



Role of Smart Fertilization in Modern Agriculture

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This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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Abstract

Global food demand is increasing rapidly owing to population growth, placing considerable pressure on agricultural systems to enhance productivity under constraints on natural resources. Although conventional fertiliser use has contributed significantly to improved yields, its excessive and imbalanced application has resulted in soil degradation, nutrient leaching, groundwater contamination, and increased emissions of nitrous oxide (N₂O), thereby reducing nutrient use efficiency (NUE). In this context, smart fertilisation has emerged as a science-driven nutrient management strategy that emphasises the application of the right nutrient source at the right rate, time and place (4R principle), supported by advanced tools such as soil and plant sensors, remote sensing, geographic information systems, and decision-support platforms. Key components include controlled-release fertilisers, nano-fertilisers, bio-formulations, fertigation systems, variable rate technology (VRT), and unmanned aerial vehicle (UAV)-based crop monitoring. Evidence from multi-location field studies across diverse agro-climatic regions of India and other countries indicates that smart fertilisation can enhance nutrient use efficiency by 50–80%, reduce fertiliser input by 19–30%, and improve crop yields by 22–30% in major crops such as rice, wheat, maize and pulses. With the global fertiliser market exceeding USD 200 billion, the adoption of precision nutrient management technologies is gaining momentum. Overall, smart fertilisation offers a sustainable intensification pathway by improving productivity while simultaneously minimising environmental externalities. However, challenges related to technology accessibility, cost, and farmer adoption remain critical constraints that require policy and institutional support.

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1. Introduction

Global food demand is projected to increase by 70% by 2050 owing to population growth and changing dietary preferences. To meet this demand, farmers worldwide have increasingly relied on chemical fertilisers, coinciding with a 39.1% rise in fertiliser consumption in India alone, from 51.01 million tonnes in 2015-16 to 70.7 million tonnes in 2024-25. Among fertilisers, urea dominates consumption because of the high nitrogen demand of most crops and the need for repeated applications throughout the crop cycle. Despite their role in boosting productivity, conventional fertilisers are beset by inherent inefficiencies. Plants absorb only 30-50% of applied nitrogen, with the remainder lost through leaching, volatilisation, and surface runoff (Mulla, 2013). Prolonged fertiliser use acidifies soils, suppresses beneficial microbial communities, and contributes to eutrophication of water bodies and emission of nitrous oxide, a potent greenhouse gas with 298 times the global warming potential of CO₂. These challenges underscore the need to transition from blanket fertilisation toward precision-based nutrient management systems. Fertilisation is an important component of precision agriculture and is crucial for ensuring high and stable crop yields (Wang *et al.*, 2025). Smart fertilisation is defined as a site-specific nutrient management approach that optimises the type, amount, timing, and method of fertiliser application based on spatial and temporal field variability, aiming to enhance crop productivity, minimise nutrient losses, and reduce environmental impact (Liu *et al.*, 2025; Raimondi *et al.*, 2021). The concept of smart fertilisation has evolved over three decades, driven by advances in GPS technology, remote sensing, IoT, and data analytics. Precision fertilisation has emerged as a critical component of modern smart agriculture, providing a transformative approach to optimising nutrient application, enhancing crop productivity, and minimising environmental harm while improving resource use efficiency (Liu *et al.*, 2025; Polwaththa *et al.*, 2024). Early precision agriculture efforts in the 1990s focused on yield mapping and variable-rate application of soil-applied inputs. Today, smart fertilisation encompasses a much broader spectrum of technologies, from nano-engineered fertiliser particles and biologically active carrier systems to autonomous drone-based nutrient delivery and AI-driven decision-support platforms (Kumari *et al.*, 2026; Shingare *et al.*, 2023). Although the manuscript discusses multiple smart fertilisation approaches, the evidence on their comparative agronomic, economic and environmental performance across crop and regional contexts has not been integrated consistently. A synthesis of these findings is therefore needed to clarify context-specific opportunities and remaining constraints. This review presents a consolidated analysis of the key components of smart fertilisation, synthesising results from multi-location field experiments conducted across India and internationally, and evaluating their agronomic, economic, and environmental outcomes. The review also identifies critical gaps in current knowledge and outlines emerging research directions that will shape the next generation of precision nutrient management systems.

1.1 Changing Agricultural Scenario in India (2025)

India's agricultural landscape is undergoing a profound structural transformation, creating a strong foundation for the adoption of smart fertilisation strategies. Rapid population growth (1.44 billion in 2025) and rising urban incomes are shifting dietary preferences toward nutrient-dense foods such as proteins, fruits, and vegetables, thereby increasing the demand for efficient and balanced nutrient management. At the same time, the marginal decline in net sown area due to urbanisation (from 141.4 to 139 million hectares) necessitates higher productivity per unit area, which can be achieved through precision-based fertiliser application.

Climate variability has emerged as the most critical constraint, with increasing incidences of droughts, floods, heat waves, and erratic rainfall affecting nutrient use efficiency. Projections of a 6-23% decline in crop yields by 2050 further emphasise the need for smart fertilisation approaches that optimise nutrient delivery in synchronisation with crop demand and environmental conditions. In this context, government initiatives such as PM-KISAN, Soil Health Card Scheme, PMFBY, e-NAM, and the Digital Agriculture Mission (2021-2025) have significantly strengthened digital infrastructure and farmer databases. With over 110 million soil health cards issued and more than 80 million farmers digitally registered, these platforms enable data-driven, site-specific nutrient management. Consequently, smart fertilisation integrating soil diagnostics, remote sensing, IoT, and decision-support systems is emerging as a critical pathway to enhance fertiliser use efficiency, reduce input costs, and ensure sustainable agricultural productivity in India.

Table 1. Comparison of conventional and smart fertilisation approaches

Sl. No	Conventional fertilization	Smart fertilization
1	Uniform application across the field	Site-specific, variable-rate application
2	Fixed timing regardless of crop stage	Demand-driven, real-time adjustment
3	30–50% NUE for nitrogen	Up to 80% NUE through precision delivery
4	High risk of leaching and volatilisation	Reduced nutrient losses through encapsulation
5	Environmental degradation	Minimised ecological footprint
6	Labour-intensive and time-consuming	Automated with sensors and GPS-guided equipment

Table 2. Global fertiliser consumption bal fertiliser nutrient consumption – 2024/25 (Million Tonnes)

Global Fertiliser Nutrient Consumption – 2024/25 (Million Tonnes)		
Nitrogen (N)		112 MT
Phosphorus (P ₂ O ₅)		48 MT
Potassium (K ₂ O)		40 MT

Source: FAO global fertiliser outlook 2025. MT = Million tonnes

Table 3. Fertiliser consumption in India

India Fertiliser Consumption by Category - 2024/25 (Million Tonnes)		
Urea (N)		33.5 MT
DAP (P)		10.8 MT
Complex NPKs		12.4 MT
SSP (P)		4.9 MT
MOP (K)		3.2 MT
Micronutrients		5.9 MT

Source: Ministry of chemicals & fertilisers

Table 4. State-wise smart fertiliser adoption index (2025)

Punjab & Haryana		82/100
Maharashtra		76/100
Karnataka		71/100
Andhra Pradesh & Telangana		68/100
Gujarat		65/100
Tamil Nadu		63/100
UP & MP (Indo-Gangetic Plain)		44/100
Bihar & Odisha		31/100
Northeast India		18/100

