has allowed farmers to optimize resource use, minimize environmental impact, and enhance overall crop productivity (Yang *et al.,* 2021).

**1. The Internet of Things (IoT) in Agriculture**

The Internet of Things (IoT) is emerging as a revolutionary force in agriculture by providing real-time monitoring and control of key agricultural parameters such as soil conditions, irrigation levels, and environmental factors. These technologies optimize resource allocation and enhance crop yields while ensuring sustainability (NIST, 2023). IoT-based smart sensors and cloud computing further enable precision farming by offering automated irrigation systems, predictive maintenance of farm equipment, and precise nutrient management (Tsouros *et al.,* 2022).

When combined with machine learning, UAVs, and big data analytics, IoT-driven precision agriculture becomes even more effective. These technologies help in pest detection, disease prediction, yield forecasting, and soil health monitoring, making agriculture more resilient, productive, and climate-adaptive (Sharma *et al.,* 2020). By leveraging AI-powered analytics and remote sensing technologies, farmers can make more informed decisions, reducing losses and maximizing output while promoting environmental conservation (Zhang & Kovacs, 2022).

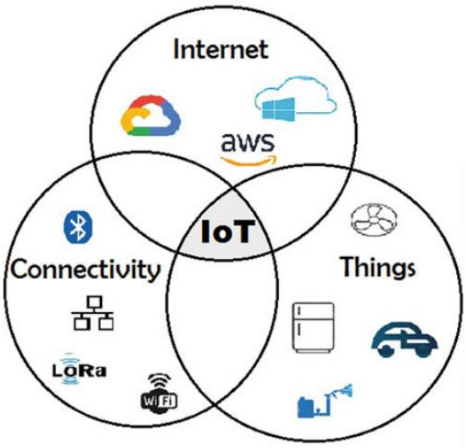
**1.1 Role of Internet of Things (IoT) in Precision Farming**

IoT-based smart irrigation systems are designed to optimize water usage, enhance crop yields and reduce the environmental impact of farming activities. These systems integrate sensors, controllers and communication networks to monitor soil moisture, weather conditions and plant needs in real-time. By utilizing data-driven algorithms, smart irrigation systems can automatically adjust watering schedules, ensuring that crops receive the right amount of water at the right time. This approach not only conserves water resources but also minimizes the risk of over or under-irrigation, leading to healthier plants and increased agricultural productivity. The implementation of IoT-based irrigation systems also allows for remote monitoring and control, providing farmers with greater flexibility and efficiency in managing their operations.

## 1.2 What is IoT?

The concept of connected device was first introduced since the 1972 but the actual term Internet of things was established by Ashton. It may be depicted as an group of interconnected computing devices consisting of mechanical and digital devices, any items or any living beings. It indicates the capacity to move information over a network without necessity of any human to human or human to computer cooperation. The Internet of things objects consist of sensors, softwares, network connections and necessary electronics and it empowers them to gather and exchange data and make them responsive.

As described in Fig. 1, with regards to interfacing the Internet of things (IoT), there are an apparently overpowering number of alternatives. Cellular, satellite, WiFi, Bluetooth, RFID, NFC, LPWAN and Ethernet are only a portion of the potential approaches to associate a sensor/gadget and within each of these options there can be different providers.

