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Smart Fertilizers: Transforming Agriculture for a Sustainable Future

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Abstract

Smart fertilizers represent a transformative approach to agricultural nutrient management, leveraging advanced technologies to optimize fertilizer application and enhance crop productivity while minimizing environmental impact. These innovative fertilizers incorporate controlled-release mechanisms, nutrient sensors, and data-driven analytics to precisely deliver nutrients to plants based on their specific needs and soil conditions. Smart fertilizers contribute to improved resource utilization, soil health, and sustainability in agriculture by maximizing nutrient efficiency and reducing leaching and runoff. Additionally, they promise to mitigate the adverse effects of conventional fertilizers on water quality and greenhouse gas emissions, thus supporting efforts towards a more environmentally friendly and resilient agricultural system.

1. INTRODUCTION

Smart fertilizers, also known as intelligent or precision fertilizers, represent a revolutionary advancement in agricultural technology, offering innovative solutions to optimize nutrient management, enhance crop productivity, and promote sustainable farming practices (Divya et al., 2023). Unlike traditional fertilizers, which provide nutrients simply and uniformly, smart fertilizers are designed with advanced formulations, delivery systems, and technologies to deliver nutrients more efficiently and precisely to crops, thereby maximizing their utilization and minimizing environmental impact.

Smart fertilizers encompass a diverse range of products and technologies, including controlled-release fertilizers, slow-release fertilizers, coated fertilizers, nutrient-enriched polymers, and nano-fertilizers. These fertilizers are engineered to release nutrients gradually over time (Raimodi et al., 2021), in response to specific triggers such as soil moisture, temperature, microbial activity, or crop demand, ensuring a steady and sustained supply of nutrients

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to plants throughout the growing season.

2. The Key Features and Components of Smart Fertilizers

❖ **Controlled Release Mechanisms:** Smart fertilizers often incorporate controlled-release mechanisms that regulate the release of nutrients over time. These mechanisms can include coatings, encapsulation, or matrix-based formulations that slow down the dissolution of nutrients. By releasing nutrients gradually, smart fertilizers ensure a more consistent and sustained supply of nutrients to crops, reducing the risk of nutrient leaching, volatilization, or runoff (Divya et al., 2023).

❖ **Nutrient Formulations:** Smart fertilizers may contain specialized nutrient formulations designed to improve nutrient availability and uptake by plants. This can include slow-release forms of nutrients, which release nutrients gradually over an extended period, reducing the frequency of fertilizer applications and minimizing nutrient losses (Divya et al., 2023), and chelated nutrients, which are bound to organic molecules (chelates) to enhance their stability and solubility in the soil, making them more readily available for plant uptake. These advanced formulations increase the efficiency of nutrient utilization by crops, ensuring that a higher proportion of applied nutrients is absorbed and utilized for growth and development.

❖ **Nutrient Monitoring and Sensing:** Some smart fertilizers are equipped with sensors or monitoring devices that measure soil nutrient levels, crop nutrient status, or environmental parameters in real-time. These sensors provide valuable data on soil fertility, crop nutrient requirements, and nutrient dynamics, allowing farmers to make informed decisions about fertilizer application rates, timing, and placement. By adjusting fertilizer application based on real-time data, farmers can optimize nutrient delivery to crops, minimize over-application or under-application of fertilizers, and reduce nutrient losses to the environment.

❖ **Site-Specific Application:** Smart fertilizers enable site-specific or variable-rate application of nutrients, allowing farmers to tailor fertilizer inputs to the specific needs of different areas within a field. This precision approach considers spatial variability in soil properties, crop nutrient requirements, and environmental conditions, ensuring that nutrients are applied where they are most needed. By optimizing nutrient distribution across the field, smart fertilizers minimize nutrient waste,

improve nutrient use efficiency, and enhance crop yields and quality.

❖ **Fertilizer Coatings and Additives:** Smart fertilizers may contain specialized coatings or additives that enhance nutrient stability, solubility, or uptake efficiency. Coatings can protect nutrients from degradation or loss, improve their release kinetics, or enhance their interaction with soil and plant roots. Additives such as surfactants or adjuvants can improve nutrient dispersal, absorption, or retention in the soil, increasing the effectiveness of fertilizer applications.

❖ **Integration with Precision Agriculture Technologies:** Smart fertilizers can be integrated with other precision agriculture technologies, such as GPS-guided equipment, remote sensing, and data analytics platforms. This integration allows for more accurate and efficient fertilizer application decisions based on spatial variability in soil properties, crop growth, and environmental conditions. By combining real-time data with advanced fertilizer technologies, farmers can optimize nutrient management practices, improve crop productivity, and minimize environmental impacts.