Source: NITI Aayog agricultural technology report 2024

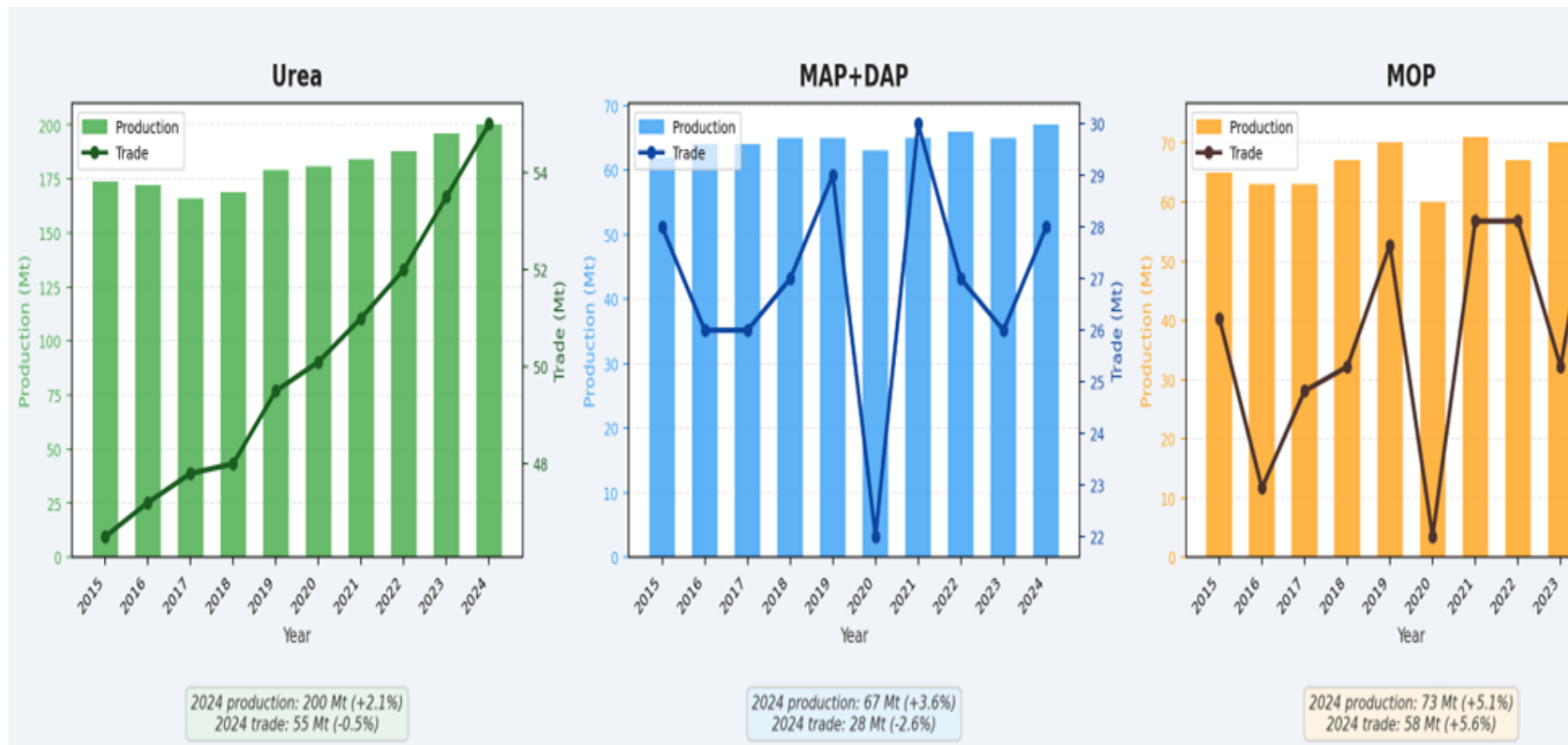


Fig. 1. Estimation of production and trade of fertilisers in 2024
Source: IFA data reflects preliminary estimates

1.2 Fertiliser Consumption Trends and Nutrient-wise Analysis

Global fertiliser consumption patterns reveal a strong dominance of nitrogen (N) fertilisers, followed by phosphorus (P_2O_5) and potassium (K_2O). The FAO estimates total global fertiliser nutrient consumption at approximately 200 million tonnes (NPK combined) for 2024-25, with the distribution presented in Table 2.

1.3 India's Fertiliser Consumption by Nutrient (2024-25)

India is the second-largest consumer of fertilisers globally after China. Urea (N) is the dominant fertiliser and accounts for approximately 55-60% of total fertiliser consumption. Phosphatic fertilisers (DAP, SSP) and complex NPK fertilisers constitute the second tier. Potassic fertilisers (MOP) remain relatively low due to limited domestic production and high import dependence.

1.4 State-wise Smart Fertiliser Adoption Index (2025)

Table 4 presents regional differences in the reported smart fertiliser adoption index for 2025, with the highest values shown for Punjab and Haryana and the lowest for Northeast India.

1.5 Production and Trade Estimates

Fig. 1 summarises preliminary estimates of fertiliser production and trade in 2024 for urea, MAP + DAP and MOP, illustrating differences among these fertiliser categories.

2. Advanced Fertiliser Formulations as the Foundation of Smart Fertilisation

Advanced fertiliser formulations represent the foundational layer of smart fertilisation. By engineering the physical and chemical characteristics of fertiliser materials, scientists have developed products that can control nutrient release, enhance bioavailability, reduce environmental losses, and complement biological nutrient cycling processes in soil.

2.1 The 4R Framework

The foundation of smart fertilisation rests on the globally recognised '4R Nutrient Stewardship' framework, developed collaboratively by the International Plant Nutrition Institute (IPNI) and adopted by national agricultural extension systems worldwide. The four rights are:

- **Right Source:** Selecting the appropriate fertiliser form that matches the specific crop's nutritional requirements and the soil's chemical and biological environment.
- **Right Rate:** Applying the correct quantity based on comprehensive soil testing, crop nutrient budgets, and economically optimised yield targets.
- **Right Time:** Aligning application with peak crop demand at critical vegetative and reproductive growth stages to maximise synchrony of nutrient supply and uptake.
- **Right Place:** Positioning fertiliser near the root zone through band placement, fertigation or deep placement to minimise surface losses and enhance root contact.

Together, the 4Rs form an actionable decision-support scaffold that underpins all advanced fertilisation technologies described in this review. Adoption of the 4R framework has been correlated with NUE improvements of 15–25% even without additional technological inputs, making it an accessible entry point for smallholder farmers transitioning toward precision nutrient management.

2.2 Slow and Controlled Release Fertilisers

Slow/controlled-release fertilisers are encapsulated or chemically modified formulations that release nutrients over an extended period, substantially prolonging plant-available nutrient supply compared with conventional water-soluble fertilisers. They possess high molecular weight and complex chemical structure, often comprising polymer, sulphur or resin coatings that regulate nutrient diffusion based on soil temperature, moisture and microbial activity.

The mechanisms of controlled release differ by coating type. Sulphur-coated urea (SCU) releases nitrogen primarily through microbial degradation of the sulphur layer, making nutrient release temperature-sensitive and typically synchronised with warmer growing periods when crop demand is highest. Polymer-coated fertilisers release nutrients via osmotic diffusion through semi-permeable membranes with release rates governed by temperature and coating thickness. Resin-coated products offer the most precise control and the longest longevity.

Shivay *et al.* (2016) conducted a two-year field experiment on wheat (*Triticum aestivum* L.) at IARI, New Delhi, on sandy clay loam soil, investigating the effect of sulphur-coated urea (SCU) across sulphur levels of 1-5%. The results revealed a progressive increase in grain nitrogen concentration (1.89-2.07%) and total nitrogen uptake (116.1-134.6 kg ha⁻¹) with increasing sulphur coating levels, compared to 108.6 kg ha⁻¹ for prilled urea. The superior performance of 5% SCU was attributed to slow and regulated nitrogen release, reduced nitrogen losses, and synergistic sulphur–nitrogen interaction that collectively enhanced NUE and crop uptake.

Table 5. Major manufacturing companies of customized fertilisers in India along with their formulation (Rajasekhar *et al.*, 2023)

Company	Crops	Formulations (N:P:K:S:Zn:B)/ N:P:K:Zn/N:P:K:S:M g:Zn:B:Fe/N:P:K:S:Zn : B)	Places
Tata Chemicals Limited (TCL)	Potato	8:16:24: 6:0.5:0 .15	Agra, Aligarh, Budaun, Bulandshahar and Baghpath
Tata Chemicals Limited (TCL)	Wheat	10:18:25: 3:0.5 :0.5	Muzaffarnagar, Barielly, Bijnore, Hathras, Pilibhit, Mathura, Meerut and Etah
Tata Chemicals Limited (TCL)	Paddy	15:32:8:0.5, 18:33 :7:0.5, 18:27:1 4:0 .5	Andhra Pradesh
Tata Chemicals Limited (TCL)	Maize	14:27:10: 4:0.5	Karimnagar, Warangal and Ranga Reddy
Tata Chemicals Limited (TCL)	Sugarcane	7:20:18: 6:0.5	Western UP
Nagarjuna Fertilisers Corporation Limited (NFCL)	Rice	11:24:6: 3:0.5	Andhra Pradesh

Similarly, Liao *et al.* (2020) demonstrated in China that biochar-based controlled-release nitrogen fertiliser (BCRNF) applied to oilseed rape (*Brassica napus* L.) on sandy loam soil achieved the highest nitrogen uptake, agronomic nitrogen efficiency and NUE compared to urea alone and biochar-urea combinations. BCRNF's synchronised, slow nitrogen release minimised leaching and volatilization losses, while biochar improved soil physical properties, moisture retention, and microbial activity, culminating in enhanced root growth and nitrogen absorption efficiency.