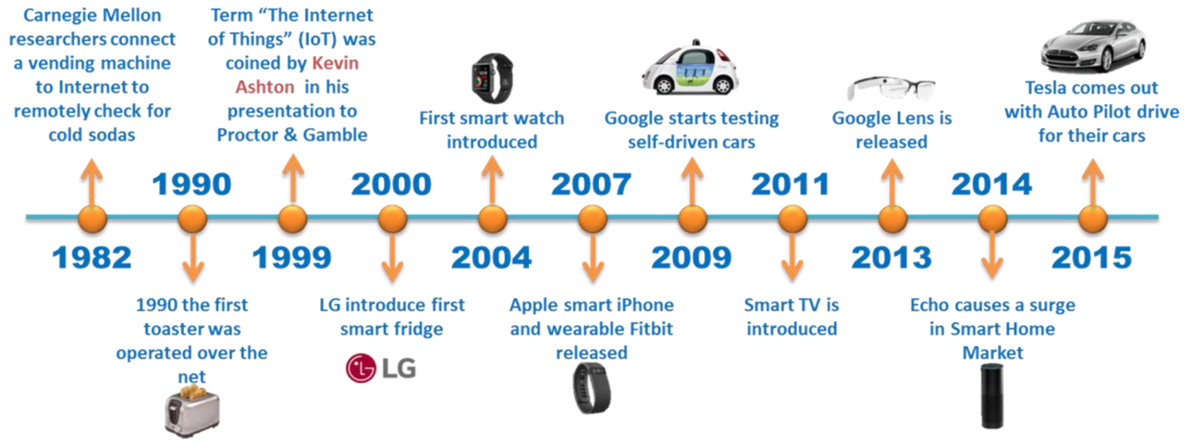


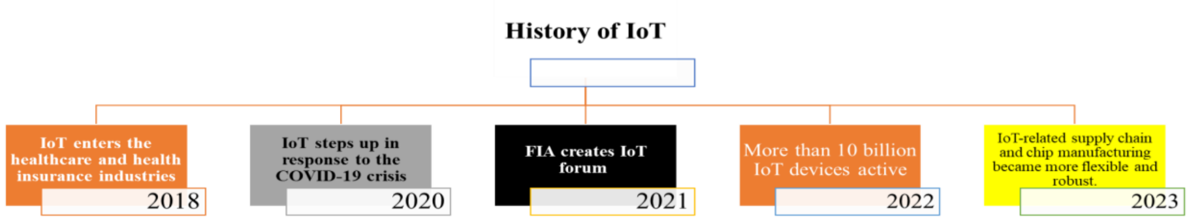

**IoT framework**

**Definition:**

- ❖ IoT is the network of physical objects or "things" embedded with electronics , software , sensors and network connectivity , which enables these objects to collect and exchange data.
- ❖ It refers to a system of interrelated, internet – connected objects that are able to collect and transfer data over a wireless network without human intervention.
- ❖ The IoT is a giant network of connected things and people – all of which collect and share data about the way they are used and about the environment around them.

### 1.3 History of IoT




### 1.4 The key role played by IoT in smart agriculture

1. Water management
2. Irrigation management
3. Soil management
4. Weather management
5. Precision farming
6. Nutrient management
7. Waste management
8. Livestock monitoring
9. Tracking and tracing
10. Crop management

### 1.5 Sensors used in IoT

A sensor is indeed a device that monitors several parameters, such as pressure, light, moisture level, and so on. Most of the time, the sensor output is an electrical signal, which is sent to a micro-controller for the further analysis on a network.

An intelligent sensor node comprises of three components namely: Sense, Compute, and Communicate. The sensing component is responsible for capturing the real-world parameters such as moisture, temperature, etc. The computational component preprocesses the captured parameter value and the communication component makes sure that the gateway sensor nodes are able to communicate with gateway nodes and can share the information among them. A variety of sensors are available for measuring and calculating the specifications of a farming field. (Sinha, B.B. and Dhanalakshmi, R., 2022).

**Table 1: Different types of sensors used in IoT and their functions:**

| Sensor Type | Function |
|---|---|
| pH Sensor | Measures soil acidity or alkalinity to optimize crop growth conditions. |
| PIR Sensor | Detects motion and temperature variations to monitor field activity. |
| UV Sensor | Tracks ultraviolet radiation to assess plant health and environmental effects. |
| Weed Seeker | Identifies and selectively sprays weeds to minimize herbicide usage. |
| Wind Speed Sensor | Measures wind conditions for weather forecasting and farm operations. |
| Soil Moisture Sensor | Determines soil water content to optimize irrigation and plant growth. |
| Temperature Sensor | Monitors soil and ambient temperature for nutrient absorption and crop health. |
| Gas Sensor | Detects gases like $CO_2$ and methane to monitor air quality and storage conditions. |
| Humidity Sensor | Measures air moisture levels to ensure optimal plant growth and climate control. |
| Motion Detector Sensor | Identifies movement in the field to prevent intrusions and crop damage. |
| GPS | Provides precise location tracking for farm equipment and livestock. |
| Photodiode Sensor | Analyzes soil properties such as organic matter and moisture using light. |
| Tensiometer | Measures soil water tension to assist in irrigation scheduling and water management. |

**Table 2: Devices used in IoT:**

| **Hardwares used in IoT** | **Description** |
|---|---|
| ESP8266 | The ESp8266 is a Wi-Fi module that helps in establishing wireless connection between different components of IoT-based smart agriculture. |
| RTC module | It enables the module to keep track of precise timings of any operation to be performed by the designed IoT system. |
| DHT11 | The DHT11 is a widely used sensor for measuring humidity and temperature. The sensor has a precision of ±1 ◦C and ±1% when measuring temperature between 0 C and 50 C & humidity between 20% and 90%. |
| ESP-32 Microcontroller | To process different algorithm |
| DS18B20 | Measure soil temperature |
| Capacitive Soil Moisture Sensor V2.0 | Soil moisture detection |

### 1.6 Advantages of IoT in Agriculture

- Minimize human effort and save time.
- Leads to more automation and technical optimization.
- Help us to reduce waste and use our natural resources effectively.
- Lower production risk due to better control over the internal process.
- Enhanced production levels.
- Decisions can be made in real-time and from anywhere.
- Reduces overall water consumption.
- Reduce soil erosion and leaching of nutrients.