❖ **Environmental Sustainability:** One of the key benefits of smart fertilizers is their contribution to environmental sustainability in agriculture. By improving nutrient use efficiency and minimizing nutrient losses to the environment, smart fertilizers help reduce nutrient pollution of water bodies, greenhouse gas emissions from fertilizer production and application, and other negative environmental impacts associated with conventional fertilizer use. By promoting more sustainable nutrient management practices, smart fertilizers support the long-term health and resilience of agricultural ecosystems while enhancing productivity and profitability for farmers.

3. Smart Fertilizers Available in the Market

In Indian farming conditions, several smart fertilizers are available that cater to the diverse needs of farmers across different regions and cropping systems. While the adoption of smart fertilizers may vary depending on factors such as crop type, soil fertility, and local agricultural practices, the following are some examples of smart fertilizers commonly used in Indian agriculture (Table 1):

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Table 1: Smart fertilisers in the Indian market

Sl. No.	Smart Fertilizer	Description	Benefits	Examples
1.	Polymer-coated urea	Urea granules coated with polymer for controlled nitrogen release.	Reduces nitrogen losses through leaching and volatilization, improving nitrogen use efficiency (NUE) and reducing fertilizer applications.	Skysulf Urea polymer coated by Maruthi Corporation
2.	Chelated micronutrient fertilizers	Micronutrients (e.g., iron, zinc) in chelated form for better plant uptake.	Corrects micronutrient deficiencies, enhances crop growth, yield, and quality even in high pH soils.	Mahadhan Chelated Zn as Zn-EDTA by Smartchem Technologies Limited
3.	Slow-release fertilizers	Nutrients are released gradually, ensuring a sustained supply over time.	Minimizes nutrient losses, improves NUE, extends nutrient availability, and reduces the need for frequent applications.	Nutricote 13-11-11 Type 180 by Dhanashree agro industries
4.	Biofertilizers	Contains beneficial microorganisms that promote nutrient availability and soil health.	Enhances soil fertility, nitrogen fixation, and phosphorus solubilization, reducing dependence on chemical fertilizers.	Mrida Rakshak Gold by Indian Organic Biofertilisers
5.	Fertigation fertilizers	Water-soluble fertilizers used in drip irrigation systems.	Ensures precise nutrient delivery, reducing nutrient losses and improving efficiency in challenging terrains.	Polyfeed drip by Nagarjuna fertilisers and chemicals limited
6.	Customized NPK blends	Tailored blends of nitrogen, phosphorus, and potassium to meet specific crop and soil requirements.	Provides balanced nutrition based on crop growth stages, improving yield, quality, and crop resilience.	Polyfeed 19-19-19+MEN by Nagarjuna fertilisers and chemicals limited
7.	Soil health enhancers	Organic or bio-based products that improve soil structure and fertility.	Enhances soil health by restoring organic matter, promoting water retention, and supporting microbial activity for sustainable agriculture.	Soil Shakthi Soil Health Conditioner from Khedut fertilisers; Kohinoor-Soil Health Improver from Agri Life

These smart fertilizers offer innovative solutions to improve crop productivity, sustainability, and profitability in Indian farming conditions. Farmers can choose the most suitable smart fertilizers based on their crop requirements, soil characteristics, and local agro-climatic conditions to achieve optimal results and ensure the long-term health of their agricultural ecosystems.

4. The Effect of Smart Fertilizers on Crop Production

➤ **Optimized Nutrient Management:** Smart fertilizers provide precise nutrient control, allowing farmers to tailor inputs according to crop needs, soil conditions, and growth stages. Through advanced formulations, they deliver nutrients at the right time, in the correct form, ensuring efficient uptake and utilization. This targeted

approach minimizes nutrient imbalances, promoting balanced plant nutrition and enhancing crop productivity. In a study by Jia et al. (2022), applying 150 mg of Nano-hydroxyapatite (phosphorus) per kg of soil to maize resulted in increased bioavailable phosphorus, enhanced plant growth-promoting rhizobacteria (PGPR), and improved soil organic matter and electrical conductivity. Additionally, the soil exhibited higher levels of low molecular weight metabolites, including sugars, amino acids, and phenolic acids.