2.3 Nano-fertilisers

Nano-fertilisers are nutrient carriers fabricated at the nanoscale (1-100 nm) characterised by a high surface area-to-volume ratio, superior diffusion rates, and enhanced solubility. These properties translate into a threefold increase in NUE compared with conventional fertilisers, alongside improved soil aggregation and moisture retention capacity. Nano-scale formulations can be applied as soil amendments, root dips or foliar sprays, enabling multi-route delivery that conventional fertilisers cannot match. The nano-fertiliser category encompasses several product types: nano-encapsulated conventional nutrients (e.g., nano-urea, nano-DAP, nano-zinc), nano-clay carriers loaded with nutrients; carbon nanotube and graphene-based delivery systems and nano-hydroxyapatite for slow phosphorus release. Each type offers unique advantages in terms of nutrient loading capacity, release kinetics, plant uptake pathways and compatibility with soil microbiomes.

Arya *et al.* (2022) conducted a field experiment to assess the effect of foliar nano-urea application on the yield attributes and yield of pearl millet (*Pennisetum glaucum* L.) at Eastern Block Farm of Tamil Nadu Agricultural University, Coimbatore during the summer of 2022 and reported that the application of 50 % RDN as basal + 0.5 % Nano-urea foliar spray @ panicle initiation and booting stage resulted in significantly more productive tillers plant⁻¹ (3.79), earhead length (26.82 cm), earhead girth (7.9 cm), number of grains earhead⁻¹ (2.462) and test weight (15.64 g), compared to other treatments.

Deo *et al.* (2022) evaluated the partial replacement of soil-applied phosphorus with nano-DAP foliar sprays in rice grown on sandy loam soil in Chhattisgarh. Treatment T₅ (50% P + 100% NK + root dipping + two nano-DAP foliar sprays at 20-25 and 45-50 DAT) recorded the highest agronomic use efficiency for nitrogen (31.0 kg grain/kg nutrient applied), phosphorus (123.4) and potassium (77.6), alongside the highest production efficiency (N: 48.2, P: 198.6, K: 48.9 kg grain/kg nutrient absorbed). The improvement was attributed to enhanced leaf absorption, avoidance of soil phosphorus fixation losses and synergistic effects on root growth and metabolic activity.

Tarafdar *et al.* (2014) conducted an experiment in Rajasthan and confirmed that nano-zinc application in pearl millet significantly increased shoot length (175 cm), root length (61.1 cm), root area (74.7 cm²), and leaf protein content (52.3 mg kg⁻¹) compared with the control (37.7 mg kg⁻¹), demonstrating nano-zinc's role in enzyme activity, auxin synthesis, and protein metabolism.

Yadav *et al.* (2023) conducted an experiment in Kanpur, Uttar Pradesh, during the 2021–2022 rabi season to examine the combined effects of foliar nano-urea and boron application on the growth, yield attributes and yield of wheat (*Triticum aestivum* L.). The results showed that foliar application of nano-urea at 3000 ppm improved growth, yield attributes and yield, including plant height (82.23 cm), dry weight plant⁻¹ (22.41 g), number of leaves plant⁻¹ (27.17), leaf area plant⁻¹ (433.69 cm²), at 75 DAS, days of heading (78.96), days of maturity (123.40), number of tillers plant⁻¹ (6.15) over other treatments.

2.4 Bio-formulations

Bio-formulations are carrier-based preparations enriched with beneficial plant-associated microorganisms, designed to overcome the limitations of direct soil inoculation under adverse field conditions. They enhance nutrient availability through biological nitrogen fixation, phosphorus solubilisation and growth-promoting phytohormone production. Modern bio-formulations employ liquid, wettable powder or granular carrier systems that protect microbial viability during storage. The principal microbial groups employed in bio-formulations for smart fertilisation include: (i) nitrogen-fixing bacteria (*Azotobacter*, *Rhizobium*, *Azospirillum*, and cyanobacteria); (ii) phosphate-solubilizing bacteria (PSB) such as *Bacillus* and *Pseudomonas* species; (iii) potassium-mobilizing bacteria; (iv) arbuscular mycorrhizal fungi (AMF) that extend root absorptive surface area and (v) plant growth-promoting rhizobacteria (PGPR) that produce auxins, gibberellins, and cytokinins that stimulate root development.

Kapur *et al.* (2020) in Gujarat, on medium black soil, demonstrated that T₄ (75% RDF + liquid biofertilizer, LBF) in brinjal produced a fruit yield of 38.8 t ha⁻¹, comparable to 100% RDF (39.04 t ha⁻¹) while reducing chemical fertiliser input by 25%. LBF enhanced microbial activity, biological nitrogen fixation and phosphorus solubilization, ensuring continuous nutrient supply throughout the crop cycle.

Sahay *et al.* (2018) in Lucknow demonstrated that dual inoculation with Halo-Azotobacter and Halo-PSB in paddy (T₄) produced the highest grain yield (47.2 q ha⁻¹) and straw yield (67.4 q ha⁻¹) through complementary nutrient mobilization mechanisms including IAA, GA and cytokinin production by Halo-Azotobacter acting synergistically with phosphorus solubilization by Halo-PSB which collectively enhanced photosynthesis and assimilate translocation.

2.5 Smart Nutrient Delivery Systems through Foliar Application

Mavarkar *et al.* (2017) conducted a field experiment in Shivamogga, Karnataka, to evaluate the effect of foliar application of water-soluble fertilisers (18:18:18 and Multi-K) on growth and yield of hybrid maize under rainfed conditions. The results indicated that RDF alone recorded lower growth and yield parameters, whereas foliar sprays significantly improved plant performance. Among individual treatments, higher concentrations of 18:18:18 (1.5%) and Multi-K (1.5%) enhanced leaf area, plant height, and yield

attributes. The combined application of 18:18:18 and Multi-K proved more effective than their individual use. Notably, the treatment with 1.0% 18:18:18 + 1.5% Multi-K recorded the highest plant height, grain yield, and stover yield. Yield attributes such as cob length, grains per cob, and test weight also improved under combined foliar nutrition. Overall, foliar feeding along with basal fertilisation significantly increased maize productivity.

Sharma *et al.* (2024) conducted an experiment to evaluate the effect of foliar application of N, P, K and Zn on maize under rainfed conditions. The study included 19:19:19 (1.0%) alone and in combination with ZnSO_4 (0.5%) applied at critical growth stages. Results showed that foliar nutrition significantly improved growth and yield attributes over the control. The combined application of 19:19:19 + ZnSO_4 recorded higher grain yield and nutrient uptake. Yield components such as cob length, grains per cob and test weight were also enhanced. Overall, foliar feeding with balanced nutrients and micronutrients proved effective in increasing maize productivity.

Jadhav *et al.* (2017) conducted an experiment in Maharashtra to evaluate the effect of micronutrient application (ZnSO_4 and CuSO_4) along with recommended dose of fertilisers (RDF) on nutrient content (N, P, K, and S) in coriander. The experiment included different treatments involving foliar spray and soil application of zinc and copper. The results showed that the application of RDF + ZnSO_4 @ 20 kg ha⁻¹ through soil (T_6) recorded the highest nitrogen (1.64%), phosphorus (0.27%), potassium (1.69%), and sulphur (0.26%) content compared with the control. Among copper treatments, RDF + CuSO_4 @ 20 kg ha⁻¹ (T_{10}) also showed improved nutrient content. Foliar sprays were comparatively less effective than soil application. The control treatment recorded the lowest nutrient values. The differences were statistically significant, as indicated by the critical difference values at the 5% level. Overall, soil application of ZnSO_4 proved most effective in enhancing nutrient uptake in coriander.