## 2. Role of Artificial Intelligence (AI) in Precision Farming

Artificial Intelligence (AI) is a branch of computer science aimed at developing intelligent machines capable of simulating human intelligence processes, including learning, reasoning, and self-correction. These processes are fundamental to various applications such as expert systems, speech recognition, and machine vision (Russell & Norvig, 2003). AI is not about "Man vs. Machine" but rather a synergy between "Man and Machine," allowing for enhanced decision-making and efficiency in various fields, including agriculture.

The term **Artificial Intelligence** was coined by John McCarthy, who envisioned machines that could perceive their environment and take actions to maximize success (Russell & Norvig, 2003). In modern agriculture, AI is revolutionizing traditional farming methods by integrating machine learning, computer vision, and data analytics to create predictive, intelligent systems. These AI-driven solutions optimize resource utilization and improve efficiency in crop management, irrigation, and predictive analytics (Sinha & Dhanalakshmi, 2023).

AI applications in precision farming include weed identification, chemical spraying, mapping, and site-specific crop management. By leveraging real-time data from sensors and satellite imagery, AI enables farmers to monitor crop health, detect diseases early, and implement targeted interventions, reducing losses and improving yield (Sinha & Dhanalakshmi, 2023). Additionally, AI-powered automation enhances irrigation efficiency by analyzing soil moisture levels and weather conditions to optimize water distribution.

With growing concerns over climate change, food security, and sustainable agriculture, AI has emerged as a transformative tool in addressing these challenges. However, its widespread adoption also presents ethical considerations, such as data privacy and the digital divide among farmers (Russell & Norvig, 2003) and Rimpika *et al.,* (2023).

### 2.1 Real-World Challenges

1. **Technological Adoption Barriers**: Many farmers, especially in resource-constrained regions, face difficulties in implementing AI due to high costs, lack of infrastructure, and insufficient technical expertise.
2. **Data Privacy Concerns**: The collection and use of agricultural data raise concerns regarding security, ownership, and potential misuse by corporations or third parties.
3. **Digital Divide**: The unequal distribution of AI technology could widen the gap between large agribusinesses and smallholder farmers, leading to disparities in productivity and market competitiveness.
4. **Algorithm Bias and Ethical Issues**: AI models may unintentionally favor certain crops, farming techniques, or regions, resulting in biased recommendations that do not cater to diverse agricultural settings.
5. **Regulatory and Policy Challenges**: Governments and agricultural organizations must establish policies to regulate AI use, ensuring fair and sustainable farming practices.

### 2.2 Methodology

A systematic approach is essential for integrating AI into precision farming:

1. **Data Collection**: AI utilizes multiple data sources to improve precision farming outcomes:
   - **Remote Sensing**: Drones, satellites, and high-resolution imaging capture field data, detecting crop health, soil moisture, and pest infestations.
   - **Sensor Networks**: Soil sensors monitor pH levels, moisture, temperature, and nutrient content in real-time.
   - **Weather Data**: AI integrates meteorological information to predict temperature, rainfall, and potential climate threats.
   - **Historical Farm Records**: Machine learning models analyze past agricultural data to optimize crop selection, yield prediction, and resource allocation.
2. **Weed Identification and Control**:
   - **Computer Vision-Based Weed Detection**: AI-powered cameras and deep learning algorithms differentiate between crops and weeds by analyzing plant features such as shape, color, and texture.
   - **Robotic Weed Removal**: Autonomous machines equipped with AI selectively remove weeds without damaging crops, reducing dependency on herbicides.
   - **Smart Herbicide Application**: AI-driven sprayers identify weed-prone areas and apply precise amounts of herbicide, minimizing chemical overuse and environmental impact.
3. **GIS Mapping & Analysis**:
   - **Geographic Information System (GIS)** technology maps soil variability, water distribution, and pest occurrence, allowing for targeted interventions.
   - **Spatial Analysis**: AI-powered algorithms identify patterns and optimize field zoning for efficient crop rotation and resource application.
4. **AI-Based Decision Support**:
   - **Machine Learning Predictions**: AI analyzes data to predict crop diseases, detect nutrient deficiencies, and forecast optimal planting and harvesting periods.
   - **Adaptive Irrigation Systems**: AI-driven irrigation models adjust water distribution based on soil moisture levels and weather forecasts.

- **Yield Optimization**: AI integrates multi-source data to provide real-time recommendations on fertilizer use, pest control, and harvesting strategies.

5. **Automation & Smart Equipment**:
    - **Autonomous Tractors & Drones**: AI-powered machinery performs seeding, irrigation, and spraying with high precision.
    - **Robotic Harvesting**: AI-enabled robots identify ripe crops and perform selective harvesting, reducing labor costs and post-harvest losses.