➤ **Enhanced Nutrient Use Efficiency:** Smart fertilizers use technologies like controlled-release, chelation, and slow-release formulations to enhance nutrient utilization by crops. By gradually releasing nutrients, they reduce losses from leaching, volatilization, and fixation, ensuring

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more nutrients are available for plant uptake. This improves nutrient efficiency, lowers input costs, and reduces environmental pollution from runoff.

➤ **Increased Crop Yields and Quality:** Smart fertilizers deliver nutrients precisely, supporting healthy plant growth, robust root development, and optimal yields. They improve crop resistance to biotic and abiotic stressors like pests, diseases, drought, and salinity, enhancing yield and quality. By increasing nutrient use efficiency, smart fertilizers reduce phosphate use by 50-75% while boosting yields by 10%, raising farmers' income by 15-20%. Additionally, they improve product attributes such as taste, texture, nutritional value, and shelf-life, aligning with consumer preferences. Similarly, in a few field trials in China, controlled-release fertilizers increased rice yields by 10-40% compared to urea, even boosting yields by 15% with reduced nitrogen use (Praveen and Garg, 2022).

➤ **Sustainable Agriculture Practices:** Smart fertilizers promote sustainable agriculture by reducing the environmental impact of conventional fertilizers. They minimize nutrient losses, protect water quality, prevent soil degradation, and preserve biodiversity. They conserve natural resources, mitigate the effect of climate change for the long-term resilience of agricultural systems. By using 20-30% less nitrogen, smart fertilizers lower CO₂ emissions from production and significantly reduce N₂O emissions, a potent greenhouse gas. While common nitrogen fertilizers lose 1-5% of applied nitrogen as N₂O, smart fertilizers emit less during the growing season. Over the past 150 years, N₂O levels have increased by 18% due to nitrogen fertilizer use globally (Praveen and Garg, 2022).

➤ **Precision Agriculture Integration:** Smart fertilizers can be integrated with precision agriculture technologies, such as soil sensors, drones, and satellite imagery, to optimize nutrient management decisions. Real-time monitoring of soil fertility, crop growth parameters, and environmental conditions allows farmers to adjust fertilizer application rates, timing, and placement with precision, based on localized variability within fields. This integration of smart fertilizers with precision agriculture tools enables farmers to adopt a site-specific, data-driven approach to nutrient management, maximizing resource efficiency and crop production potential.

➤ **Economic Benefits for Farmers:** While smart fertilizers may involve higher initial investment costs compared to conventional fertilizers, their potential to

increase crop yields, improve product quality, and reduce input costs can result in long-term economic benefits for farmers. Improved profitability and economic returns from crop production contribute to the financial viability and sustainability of farming operations, enhancing the livelihoods of farmers and rural communities.

5. Scenarios where Smart Fertilizers are Advantageous

Smart fertilizers offer significant benefits in various agricultural contexts where efficient nutrient management and sustainability are critical:

✓ **Precision Agriculture:** In precision farming, where technologies like GPS, drones, and sensors are used, smart fertilizers enable targeted nutrient application, optimizing resource use and crop yields.

✓ **High-Value Crops:** For crops like fruits and vegetables that have specific nutrient needs, smart fertilizers provide precise nutrition, improving yield, quality, and market value.

✓ **Nutrient-Deficient Soils:** In areas with poor soil fertility, smart fertilizers address specific nutrient deficiencies, ensuring optimal crop growth and productivity.

✓ **Water-Scarce Areas:** In drought-prone regions, controlled-release smart fertilizers enhance nutrient efficiency and reduce leaching, supporting crop growth with limited water.

✓ **Environmentally Sensitive Areas:** In ecosystems prone to pollution, smart fertilizers minimize nutrient runoff, protecting water quality and biodiversity.

✓ **Organic Farming:** For organic systems, bio-based smart fertilizers improve soil fertility and nutrient cycling without compromising organic standards.

✓ **Climate-Impacted Areas:** Smart fertilizers help farmers adapt to climate change, supporting nutrient management and crop resilience in shifting conditions.

✓ **Large-Scale Farms:** In large farming operations, smart fertilizers streamline nutrient management, reducing costs and boosting profitability.

✓ **Integrated Crop-Livestock Systems:** In these systems, smart fertilizers complement organic inputs, ensuring balanced nutrient cycling and efficiency.