Roohi *et al.* (2021) conducted an experiment in Haryana to evaluate the effect of foliar application of NPK and micronutrients on growth and yield of sugarcane. The results showed that T_6 (RDF + 2% NPK + 0.5% ZnSO_4 + 1% FeSO_4) recorded the highest cane yield (78.16 t/ha) along with superior growth parameters such as cane length, girth, and internodes. Treatments T_1 and T_7 also performed well due to combined micronutrient application. In contrast, RDF alone (T_8) recorded the lowest growth and yield values. Foliar application of ZnSO_4 , FeSO_4 , and urea significantly improved cane weight and yield over control. The statistical analysis indicated significant differences for most yield parameters. Overall, integrated nutrient management through foliar feeding enhanced sugarcane productivity.

Shingare *et al.* (2023) conducted an experiment in Uttar Pradesh to study the effect of sulphur and foliar iron (FeSO_4) application on groundnut growth and yield. Increasing sulphur levels from 20 to 60 kg/ha improved plant height, dry weight, and kernel yield. Similarly, higher FeSO_4 concentrations (up to 1%) enhanced performance. The best results were obtained with 60 kg/ha sulphur + 1% FeSO_4 , giving the highest yield (2.47 t/ha). The control treatment recorded the lowest yield (1.40 t/ha). The F-test indicated that the results were statistically significant. Overall, the combined application of sulphur and iron improved groundnut productivity.

3. Fertiligation in Modern Agriculture

Fertiligation is a cultivation practice in which soluble fertilisers are dissolved in irrigation water and delivered directly to the root zone through drip or sprinkler systems. This method facilitates precise, uniform nutrient distribution, reduces losses through leaching and volatilization, and enables real-time adjustment of nutrient supply to match crop demand across growth stages. Fertiligation is considered one of the more water- and nutrient-efficient delivery systems available to modern agriculture.



Fig. 2. Fertiligation practice

3.1 Principles and Design of Fertiligation Systems

Fertilisers used in fertiligation must possess high water solubility, minimal conditioning agents, negligible insoluble material (<0.02% w/w) and compatibility with irrigation water without causing pH extremes or emitter clogging. Suitable sources include urea,

ammonium sulphate, mono ammonium phosphate, mono potassium phosphate, calcium nitrate, and potassium chloride. The incompatibility of certain fertiliser combinations notably calcium nitrate with phosphate or sulphate sources must be accounted for during system design.

Drip fertigation systems consist of a water source, filtration unit (screen or disc filters with 120-200 mesh), fertigation injection equipment (venturi injector, fertiliser pump, or pressure differential tank), distribution mainlines, sub-mainlines, laterals, and emitters. Emitter flow rates (0.6-8 L/h) and spacing determine application uniformity, which is quantified by the Distribution Uniformity coefficient (DU). Modern systems achieve DU values exceeding 92-95%, compared to 75-85% for surface irrigation. Nutrient scheduling in fertigation follows crop nutrient uptake curves derived from destructive biomass analyses conducted at multiple growth stages. Nitrogen, which accounts for the largest nutrient demand in most crops, is typically split across 8-14 fertigation events during the growing season, with higher application frequencies during rapid vegetative growth and grain filling. Phosphorus is concentrated in early fertigation events coinciding with root establishment, while potassium application is intensified during pod fill and grain maturation.

Khanna *et al.* (2018) conducted an experiment at GKVK, Bangalore, to examine the effects of water and nutrient management practices on maize yield attributes. The results showed that drip fertigation at 125% RDF (WSF) recorded significantly higher yield attributes compared with conventional fertiliser. This was attributed to the rapid availability of water-soluble fertilisers, which ensured uniform and precise nutrient delivery to the active root zone. A continuous and synchronised nutrient supply during critical phenological stages enhanced photosynthetic efficiency and assimilate translocation, resulting in improved cob development and grain filling.

Bharath Raj *et al.* (2015) conducted an experiment at GKVK, Bangalore, to examine NPK uptake at harvest (kg ha^{-1}) in hybrid Bt cotton under different surface-fertigation schedules and fertiliser doses. The study included surface irrigation (100%) and split fertigation treatments. Higher NPK uptake was observed than under conventional soil application, owing to better nutrient use efficiency. Fertigation ensures continuous nutrient availability and diffusion in the root zone, which enhances root absorption efficiency. More split applications helped maintain an optimum nutrient concentration in the root zone and also supported the crop through the peak reproductive stage.

Rajwade *et al.* (2020) conducted an experiment at Raipur to study the nitrogen, phosphorus and potassium content (%) of soybean as influenced by fertigation the results revealed that in T_3 (125% RDF through fertigation) was most effective, and recorded the highest NPK content because it supplied nutrients regularly and efficiently in accordance with crop requirement. This method minimised nutrient losses and improved uptake efficiency compared with conventional application. Higher nutrient content was observed in seeds than in stover because of nutrient translocation towards grains during maturity.

Badr *et al.* (2010) conducted an experiment in Egypt to examine how different fertigation levels affected nitrogen (N), phosphorus (P), and potassium (K) uptake, recovery, and fertiliser use efficiency (FUE) in tomato. Compared with traditional furrow irrigation, all fertigation treatments significantly increased nutrient uptake, with the highest values at 100% fertigation (N: 172, P: 27, K: 117 kg/ha). Nutrient recovery percentages also improved steadily with fertigation, indicating better absorption of applied fertilisers by plants. Fertiliser use efficiency (FUE) rose from 95 under furrow irrigation to 150 under 100% fertigation, showing more yield per unit of fertiliser. Intermediate levels (50% and 75%) also performed better than conventional methods but produced slightly lower values than full fertigation. The LSD values indicated that these differences are statistically significant, confirming the superiority of fertigation over traditional methods.

Hadole *et al.* (2020) conducted an experiment in Maharashtra to analyse the economics of brinjal fruit yield under different levels and methods of fertiliser application. The results indicated that T_3 (drip fertigation at 125% RDF) emerged as the best treatment, recording the highest net return and B:C ratio, indicating the most economical use of inputs. Although 150% RDF (T_4) produced the highest yield, the additional cost of fertiliser increased the total cultivation cost, thereby reducing net return and B:C ratio.

4. Soil and Plant Sensors in Modern Agriculture

Sensors are electronic or optical devices that detect and quantify physical, chemical or biological variables, converting them into processable signals for real-time decision-making. In precision fertilisation, sensors monitor soil nutrient status, pH, moisture, and plant physiological indicators to guide timely and site-specific fertiliser application.

4.1 Types and Working Principles of Agricultural Sensors

Agricultural sensors can be broadly categorised into soil sensors and plant sensors, each serving distinct diagnostic functions in precision nutrient management.

Soil nutrient sensors include (i) Ion-Selective Electrodes (ISE) for direct, real-time measurement of nitrate, potassium, and ammonium ions; (ii) Optical sensors that estimate nutrient levels through light absorption and reflectance analysis, enabling rapid non-destructive field assessment and (iii) electrochemical sensors for high-precision ion detection. Soil pH is monitored by ISFET/glass electrode sensors, while soil moisture is quantified through tensiometers and Time Domain Reflectometry (TDR). Electrical conductivity sensors provide a proxy for overall soil salinity and nutrient content, whereas near-infrared (NIR) spectroscopy sensors can simultaneously estimate multiple soil properties including organic matter, moisture, and total nitrogen. Plant sensors encompass infrared thermocouples (canopy temperature for stress detection), sap flow sensors (stem water and nutrient transport efficiency), and dendrometers (stem diameter variation as a water stress indicator). Chlorophyll meters (SPAD)

provide rapid, non-destructive estimation of leaf chlorophyll content as a proxy for nitrogen status. Active optical sensors such as the Greenseeker and Crop Circle emit their own light source and measure crop reflectance to compute vegetation indices including NDVI and GNDVI for nitrogen recommendation algorithms.