**2.3 Key AI Applications in Precision Farming**

1. **Crop Health Monitoring**: AI-powered computer vision and deep learning detect diseases and nutrient deficiencies early, reducing losses and minimizing pesticide use.
2. **Precision Irrigation**: AI-based models process soil moisture and weather data to optimize water use, reducing waste and improving water conservation efforts.
3. **Weed Detection & Control**: AI-enabled robotics distinguish between crops and weeds, allowing for targeted and automated weed management using less herbicide.
4. **Livestock Management**: AI-powered wearable devices and sensors track animal health, optimizing feeding schedules, disease prevention, and improving livestock welfare.
5. **Supply Chain Optimization**: AI enhances logistics by predicting market demand, optimizing storage conditions, and reducing post-harvest losses.
6. **Yield Forecasting and Risk Assessment**: AI-driven predictive analytics help farmers anticipate crop performance, mitigate risks, and make informed investment decisions.

**2.4 Types of machine learning algorithms commonly used for identification of objects:**

**1. Supervised Learning Algorithms:**

a) Support Vector Machines (SVM): SVMs are effective for binary classification tasks and can be used to classify weeds versus crops based on features extracted from images.

❖ The goal of the SVM algorithm is to create the best line or decision boundary that can segregate n-dimensional space (Cortes and Vapnik, 1995) into classes so that we can easily put the new data point in the correct category in the future (Burks *et al.,* 2005). This best decision boundary is called a hyperplane.

**b) Random Forest:**

- *Random Forest is a classifier that contains a number of decision trees on various subsets of the given dataset and takes the average to improve the predictive accuracy of that dataset."* (Breiman, 2001).
- Instead of relying on one decision tree, the random forest takes the prediction from each tree and based on the majority votes of predictions, and it predicts the final output. (Pal, 2005).

**2. Deep Learning Algorithms:**

a) Convolutional Neural Networks (CNN): Convolutional Neural Networks, or CNNs, are a specialized class of neural networks designed to effectively process grid-like data, such as images.

❖ Image classification: CNNs are the state-of-the-art models for image classification. They can be used to classify images into different categories, such as cats and dogs, cars and trucks, and flowers and animals. (LeCun *et al.,* 1998).

❖ Object detection: They can also be used to localize objects in images, which means that they can identify the location of an object in an image.

❖ Image segmentation: CNNs can be used to segment images, which means that they can identify and label different objects in an image. This is useful for applications such as medical imaging and robotics. (Kamilaris and Prenafeta-Boldú, 2018).

**Artificial Neural Network (ANN)**

❖ Image data augmentation is used to increase the training set for achieving improved accuracy and eliminate the problems of overtraining (Rumelhart, Hinton and Williams, 1986).

❖ A simple neural network contains an input, hidden, and output layer with linkages

❖ Inspired by the way neurons are organized and interconnected in a brain. (Mohanty, Hughes and Salathé, 2016).

**Recurrent Neural Networks (RNN):** RNNs can be used for sequential data and time-series analysis, which can be useful for tracking the growth and spread of weeds over time.

**3. Object Detection Algorithms:**

❖ YOLO (You Only Look Once): YOLO is a real-time object detection algorithm developed by Joseph Redmon and Ali Farhadi in 2015. It is a single-stage object detector that uses a convolutional neural network (CNN) to predict the bounding boxes and class probabilities of objects in input images. (Redmon *et al.,* 2016).

- The YOLO algorithm divides the input image into a grid of cells, and for each cell, it predicts the probability of the presence of an object and the bounding box coordinates of the object. It also predicts the class of the object.
- Its speed and accuracy have made it a preferred choice for agricultural applications, such as weed and pest detection (Sa *et al.,* 2017).
- YOLO has been developed in several versions, such as YOLOv1, YOLOv2, YOLOv3, YOLOv4, YOLOv5, YOLOv6, and YOLOv7.

4. **Regression algorithm:**

   Regression algorithms are the supervised learning algorithm in which the relationship between input and output is based on the training data and it predicts the output numerical value for the unseen input. Simple and multiple linear regression, polynomial regression, and logistic regression are some of the common regression algorithms.

5. KNN: it is a simple supervised classification algorithm. In this the dataset is divided into different classes based on their outputs. Thereafter, a new sample object is assigned a particular class based on its k-nearest neighbours. (Sharma *et al.,*2020).

## 3. Role of Drones in Precision Farming

### 3.1. Introduction

Drones, or Unmanned Aerial Vehicles (UAVs), have become integral to modern agriculture, enhancing efficiency, reducing costs, and improving data collection. Their integration into precision farming enables real-time monitoring, targeted resource application, and informed decision-making for farmers. Equipped with advanced sensors, artificial intelligence, and machine learning capabilities, drones offer critical insights into crop health, soil conditions, and pest infestations (Zhang & Kovacs, 2022).

### 3.2. Types of Drones According to Classification

Drones in precision farming are classified based on design, functionality, and regulatory frameworks, as outlined by institutions such as the **Federal Aviation Administration (FAA)**, **European Union Aviation Safety Agency (EASA)**, and **International Civil Aviation Organization (ICAO)** (FAA, 2023; EASA, 2023).