6. Challenges in Using Smart Fertilizers

The adoption of smart fertilizers in India faces several challenges:

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- **Cost:** The high initial cost of smart fertilizers is a barrier, especially for small farmers with limited resources.
- **Lack of Awareness:** Many farmers are unaware of smart fertilizers and their benefits due to limited access to extension services and training.
- **Complex Application:** Specialized equipment and technical knowledge are often required for smart fertilizers, which may be unavailable in rural areas.
- **Limited Availability:** Access to smart fertilizers is hindered by poor distribution networks and supply chain issues in remote regions.
- **Traditional Practices:** Farmers may resist adopting new methods due to comfort with traditional practices and insufficient support for integrating smart fertilizers.
- **Risk Aversion:** Fear of crop damage, yield variability, and financial loss makes farmers hesitant to try unfamiliar technologies.
- **Data Challenges:** Effective use of smart fertilizers requires data on soil, crops, and environment, which many farmers lack the resources or expertise to obtain.
- **Regulatory Barriers:** Inconsistent regulations and lack of policy support limit the development and accessibility of smart fertilizers.
- **Infrastructure Gaps:** Poor infrastructure, including electricity, internet, and digital devices, hampers the use of technology-dependent smart fertilizers.

Addressing these challenges will require collaborative efforts from policymakers, researchers, and agribusinesses, focusing on education, policy support, and infrastructure development.

7. Steps to Ensure Proper Application of Smart Fertilizers and Maximize their Benefits

- ❖ **Soil Testing and Analysis:** Before applying smart fertilizers, conduct soil testing to assess soil fertility, pH levels, and nutrient deficiencies. Collect soil samples from multiple locations within the field and send them to a reputable laboratory for analysis. Use the soil test results to determine the specific nutrient requirements of your crops and tailor your fertilizer application accordingly.
- ❖ **Crop Nutrient Requirements:** Understand the nutrient requirements of your crops at different growth stages. Refer to crop-specific nutrient management guidelines or consult agricultural experts for recommendations. Identify the critical nutrient deficiencies that need to

be addressed and select smart fertilizers containing the required nutrients in the appropriate form and concentration.

- ❖ **Selection of Smart Fertilizers:** Choose smart fertilizers based on the nutrient needs of your crops, soil conditions, and agronomic practices. Consider factors such as nutrient content, release characteristics (e.g., controlled-release, slow-release), and compatibility with other inputs (e.g., pesticides, organic amendments).

- ❖ **Application Timing and Rates:** Apply smart fertilizers at the appropriate timing and rates to coincide with crop growth stages and nutrient uptake patterns. Follow recommended application rates provided on the product label or based on agronomic recommendations to avoid under or over-application of nutrients.

- ❖ **Application Methods:** Use suitable application methods to ensure uniform distribution of smart fertilizers across the field. For granular or powdered fertilizers, apply evenly using broadcast spreading equipment, seed drills, or fertilizer applicators. For liquid fertilizers, apply through drip irrigation systems, fertigation equipment, or foliar sprays, ensuring proper coverage of foliage and root zones.

- ❖ **Placement and Incorporation:** Consider the placement and incorporation of smart fertilizers to maximize nutrient availability and minimize losses. Incorporate granular or powdered fertilizers into the soil through tillage or mechanical incorporation to enhance contact with root zones and reduce surface runoff. Inject liquid fertilizers directly into irrigation systems or apply them as foliar sprays to facilitate rapid absorption by crops.

- ❖ **Monitoring and Adjustment:** Monitor crop responses and nutrient levels in the soil throughout the growing season to assess the effectiveness of smart fertilizer applications. Adjust fertilizer management practices as needed based on crop performance, weather conditions, and soil nutrient status. Consider using precision agriculture technologies such as soil sensors, remote sensing, and data analytics to optimize nutrient management decisions and fine-tune fertilizer applications.

- ❖ **Record Keeping and Evaluation:** Maintain accurate records of smart fertilizer applications, including product details, application rates, timing, and field locations. Evaluate the impact of smart fertilizers on crop yields, quality, and profitability compared to conventional

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fertilizers or untreated controls. Use this information to make informed decisions for future fertilizer management strategies and optimize nutrient use efficiency over time. By following these steps and integrating smart fertilizers into nutrient management practices, we can harness their benefits to improve crop productivity, efficiency, and sustainability in your agricultural operations.

8. Conclusion

Smart fertilizers represent a transformative innovation that has the potential to contribute to the sustainability, productivity, and resilience of global agriculture, ensuring food security, environmental stewardship, and economic prosperity for future generations. By embracing smart fertilizers as part of a holistic approach to nutrient management, farmers can unlock new opportunities for sustainable intensification and meet the challenges of feeding a growing world population while safeguarding natural resources and ecosystems.

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