Fig. 3. Soil and plant sensors

Table 6. Sensor types and their characteristics

Sl. No	Sensor type	Measured parameter	Principle	Response time	Field suitability
1	ISE (Ion-Selective)	NO_3^- , K^+ , NH_4^+	Electrochemical	Seconds	High
2	SPAD meter	Leaf chlorophyll (N proxy)	Optical transmittance	Seconds	Very high
3	TDR probe	Soil moisture	Electromagnetic	Minutes	High
4	Greenseeker	NDVI (N status)	Active reflectance	Real-time	High (tractor-mounted)
5	NIR spectrometer	Organic C, N, moisture	Near-infrared absorbance	Seconds	Medium
6	ISFET sensor	Soil pH	Field-effect transistor	Real-time	Medium-high

4.2 Emerging Sensor Technologies and IoT Integration

The next generation of agricultural sensors is moving beyond single-parameter measurement toward multi-sensor fusion platforms that simultaneously monitor soil moisture, temperature, pH, electrical conductivity, and nitrate concentration at multiple soil depths. These platforms transmit data wirelessly to cloud-based decision engines via IoT protocols (LoRaWAN, NB-IoT, or 4G/5G), enabling remote agronomist advisory and automated fertigation system control. Biosensors that detect plant volatile organic compounds (VOCs) emitted under nutrient stress represent a particularly promising frontier. Early research suggests that specific VOC profiles may distinguish between nitrogen, phosphorus and potassium deficiencies with greater specificity than optical reflectance indices, offering the prospect of deficiency-specific, real-time fertiliser prescription without soil or tissue sampling. The commercialisation timeline for such technologies is estimated at 5-10 years, contingent on miniaturisation and cost reduction of spectrometric detection modules.

Mitra *et al.* (2023) conducted an experiment in West Bengal to evaluate NDVI-based nitrogen management in wheat at 45 and 65 DAS, coinciding with the second and third irrigations. NDVI readings were used to determine the need for topdressing, with 65 DAS corresponding to the jointing stage, the last critical stage for prescriptive nitrogen application. Sensor-guided treatments recorded higher NDVI values and better response indices, improving in-season yield prediction compared to fixed nitrogen rates. Low NDVI (T_1) indicated poor canopy development and severe nitrogen deficiency. Excess nitrogen increased canopy greenness but did not proportionally increase yield, indicating luxury consumption. Moderate nitrogen application (T_8) maintained balanced NDVI values and achieved the highest Response Index. T_8 also recorded the highest grain yield and total nitrogen uptake due to real-time, demand-based nitrogen application. Optimised nitrogen supply at the CRI stage improved tillering, photosynthesis, biomass production, agronomic efficiency, and nitrogen use efficiency.

Li *et al.* (2019) investigated an ISE-based on-site soil nitrate-nitrogen detection system. A soil moisture sensor (ECH2O-5TE, Decagon, WA, USA) produced volumetric moisture readings that were used to determine the soil's net weight. The sensor was claimed to have a detection precision of $\pm 3\% \text{ m}^3/\text{m}^3$. Reagents used were all of analytical grade. The testing solution was prepared with deionised water. Standard soil chemical properties were provided by the soil testing centre of the China Agricultural University with commercial analytical instruments. Soil $\text{NO}_3\text{-N}$ detection results were compared among three direct methods standard Spectrometric results, laboratory ISE testing, and on-site ISE based monitoring. Testing efficiency was also evaluated by comparing the time and labour required to process twelve soil samples using UV-Vis, ISEOS and ISELT methods.



Fig. 4. Variable-rate technology

Nandi and Shrestha (2024) examined low-cost and higher-end soil moisture sensors across different moisture ranges and soil textures. Capacitive soil moisture sensors measure a change in the capacitance to determine the VWC. These sensors commonly consist of two parallel plates separated by a dielectric medium. The dielectric constant varies with the VWC. Low soil VWC corresponds to a low dielectric constant and, consequently, low capacitance between the plates. If the VWC in the soil increases, the dielectric constant also increases, and consequently, the capacitance between the two plates also increases.

5. Variable-Rate Technology in Modern Agriculture

Variable Rate Technology (VRT) enables the automated, spatially differentiated application of agricultural inputs like fertilisers, pesticides, seeds, and irrigation across heterogeneous landscapes, precisely matching input rates to localised crop demand. VRT represents the operational interface between data-driven nutrient prescriptions and physical fertiliser delivery, making it indispensable in any comprehensive smart fertilisation programme.

5.1 VRT Workflow, Classification, and Components

VRT systems operate through a structured seven-step workflow:

1. **Data Collection:** Information about the field is gathered, including soil properties, nutrient levels, crop yield history, moisture status, and field variability through soil sampling, yield monitors, and sensors.
2. **Data Analysis:** Collected data are analysed using software and GIS tools to identify variability within the field, determining which areas need more or fewer inputs such as fertilisers, seeds, or water.
3. **Prescription Map Generation:** Based on the analysis, a prescription map is created that divides the field into management zones and specifies the exact input rate required for each zone.
4. **Equipment Setup with VRT:** The prescription map is uploaded into VRT-enabled machinery. Equipment such as seeders, sprayers, or fertiliser applicators are calibrated to automatically adjust application rates according to the map.
5. **Field Application:** During field operations, the VRT equipment applies inputs at variable rates in real time. GPS and controllers ensure that each zone receives the prescribed amount.
6. **Applied Mapping and Record Keeping:** Results are recorded and mapped for future reference, helping in evaluating crop response and efficiency.
7. **Yield and Efficiency Evaluation:** Crop response and efficiency are evaluated by comparing yield data with input records to refine future prescription maps.

VRT systems are broadly classified as map-based (prescription maps prepared in advance using GIS and GPS data) and sensor-based (real-time applicator-mounted sensors that calculate application rates on-the-go without pre-existing maps). Map-based systems offer higher spatial precision when ground-truthed soil data are available, while sensor-based systems provide greater flexibility and eliminate the time lag between data collection and application. Hybrid systems combining both approaches are increasingly prevalent in large-scale commercial farming operations.

Patle *et al.* (2025) conducted a comparative evaluation of conventional fertiliser application and sensor-based variable-rate fertilisation systems in maize at Coimbatore, Tamil Nadu. The study examined nitrogen application at different crop growth stages. Total nitrogen use and resulting grain yield were recorded. Both treatments received the same base dose, but differences were observed at later growth stages. Conventional methods applied higher fixed nitrogen doses, whereas sensor-based systems applied nitrogen based on real-time crop requirements. The sensor-based approach reduced total nitrogen use from 245 to 198 kg N ha⁻¹, representing a significant reduction. Despite lower nitrogen input, the VRT system achieved a 22–28% increase in grain yield.

Lan *et al.* (2008) conducted an experiment in China to study variable rate fertilisation for maize and its effects based on the site-specific soil fertility and yield the results revealed that variable rate fertilisation is based on site-specific nutrient management, where fertiliser rates are adjusted according to soil fertility and crop demand. It improves nutrient use efficiency by synchronising

nutrient supply with maize uptake. VRF enhances root growth, phosphorus uptake, and biomass accumulation. Improved nutrient availability leads to higher grain yield compared to uniform fertilisation. Lower fertiliser input reduces production costs while increasing economic returns. Consequently, VRF achieved a higher output-input ratio and supports sustainable maize production.

Jang *et al.* (2020) conducted an experiment in Korea to examine the effects of various plant extracts on growth, nutrient levels and antioxidant activity in *Peucedanum japonicum* Thunb. The figure showed the effect of different treatments (CON, SL, SS, CC, ON, TM) and concentrations (Control, 0.5%, 1%, 3%) on plant height and shoot fresh weight. Plant height was generally higher in treated plants compared with the control, with the 3% concentration often yielding the maximum growth, especially in SL and TM treatments. Statistical letters (a, b, c, etc.) indicate significant differences, where “a” represents the highest performance. Similarly, shoot fresh weight increased with treatment intensity, with SL at 3% showing the highest biomass accumulation. Moderate improvements were also observed in SS, CC, and ON treatments across concentrations. Overall, increasing concentration enhanced both plant height and shoot fresh weight, indicating a positive response to the treatments.