#### 3.2.1 Based on Design

**Fixed-Wing Drones**: Resembling small airplanes, these drones are efficient for covering extensive agricultural fields due to their long flight endurance. They require runways for takeoff and landing but offer excellent stability and fuel efficiency, making them ideal for large-scale farming (Iowa State University, 2023).

**Rotary-Wing Drones**: Typically quadcopters or hexacopters, these drones offer superior maneuverability and are suitable for close-range monitoring and spraying applications. Their ability to hover makes them effective for precision tasks like targeted pesticide application (Iowa State University, 2023).

**Hybrid Drones**: Combining fixed-wing and rotary-wing designs, hybrid drones provide both extended range and vertical takeoff capabilities, making them versatile for various agricultural tasks (Zhang & Kovacs, 2022).

### 3.2.2 Based on Functionality

**Surveillance Drones**: Equipped with high-resolution cameras and multispectral sensors, these drones monitor crop health, soil conditions, and livestock management, providing detailed analyses for informed decision-making (Yang *et al.,* 2021).

**Spraying Drones**: Designed for precise application of pesticides, herbicides, and fertilizers, these drones utilize automated spraying mechanisms to ensure even distribution, reducing environmental impact (Time, 2023).

**Mapping Drones**: With advanced imaging systems, mapping drones generate topographic and vegetation index maps, aiding in identifying areas requiring intervention (Tsouros *et al.,* 2022).

**Multi-Purpose Drones**: These versatile drones can handle multiple agricultural tasks, including monitoring, mapping, and spraying, often integrating AI and IoT technologies to optimize farming operations (Zhang & Kovacs, 2022).

### 3.2.4. Based on Weight Category

**Micro Drones (<250g)**: Ideal for basic farm surveillance and small-scale monitoring, these lightweight drones are easy to deploy for short-range applications (FAA, 2023).

**Small Drones (250g - 25kg)**: Commonly used in agriculture for mapping, spraying, and crop monitoring, these drones balance portability and performance (EASA, 2023).

**Medium Drones (25kg - 150kg)**: Suitable for extensive precision agriculture operations requiring heavier payloads, these drones can carry advanced sensors and larger spraying systems (ICAO, 2023).

**Large Drones (>150kg)**: Employed in industrial-scale farming, large drones are capable of carrying substantial payloads and operating autonomously over vast agricultural landscapes (NIST, 2023).

## 4. Applications of Drones in Agriculture

Table 3. Drones serve various applications in precision agriculture:

| Application | Description |
|---|---|
| **Crop Monitoring** | Capturing high-resolution images to detect disease outbreaks, pest infestations, and water stress, enabling timely interventions (Zhang & Kovacs, 2022). |
| **Precision Spraying** | Applying pesticides and fertilizers with accuracy, reducing waste and environmental impact (Time, 2023). |
| **Soil and Field Analysis** | Utilizing multispectral imaging to assess soil health, optimize irrigation, and improve crop yield predictions (Yang *et al.,* 2021). |
| **Livestock Monitoring** | Tracking livestock movement and assessing health conditions in large-scale farms, enhancing management efficiency (FAA, 2023). |
| **Disaster Management** | Providing rapid assessment after natural disasters such as floods or droughts, aiding in swift recovery efforts (EASA, 2023). |

## 5. Technological Advancements in Agricultural Drones

Modern agricultural drones are equipped with various advanced technologies:

**Multispectral and Hyperspectral Sensors**: These sensors analyze plant health and detect stress factors before visible symptoms appear, allowing for proactive management (Yang *et al.,* 2021).

**LiDAR Technology**: Provides 3D mapping for precise land analysis and terrain modeling, aiding in effective planning and resource allocation (Zhang & Kovacs, 2022).

**Artificial Intelligence and Machine Learning**: Enhance data processing for predictive analysis and automated decision-making, improving efficiency and accuracy in farming operations (Tsouros *et al.,* 2022).

**Autonomous Navigation**: Reduces human intervention by utilizing GPS and AI-driven path planning, enabling drones to operate seamlessly across fields (FAA, 2023).

## Conclusion:

The integration of IoT, AI, and drones in precision agriculture has revolutionized traditional farming by enabling data-driven decision-making, optimizing resource use, and increasing productivity. IoT facilitates real-time monitoring of soil, crop health, and environmental conditions, improving farm efficiency and sustainability. AI-driven technologies, such as machine learning and computer vision, enhance predictive analytics for yield forecasting, weed detection, and automated decision-making. Drones play a crucial role in precision farming by enabling aerial surveillance, multispectral imaging, and precision spraying, reducing labor and input costs. These technologies collectively help in addressing challenges related to climate change, resource depletion, and food security. Despite their advantages, widespread adoption faces barriers such as high costs, lack of technical knowledge, and infrastructure limitations, especially in developing regions. Ethical concerns related to data privacy, algorithm bias, and farmer dependency on technology must also be considered. Future advancements in AI and IoT are expected to enhance automation, interoperability, and decision-making accuracy in agriculture. Governments and policymakers need to invest in digital infrastructure and training programs to facilitate broader adoption. Overall, the synergy of IoT, AI, and drones is transforming agriculture into a highly efficient, sustainable, and resilient industry.