6. Remote Sensing & UAVs in Modern Agriculture

6.1 Remote Sensing

Remote sensing is the science of acquiring information about objects or phenomena without direct physical contact, using sensors that detect reflected or emitted electromagnetic radiation. In smart fertilisation, both passive sensor systems (sun-illuminated reflectance captured by satellite) and active sensor systems (satellite-emitted radar or LiDAR signals independent of sunlight) are deployed to detect spatial variability in crop growth, nutrient deficiency, biomass, and stress across large field areas. Key applications of remote sensing in smart fertilisation include: nutrient deficiency detection through spectral signatures (N, P, K stress manifest as distinct reflectance patterns particularly in the red-edge and near-infrared bands); generation of spatially explicit fertiliser prescription maps from satellite imagery; crop health monitoring via vegetation indices (NDVI, GNDVI, SAVI, EVI); identification of optimal fertiliser timing by tracking phenological stages; and biomass and yield potential estimation to calibrate nutrient requirements.

The Sentinel-2 satellite constellation, operated by the European Space Agency, provides 10 m resolution multispectral imagery with a 5-day revisit cycle at no cost, making it increasingly accessible to agricultural researchers and extension services worldwide. In India, the ISRO's ResourceSat-2A and the Cartosat series provide complementary optical and thermal data used in national-scale crop monitoring programmes including the Fasal (Forecasting Agricultural Output using Space, Agro-meteorology, and Land-based observations) initiative.

Recent advances in hyperspectral satellite sensing (Hyperspectral Imager, or HySI) have enabled detection of not just broadband nutrient stress indicators but specific molecular absorption features associated with chlorophyll degradation, canopy water content, and lignin–cellulose ratios, providing a much richer phenotypic dataset for nutrient management prescription. Machine learning algorithms trained on these hyperspectral datasets can distinguish between nitrogen, phosphorus, and micronutrient deficiencies with accuracy exceeding 85% in controlled validation studies.



Fig. 5. Remote sensing applied in agriculture

6.2 UAV-based Foliar Nutrient Application

UAVs (drones) are remotely piloted or autonomously navigated aircraft equipped with multispectral cameras, LiDAR, or spray systems for high-resolution field diagnostics and precision input delivery. Agricultural drone use in India is projected to grow substantially during 2021–2030, with spraying commanding the highest adoption rate, followed by sensing/imaging at moderate adoption levels and sowing/planting at low adoption levels. Agricultural UAVs used for nutrient spraying typically carry 10-30 litre payload tanks, operate at 1.5-3 m canopy height, and achieve application rates of 15-45 litres per hectare. Ultra-low volume (ULV) spray nozzles produce droplets in the 50-150 μm range, optimising coverage and penetration of dense canopies while minimising off-target drift. Compared to manual knapsack spraying, UAV application reduces labour requirement by 90%, increases canopy coverage uniformity by 15-25%, and reduces water use by 60-80%.

Ramesh *et al.* (2024) conducted an experiment in Tamil Nadu to examine the effect of drone-based foliar application of Pulse Wonder on the yield attributes and yield of greengram. The results showed that T₄ (drone spray of 2% pulse wonder with 30 L ha⁻¹) recorded the highest yield. This increase in yield was mainly due to uniform spray coverage, efficient nutrient absorption, and timely supply of growth-promoting nutrients through drone application.

Ramesh *et al.* (2024) conducted an experiment in Tamil Nadu to examine the effect of drone-based foliar application of Pulse Wonder on the yield attributes and yield of greengram. The results showed that drone-based foliar application of pulse wonders significantly improved NPK uptake and nitrate reductase activity in greengram compared to manual spraying and control. This was due to uniform droplet size, better spray distribution, and enhanced leaf surface coverage. Improved nitrogen uptake stimulated nitrate reductase activity, indicating efficient nitrogen assimilation. Phosphorus uptake increased by avoiding soil fixation, while potassium uptake improved due to its high mobility through foliar application.



Fig. 6. Application of UAV-based foliar nutrient

Hemalatha *et al.* (2025) conducted an experiment in Tamil Nadu to examine the effects of drone-based and manual nutrient spraying on the growth and yield of black gram. The results showed that T₆ recorded the highest gross income, net income, and B:C ratio even though the cost of cultivation was comparatively higher. This was due to precise droplet deposition, uniform canopy coverage, and enhanced foliar nutrient absorption under drone spraying. Improved nutrient use efficiency led to superior crop growth and yield.

7. Integrated Smart Fertilisation Systems

The greatest gains from smart fertilisation are achieved not through individual technologies in isolation, but through their systematic integration into coherent, data-driven nutrient management platforms. Integrated smart fertilisation systems combine advanced fertiliser formulations with sensor networks, remote sensing data, VRT application equipment, and decision-support algorithms into a unified workflow that automates the “observe-analyse-prescribe-apply-evaluate” cycle of precision nutrient management.

An illustrative example of an integrated system architecture consists of the following layers: (1) Data acquisition layer comprising ground-based soil sensors, proximal crop sensors, UAV multispectral surveys, and satellite imagery; (2) Data integration and analytics layer-cloud-based platforms that fuse multi-source data streams, apply machine learning models to generate spatially explicit nutrient prescription maps, and update recommendations in near-real-time as new sensor data arrive; (3) Decision support layer-GIS-based prescription map delivery to farmer smartphones via mobile apps or SMS-based advisory services; (4) Application layer VRT-enabled tractor-mounted fertiliser applicators, drip fertigation automation or UAV spray operations that execute the prescription with minimal operator input.

India's Digital Agriculture Mission, launched in 2021 and operationalised through the Indian Digital Ecosystem of Agriculture (IDEA) framework, provides the foundational infrastructure for such integrated systems. The Unified Farmer Service Interface (UFSI) aggregates soil health card data, crop insurance records, market prices, and weather information into a unified farmer digital identity, potentially enabling prescription nutrient management at scale across the country's 140 million agricultural households.

Several state governments have piloted integrated precision nutrient management programmes. Karnataka's 'FRUITS' (Farmer Registration and Unified Beneficiary Information System) platform has been extended to include soil health monitoring, enabling integration of soil testing data with input subsidy disbursement. Andhra Pradesh's 'Rythu Sadhikara Samstha' has deployed 500+ remote soil moisture and weather stations across the state, providing real-time data for irrigation and fertilisation scheduling advisories delivered to farmers via the YSR Rythu Bharosa app.

8. Smart Fertilisation in Protected Cultivation

Protected cultivation, encompassing polyhouses, net houses, shade net structures, naturally ventilated polyhouses (NVPH), and hi-tech glasshouses, represents the most intensive and technologically advanced segment of Indian agriculture. As of 2025, India has approximately 0.4 million hectares under various forms of protected structures, growing approximately 18% annually, driven by horticultural crop demands, export requirements, and the National Horticulture Mission. Protected cultivation creates a controlled microenvironment that modifies temperature, humidity, light intensity, and CO₂ concentration. Within this precision environment, smart fertilisation is not merely desirable but essential, since crops grown in soilless media or controlled substrates have no access to natural soil nutrient reserves and are entirely dependent on externally supplied fertigation programmes.

8.1 Soilless Growing Media and Nutrient Delivery

Smart fertilisation in protected cultivation is intrinsically linked to growing media selection. The primary soilless media systems include: (i) Cocopeat-based substrates – derived from coconut husk fibre, with high water-holding capacity (60-70%), low EC, and excellent root aeration; (ii) Rockwool slabs – mineral fibre substrate widely used for hydroponic tomato and cucumber in European-style glasshouses, offering precise water and nutrient management; (iii) Perlite and vermiculite mixes – inorganic lightweight aggregates providing excellent drainage; (iv) Nutrient Film Technique (NFT) and Deep Water Culture (DWC) – fully hydroponic systems with roots suspended in flowing or recirculating nutrient solution; and (v) Aeroponics – high-pressure mist delivery of nutrients directly to exposed roots. In cocopeat-based protected cultivation, slow-release fertiliser granules (e.g., Osmocote 5-6 months formulation) are often incorporated at transplanting as a base dressing, supplemented by liquid fertigation programmes that fine-tune macro and micro-nutrient delivery throughout the crop cycle. This hybrid approach combines the stability of CRF base feeding with the precision of liquid fertigation adjustments, representing the most advanced form of smart fertilisation currently practiced in Indian commercial horticulture.

Singh *et al.* (2024) conducted an experiment in Punjab combining two irrigation schedules (I₁: stage-based PE irrigation and I₂: continuous 100% PE) with five nutrient treatments (F₁–F₅), resulting in 10 treatment combinations. I₁ applied water according to crop growth stages, while I₂ maintained a constant irrigation level throughout the crop period. Nutrient treatments varied from conventional soil fertilisation (F₁) to complete fertigation (F₄) and higher-dose fertigation (F₅). The results indicated that I₂ recorded slightly higher available N, P, and K at both 0–15 cm and 15–30 cm depths compared to I₁. Among nutrient treatments, F₅ showed the highest nutrient availability, followed by F₄, demonstrating the superiority of fertigation over conventional methods. Statistical analysis confirmed that fertigation significantly influenced soil nutrient status, while irrigation effects were comparatively less pronounced. The interaction between irrigation and nutrient treatments was mostly non-significant, indicating that nutrient management had a stronger impact than irrigation scheduling.

Thenmozhi and Kottiswaran (2017) conducted an experiment in Tamil Nadu to assess the effects of drip fertigation and mulching on yield under polyhouse and open-field conditions using 80% and 100% RDF. A uniform basal dose of 75% RDF phosphorus (703 kg ha⁻¹) was followed by stage-wise application of water-soluble fertilisers (NPK 19:19:19, 13:00:45, 12:61:0, and urea). Treatment T₂ recorded the highest yield (46.00 t ha⁻¹ in polyhouse; 30.51 t ha⁻¹ in open field), indicating superior fertigation scheduling. Mean yield was higher under polyhouse conditions (37.61 t ha⁻¹) than open field (27.86 t ha⁻¹), reflecting better efficiency under protected conditions. Statistical parameters (SED and CD at 5%) confirmed significant effects of treatments, irrigation, and their interaction.

8.2 Sensor Integration in Protected Cultivation

Protected cultivation structures are increasingly instrumented with multi-parameter sensor networks that monitor: (i) Substrate moisture tension (tensiometers, FDR sensors) to trigger fertigation events; (ii) Leachate EC and pH to assess nutrient uptake efficiency and adjust input concentrations; (iii) Leaf area index and canopy temperature via thermal infrared sensors to detect early stress; (iv) CO₂ concentration (target: 800–1200 ppm for vegetable crops) for photosynthesis optimization; and (v) PAR (Photosynthetically Active Radiation) measurement to correlate light interception with nutrient demand and dynamically adjust fertigation rates.

The integration of these sensor data streams with cloud-based fertigation control platforms allows automated, feedback-driven nutrient management. Companies like Priva (Netherlands), Ridder (Netherlands), and Netafim (Israel) have deployed smart fertigation controllers in premium Indian polyhouses, particularly in Maharashtra, Andhra Pradesh, Karnataka, and Tamil Nadu. Indian startups including Kheyti, Eruvaka, and CropIn are developing cost-appropriate sensor-fertigation systems targeting smallholder protected cultivators.

9. Smart Nutrient Management Technologies: Global Market Dynamics and Growth Forecast

The global smart fertiliser market can be evaluated across three overlapping but distinct segments: smart fertiliser products (i.e., CRFs, SRFs, polymer-coated, bio-based), smart fertiliser application systems (i.e., precision application machinery, drone-based systems) and smart fertiliser recommendation platforms (i.e., AI-driven advisory tools, soil sensing networks). Each of these

segments is experiencing growth, driven by different but complementary forces. The variation in market sizing across segments reflects different definitions. The narrower "smart fertiliser products" segment captures only advanced-formulation physical products, while the "smart fertiliser chemistry" market encompasses the full value chain of novel nutrient compounds including biostimulants and inhibitors. When digital systems (application and recommendation platforms) are included, the addressable market expands significantly, reflecting the convergence of AgTech with traditional agrochemicals.

9.1 Regional Analysis

Asia Pacific dominates the global smart fertiliser landscape, holding approximately 35–39% of total market share in 2024. China is the single largest country market, contributing over 43% of the broader fertiliser market at USD 44.8 billion. India and Japan are also key adoption markets, driven by government-backed precision farming initiatives and high population density. The Asia Pacific region is projected to grow at a CAGR of 9.2% in smart fertilisers from 2025 to 2033, the fastest of any region. North America ranks as the second-largest market, valued at approximately USD 2.1 billion in 2024 for smart fertiliser products alone. The region benefits from advanced precision agriculture infrastructure, strong regulatory pressure to reduce fertiliser runoff (particularly into the Mississippi River basin and Chesapeake Bay), and a high degree of farm digitization. North America is the fastest-growing region for smart fertiliser product adoption, driven by USDA support for sustainable farming practices. Europe's growth is heavily shaped by the EU's Farm to Fork Strategy, which targets a 20% reduction in fertiliser use by 2030 and a 50% reduction in chemical pesticides. These mandates are creating substantial demand for efficiency-improving smart fertiliser solutions as farmers seek to maintain yields while reducing input volumes. Latin America, particularly Brazil and Argentina, is increasingly deploying drone-based and satellite-supported variable-rate fertiliser application systems, positioning the region for accelerated growth through 2030.

9.2 Product Segmentation

Within the smart fertiliser product category, polymer-coated fertilisers (PCFs) hold the largest share, accounting for approximately 52–56.7% of the market in 2024. These products use polymer membranes to control the rate and duration of nutrient release, aligning nutrient availability with crop growth stages. Sulphur-coated urea (SCU), organic-based slow-release fertilisers, and chemical inhibitor-enhanced products make up the balance. The organic-based SRF segment is growing fastest (CAGR 6.8%), reflecting farmer demand for soil health improvement alongside yield optimization. By crop type, grains and cereals account for the largest share at approximately 46–50%, given their scale of global cultivation, while fruits and vegetables are the fastest-growing application (CAGR 6.9%).

9.3 Technical Dimensions of Smart Fertilisation

Smart fertilisation is not a single technology but a stack of interoperable innovations spanning materials science, data analytics, sensor engineering, and artificial intelligence. Understanding the technical architecture is essential to appreciating the market's long-term potential and the research priorities that drive it.

9.3.1 Controlled-release and Slow-release Fertiliser Formulations

The foundational technology of smart fertilisation is the design of fertiliser formulations that release nutrients in a controlled, time-dependent, or condition-responsive manner. The primary mechanisms include:

- **Polymer coating:** A semi-permeable polymer membrane encapsulates the nutrient granule. Water diffuses inward, dissolves the nutrient, and the solution diffuses outward at a rate governed by membrane thickness, temperature, and soil moisture. Release duration can range from 30 to 360 days, selectable at manufacturing stage.
- **Sulphur coating:** A less costly alternative where elemental sulphur provides a semi-permeable barrier. Microbial oxidation of sulphur in the soil further regulates release, also adding sulphur as a secondary plant nutrient.
- **Organic slow-release:** Nutrients are bound within organic matrices (e.g., urea-aldehyde condensates, composted materials). Release occurs through microbial decomposition, linking nutrient availability directly to soil biological activity.
- **Nitrification inhibitors (NIs):** Compounds such as DMPP (3,4-dimethylpyrazole phosphate) suppress the activity of *Nitrosomonas* bacteria in the soil, slowing the conversion of ammonium (NH_4^+) to nitrate (NO_3^-) and thereby reducing leaching and N_2O emissions. Urease Inhibitors (UIs) such as NBPT delay ammonia volatilization from urea, improving nitrogen retention in the application zone.

In April 2025, BASF introduced Ampliqan® - a new nitrification inhibitor compatible with a wide range of nitrogen fertilisers, specifically designed to improve NUE and reduce greenhouse gas emissions. This product exemplifies ongoing industrial investment in formulation-level smart fertilisation chemistry.

9.3.2 Digital Technologies: IoT, AI, and Precision Application

The second major pillar of smart fertilisation is the integration of digital sensing and artificial intelligence to guide when, where, and how much fertiliser is applied. This precision application layer dramatically amplifies the efficiency gains of smart formulations. Key technology components include:

- **Soil sensors (In-Field):** IoT-enabled electrochemical sensors measure soil pH, moisture, temperature, electrical conductivity, and NPK (nitrogen, phosphorus, potassium) content in real time. These sensors communicate via Wi-Fi,

Bluetooth, LoRaWAN, or cellular networks to cloud processing platforms, providing continuous spatiotemporal data across agricultural fields.