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# NEXT-GENERATION FARMING: THE INTEGRATION OF REMOTE SENSING WITH CROP MODELS

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**Abstract:**

The integration of remote sensing (RS) with crop models has revolutionized agricultural decision-making by enhancing data accuracy, real-time monitoring, and predictive capabilities. Remote sensing provides large-scale, high-resolution spatial data on vegetation health, soil moisture, and evapotranspiration, which significantly improve the reliability of crop models. These models, such as DSSAT, APSIM, AquaCrop, and WOFOST, simulate plant growth and yield under varying environmental and management conditions. However, their accuracy is often limited by uncertainties in input parameters, such as soil properties and micro-meteorological variables. By incorporating vegetation indices (NDVI, EVI, and LAI), soil moisture estimates from sensors like SMAP and Sentinel-1, and evapotranspiration models (SEBAL and METRIC), remote sensing enhances the precision of crop simulations. Various integration techniques, including data assimilation, machine learning, and real-time model updating, ensure that RS data dynamically refines model predictions. This synergy improves yield forecasting, irrigation scheduling, and overall crop management, supporting precision agriculture and climate change adaptation. The fusion of remote sensing with crop modeling enables large-scale agricultural monitoring, early warning systems for drought and pests, and more efficient resource management. As advancements in remote sensing technologies and computational modeling continue to evolve, their seamless integration will play a pivotal role in ensuring global food security and sustainable agricultural development.

**Keywords:** Remote Sensing, Crop Models, Data Assimilation, Precision Agriculture

**Introduction:**

Agriculture is undergoing a transformative shift driven by technological advancements that enhance precision, efficiency, and sustainability. Among these advancements, the integration of remote sensing (RS) with crop models has emerged as a critical approach for improving agricultural decision-making. Remote sensing provides high-resolution spatial data on vegetation health, soil moisture, and evapotranspiration, while crop models, such as DSSAT, APSIM, AquaCrop, and WOFOST, simulate plant growth and yield under various environmental and management conditions (Jones *et al.,* 2017). The fusion of these technologies enables more accurate yield prediction, optimized irrigation scheduling, and enhanced climate change resilience, thus supporting precision agriculture and sustainable farming practices.

**Definition**

**Remote Sensing:** Remote Sensing (RS) is the process of collecting and interpreting information about an object, area, or event without being in physical contact with it (Kairu, 1982).

It typically involves capturing data from satellites, aircraft, drones, or ground-based sensors to monitor Earth's surface.

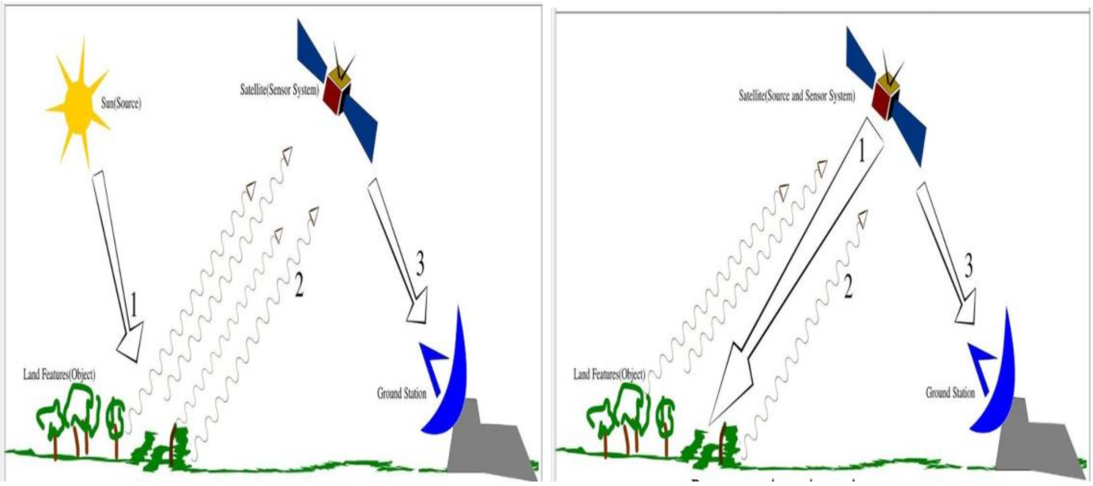
**Types of remote sensing**

**1. Passive remote sensing-**

Passive remote sensing records the electromagnetic energy that was reflected (eg. Blue, Green, Red and NIR) or emitted (eg. Thermal infrared energy) from the surface of the earth.

**2. Active remote sensing-**

Active remote sensing creates their own electromagnetic energy (example- radar gun) that is transmitted from the sensor towards the terrain, interacts with the terrain producing backscatter of energy and is recorded by the sensor’s receiver. These measurements can be made at any time of the day.