- **Remote sensing and UAVs:** Multispectral and hyperspectral imaging from drones (UAVs) and satellites enables crop health mapping through vegetation indices such as NDVI (Normalized Difference Vegetation Index) and NDRE (Normalized Difference Red Edge). These maps identify zones of nutrient deficiency or excess within a field at resolutions as fine as 5 cm.
- **Variable Rate Application (VRA):** GPS-guided machinery uses prescription maps generated from sensor and remote sensing data to apply different rates of fertiliser across different zones within a single field. Variable-rate spreaders and sprayers can adjust application in real time, eliminating over-application in high-fertility areas and remedying deficiencies in low-fertility zones.
- **AI-Driven recommendation engines:** Machine learning models, including deep learning architectures such as TabNet (achieving 95.24% accuracy in fertiliser recommendation tasks with IoT data), process multivariate inputs including soil nutrient levels, weather history, crop growth stage, and historical yield maps to generate site-specific fertiliser prescriptions. Interpretable AI techniques such as SHAP (Shapley Additive Explanations) are increasingly used to ensure agronomists understand model outputs.
- **Digital twins and mobile apps:** Integrated platforms deliver recommendations to farmers via smartphones and web dashboards. Some systems, as described in recent ScienceDirect literature, implement digital twin architectures where a virtual replica of the farm is continuously synchronised with sensor data, enabling predictive scenario modelling and automated fertigation scheduling.

In February 2024, the Mosaic Company partnered with CropX to integrate smart fertiliser solutions; in March 2024, Nutrient launched an AI-driven fertiliser recommendation tool; and in December 2024, SQM invested in Arable Labs to integrate IoT-based recommendation tools demonstrating sustained corporate investment in digital fertilisation infrastructure.

9.3.3 Fertigation System

Fertigation, the delivery of dissolved fertilisers through irrigation water, represents a particularly efficient application method. IoT-based fertigation systems, as documented in recent ScienceDirect publications, use integer linear programming (ILP) models to simultaneously minimise water and nutrient waste while meeting crop demand across diverse horticultural environments, including both soil-based and soilless systems. These systems integrate seamlessly with controlled-release formulations, providing a multi-layer smart fertilisation architecture.

9.3.4 Nutrient Use Efficiency (NUE): The Core Technical Metric

NUE is a primary quantitative measure of smart fertilisation performance. It expresses the proportion of applied nutrient that is actually taken up by the crop. Conventional nitrogen fertiliser NUE is typically 30–50%. Smart fertiliser technologies, particularly when combined with precision application, have demonstrated NUE improvements of 15–30 percentage points in controlled studies. Phosphorus and potassium use efficiencies face different challenges - P is highly reactive with soil particles while K leaches in coarse-textured soils and both are targeted by formulation-specific smart fertiliser products designed for each nutrient's soil chemistry. Improving NUE is simultaneously an economic benefit (lower input cost per unit yield) and an environmental imperative (lower leachate, lower N₂O emissions, reduced eutrophication risk).

9.4 Key Barriers to Adoption

Despite strong growth, several barriers limit the pace of smart fertilisation uptake, particularly in smallholder and developing market contexts:

- **High initial cost:** Smart fertiliser products carry a price premium of 20–60% over conventional equivalents. Precision application hardware (variable-rate spreaders, UAVs, soil sensor networks) carries capital costs that may take 3–7 years to recover for small operations.
- **Digital divide:** As noted in a 2025 PMC systematic review (PRISMA methodology, 2020–2024 literature), innovation in AI and IoT agriculture is concentrated in technologically advanced countries. Smallholder farmers in Sub-Saharan Africa, South Asia, and parts of Southeast Asia have limited access to connectivity, smart devices, and agronomic advisory services.
- **Knowledge and training gap:** Optimal use of smart fertilisers requires soil testing, crop modelling literacy, and digital platform proficiency. Extension services capable of delivering this knowledge remain underdeveloped in many regions.
- **Interoperability:** Smart agricultural systems frequently operate in proprietary silos. Sensor data, VRA prescription maps, and recommendation platform outputs may not integrate seamlessly, creating friction in implementation.

10. Challenges, Limitations, and Future Directions

10.1 Technical and Scientific Challenges

Despite considerable progress, smart fertilisation faces several unresolved technical challenges. Soil sensor accuracy degrades rapidly in heterogeneous soils with high clay content, organic matter variability, or salinity, limiting the reliability of real-time recommendations in complex soil environments. NDVI-based nitrogen algorithms trained in one agro-climatic zone frequently

underperform when transferred to different soil types, cultivars, or climatic conditions, underscoring the need for locally calibrated decision models rather than universal prescriptions.

The temporal mismatch between nutrient prescription and crop uptake remains a fundamental challenge. Prescriptions based on sampling at a single time point fail to capture within-season variability in crop demand arising from weather events, pest pressure, or genotype-environment interactions. Continuous monitoring systems partially address this gap but require robust sensor networks with low maintenance requirements and resilience to field conditions, which current sensor technologies do not fully satisfy.

Nano-fertiliser safety is an emerging concern that the scientific community is only beginning to address systematically. Nano-particles at high concentrations have been shown to inhibit soil bacterial and fungal communities, potentially disrupting ecosystem services such as organic matter decomposition and biological nitrogen fixation. Regulatory frameworks for nano-material registration and labelling in agriculture are absent in most countries, creating uncertainty for both manufacturers and farmers.

10.2 Socio-economic and Policy Barriers

The adoption of smart fertilisation technologies is highly unequal across farm size categories, agro-climatic zones, and educational levels. Large commercial farms with diversified income streams and access to institutional credit are far better positioned to invest in VRT equipment, UAVs, and sensor networks than the majority of South Asian farmers who cultivate less than 2 hectares. This technological divide risks exacerbating existing agricultural inequality unless targeted policy interventions such as technology-as-a-service models, subsidized group adoption, and public-funded demonstration networks are implemented at scale.

Fertiliser subsidy structures in India, which price urea at highly subsidized rates (approximately INR 5–6 per kg compared to market rate of INR 20–25 per kg), paradoxically incentivize over-application of nitrogen and dis-incentivize adoption of controlled-release or nano-urea alternatives that carry higher purchase prices, despite their superior NUE. Policy reform aligning subsidy structures with NUE outcomes—rather than simple quantity of fertiliser applied—is essential to create market incentives for smart fertilisation adoption.

11. Conclusion

Smart fertilisation represents a paradigm shift in nutrient management from blanket, input-intensive approaches toward intelligent, demand-driven systems that deliver the right nutrient, at the right rate, at the right time, and in the right place. This review has synthesized evidence from field experiments across diverse agro-climatic zones to demonstrate that individual smart fertilisation technologies, including advanced formulations, fertigation, sensors, VRT, and remote sensing/UAVs each deliver meaningful improvements in NUE, yield, and environmental performance. Their integration into coherent, data-driven management systems amplifies these benefits synergistically. The evidence base is now sufficient to justify confident recommendations: sulphur-coated and polymer-coated fertilisers should replace conventional urea in high-value cropping systems; nano-DAP and nano-zinc can meaningfully supplement conventional phosphorus and micronutrient programmes where soil fixation limits conventional fertiliser effectiveness; drip fertigation is economically justified for most irrigated cash crops even at smallholder scale when subsidy pathways are accessible; sensor-guided nitrogen management consistently reduces nitrogen input by 15–25% without yield penalty; and UAV-based foliar nutrition delivers superior uniformity and cost-effectiveness relative to manual spraying for established crop systems. Realizing the full potential of smart fertilisation at national scale requires simultaneous action on multiple fronts: public investment in sensor infrastructure and digital agricultural platforms; reform of fertiliser subsidy structures to incentivize efficiency over quantity; strengthening of extension networks capable of translating precision agriculture data into actionable recommendations for smallholder farmers; and rigorous long-term research on the ecological sustainability of nano-materials and intensively managed precision agriculture systems. With these enabling conditions in place, smart fertilisation can play a decisive role in achieving food security for a population of 10 billion by 2050 while keeping agriculture within planetary boundaries.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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