**i) Passive remote sensing** **ii) Active remote sensing**

**Figure 1: A diagram showing the difference between i) passive and ii) active remote sensing. (Wikimedia Commons (2015)**

**Crop models**

Crop models are computer-based simulations that predict plant growth, development, and yield based on environmental and management inputs. These models help in understanding how crops respond to various conditions such as weather, soil, irrigation, and fertilization.

Crop models are sometimes also called crop yield models or agricultural system models (Kasampalis *et al.,* 2018).

**Common Crop Models:**

- **DSSAT (Decision Support System for Agrotechnology Transfer)** – Simulates multiple crops using different environmental parameters.
- **APSIM (Agricultural Production Systems sIMulator)** – Used for long-term climate impact assessments.
- **AquaCrop (FAO Model)** – Focuses on water-limited conditions.
- **WOFOST (World Food Studies Model)** – Used for regional crop production analysis.

**Key Inputs and Outputs:**

**Inputs:** Weather (temperature, rainfall), soil properties, crop genetics, and management practices.

**Outputs:** Yield estimates, biomass production, water/nutrient use efficiency.

**Why is Integrating Remote Sensing with Crop Models Important?**

One of the main limitations of crop models is the difficulty in obtaining reliable input data. Uncertainties in the spatial distribution of soil properties, crop management practices, and micro-meteorological variables at the field level reduce the confidence in model outputs and their spatial representativeness (Stone and Meinke, 2005; Therond *et al.,* 2011). Integrating remote sensing (RS) with crop models addresses these challenges by enhancing data accuracy, enabling real-time monitoring, and improving predictive capabilities, thereby strengthening agricultural decision-making.

**How Remote Sensing Data is Integrated into Crop Models**

**1) Types of Remote Sensing Data Used in Crop Models**

**a) Vegetation Indices (VIs):**

The vegetation index (VI) is an arithmetic combination of two or more spectral bands associated with vegetation properties. It is commonly used for phenological monitoring, vegetation classification, and deriving biophysical parameters related to radiometric and structural characteristics of vegetation (Huete *et al.,* 1999).

**i) Normalized Difference Vegetation Index (NDVI):** Measures the difference between near-infrared (which vegetation strongly reflects) and red light (which vegetation absorbs). NDVI is widely used to assess plant health and vigor.

$$\mathbf{NDVI} = \frac{\mathbf{NIR - RED}}{\mathbf{NIR + RED}}$$

Where, NIR represents the near-infrared reflectance and

Red represents the red reflectance

MODIS Normalized Difference Vegetation Index (NDVI) is a freely available product with the highest spatial resolution currently used successfully in forecasting applications (Ren *et al.,* 2008; Becker-Reshef *et al.,* 2010).

**ii) Enhanced Vegetation Index (EVI):** A vegetation index designed to improve the sensitivity and accuracy of vegetation monitoring. It improves upon NDVI by incorporating background adjustment and atmospheric resistance, correcting for canopy background signals and atmospheric effects. This modification makes EVI more effective in high biomass regions, providing more precise vegetation assessments, especially in areas with dense vegetation (Matsushita *et al.,* 2007).

**iii) Leaf Area Index (LAI):** Represents the total leaf area per unit ground area, crucial for understanding photosynthetic capacity and growth.

These indices are derived from satellite imagery and are integral in monitoring crop growth stages, health, and predicting yields.

However, vegetation indices have certain operational limitations. Their values can fluctuate without actual changes in crop growth or yield potential due to environmental factors like soil and atmospheric conditions (Hatfield *et al.,* 2008). This variability makes the relationship between a vegetation index and crop characteristics inconsistent, often varying by location and time. Unlike simulation models, satellite-based vegetation indices provide broad spatial coverage but limited temporal resolution (Orlando *et al.,* 2015).

**b) Moisture Estimation:** Accurate soil moisture information is vital for modeling water availability to crops, influencing growth and yield outcomes.

**i) Soil Moisture Active Passive (SMAP):** A NASA mission that provides global soil moisture and freeze/thaw state measurements, aiding in irrigation planning, drought assessment, and climate modeling. SMAP data help reduce uncertainties in global carbon balance estimation by addressing the missing carbon sink in boreal regions. Using L-band radar and radiometer technology, SMAP delivers high-resolution soil moisture maps every two to three days, supporting agricultural productivity, water resource management, and environmental monitoring (Entekhabi *et al.,* 2010).

Additionally, SMAP data enhance land surface and hydrological modeling by improving soil moisture initialization, leading to more accurate predictions of climate and water cycle dynamics.

**ii) Sentinel-1:** A European Space Agency satellite equipped with Synthetic Aperture Radar (SAR) capable of penetrating cloud cover to deliver reliable soil moisture data.

**c) Evapotranspiration (ET):** Integrating ET estimates into crop models helps in understanding water use efficiency and scheduling irrigation.

**i) Surface Energy Balance Algorithm for Land (SEBAL):** It utilizes satellite data to estimate actual evapotranspiration (ET) by analyzing land surface energy balances, including net radiation, soil heat flux, and sensible heat flux. Additionally, SEBAL aids in assessing crop biomass production, facilitating integrated estimations of crop yield, water use, and water productivity (Zwart and Bastiaanssen, 2007).

**ii) Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC):** A variant of SEBAL, METRIC incorporates localized calibration for precise ET mapping. METRIC has been used to monitor water rights compliance and aquifer depletion, as a tool for water resource planning, and in hydrologic modeling (Morse *et al.,* 2004).

**d) Yield Estimation and Forecasting:** The integration of remote sensing data with crop models enhances yield prediction by tracking crop growth and health indicators over time. For instance, the use of satellite-derived vegetation indices in crop modeling has significantly improved yield estimations for different crops.

**2) Methods of Integration**

**i) Data Assimilation:** This method involves incorporating real-time remote sensing data into crop models to update and correct model states, leading to improved accuracy in simulations.

The development of data assimilation models is trending towards more refined, diversified, and integrated systems, enhancing their applicability in precision agriculture.

**Example:** i) Soil moisture estimations (SWI) collected from coarse resolution satellite microwave sensors are assimilated using the Ensemble Kalman filter (EnKF) to rectify errors in the water balance of the World Food Studies (WOFOST) crop model (De Wit and Van Diepen, 2007).

**ii) Data Fusion Approach:** Machine Learning Approach - Employs algorithms to learn patterns from diverse datasets, thereby enhancing the predictive capabilities of crop models.

**Example:** The Multi-modal Gated Fusion (MMGF) model, a deep learning-based approach, integrated Sentinel-2 multi-spectral imagery, weather data, soil properties, and topographic information by using modality-specific encoders and a Gated Unit (GU) module to assign adaptive fusion weights, in order to enhance yield prediction accuracy in crop models (Mena *et al.,* 2025).

**iii) Real-time Model Updating:** Continuous integration of remote sensing data allows crop models to adjust predictions dynamically, thereby reflecting current field conditions. This approach is essential for timely decision-making in precision agriculture.

**Example:** T-3D-SDL (Sparse Dictionary Learning) integrates real-time field monitoring data with 3D FEM simulations using a Bayesian framework to improve geotechnical predictions, thereby achieving high spatial resolution and minimal latency (Tian *et al.,* 2025).

**Benefits of integration:**

- Remote sensing can fill in the gaps in crop models by providing spatial information that is needed for better regional yield forecasting (Kasampalis *et al.,* 2018).
- **Improved Model Accuracy:** Remote sensing provides real-time, instantaneous, non-destructive, and high-resolution data for better model calibration (Kasampalis *et al.,* 2018).
- **Large-Scale Monitoring:** Satellites cover vast agricultural regions, reducing dependence on ground-based observations.
- **Early Warning Systems:** Helps predict droughts, pest outbreaks, and yield losses.
- **Precision Agriculture:** Enables site-specific crop management based on spatial variability.
- **Climate Change Assessment:** Facilitates the study of long-term climate impacts on agriculture.
- Remote sensing combined with field observations and crop growth models is a useful tool for evaluating crop growth conditions and yield, particularly in areas with limited data or without ground data (Akumaga *et al.,* 2023).

**Limitations:**

- **Temporal and Spatial Resolution Constraints:** Satellite data often have trade-offs between temporal and spatial resolution. High-resolution images (e.g., Sentinel-2) have a lower revisit frequency, while low-resolution products (e.g., MODIS) provide frequent data but with coarser resolution, leading to data gaps that affect model accuracy (Zhang *et al.,* 2018).

- **Data Gaps and Inconsistencies:** Missing or inconsistent data due to sensor malfunctions, satellite revisit limitations, or acquisition issues can affect model outputs (Lobell *et al.,* 2015).
- **High Cost of High-Resolution and Commercial Data:** Free satellite products (e.g., MODIS, Sentinel) have limited resolution, whereas high-resolution commercial data (e.g., PlanetScope, WorldView) are expensive. The cost of accessing high-resolution data can be a barrier, especially in developing countries (Becker-Reshef *et al.,* 2020).
- **Computational and Technical Challenges:** High-resolution satellite data require significant computational power and storage capacity. Processing large datasets and integrating them with complex crop models demands expertise in geospatial analytics, programming, and model calibration (Hunt *et al.,* 2021).
- **Complexity of Data Assimilation:** Integrating RS data into crop models requires sophisticated assimilation techniques (e.g., Kalman filtering, ensemble approaches). Many crop models (e.g., DSSAT, APSIM) were originally designed without direct RS inputs, requiring modifications to incorporate real-time data (Jin *et al.,* 2019).

**Conclusion:**

By combining real-time remote sensing data with process-based crop modeling, farmers, researchers, and policymakers can make better-informed decisions to enhance food security and agricultural productivity.

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