



 **Nutrient
Management**
Training Manual-6

ISBN : 978-93-5913-914-2

From Input To Efficiency Intensification

Scientific Basis for Sustainable Fertiliser Management



Binay Kumar Singh | Usha Das
Ravindra Singh Shekhawat | Anuj Kumar

ICAR - Indian Institute of Wheat and Barley Research
Karnal – 132 001 (Haryana)



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FOREWORD

Sustainable agricultural productivity depends on improving fertiliser-use efficiency while preserving soil and environmental health. *From Input to Efficiency Intensification: Scientific Basis for Sustainable Fertiliser Management* offers a comprehensive resource on nutrient dynamics, fertiliser-use efficiency, soil health, and sustainable nutrient management in intensive agricultural systems. The manual integrates agronomic principles with recent advances in precision agriculture, enhanced-efficiency fertilisers, microbial interventions, molecular breeding, root system engineering, and climate-smart nutrient management. It also examines the economic and policy aspects of fertiliser use, focusing on the rice–wheat production systems of the Indo-Gangetic Plains, where imbalanced nutrient application and declining soil fertility are growing challenges.

The main strength of this manual is its ability to connect fundamental scientific concepts with practical field applications. Its inclusion of nutrient management strategies, diversified cropping systems, biofertilizer applications, and region-specific recommendations enhances its relevance to researchers, students, extension personnel, policymakers, and agricultural practitioners. By emphasising balanced fertilisation, integrated nutrient management, soil biological processes, and resource-use efficiency, the manual outlines a clear path to resilient, sustainable agricultural production. This timely and significant scientific contribution by Drs. Binay Kumar Singh, Usha Das, Ravindra Singh Shekhawat, and Anuj Kumar will serve as a valuable reference for advancing sustainable nutrient use and promoting long-term agricultural sustainability.



(Ratan Tiwari)

Place: Karnal

Date: 4 August, 2026

CHAPTER 01

1. Introduction

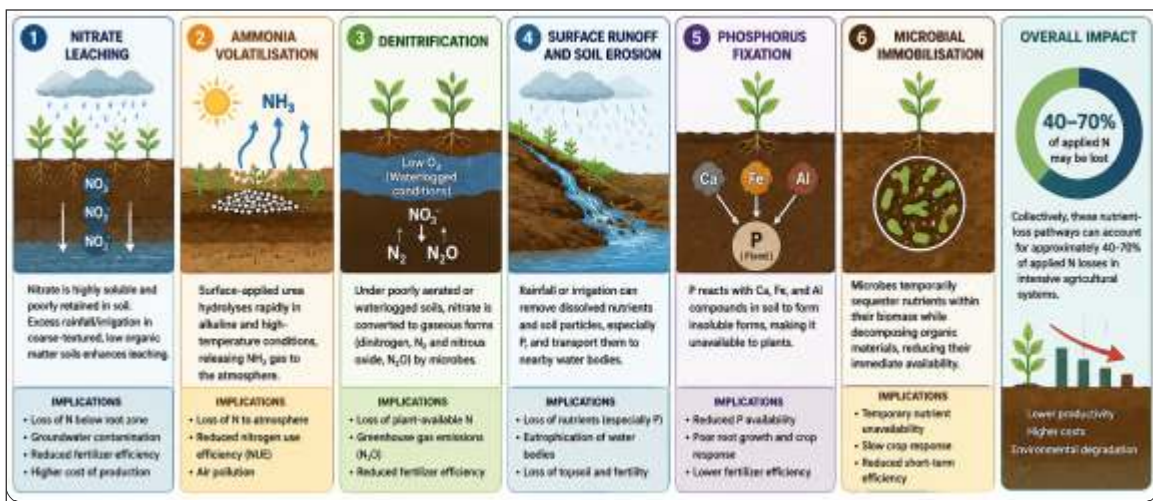
Agricultural productivity and food security in India depend on the availability and efficient use of mineral fertilisers. Today, India is the second-largest fertiliser consumer in the world. In 2024–25, India used nearly 70.7 million tonnes of fertiliser, supplying nearly 33 million tonnes of N, P, and K. Despite a large domestic fertiliser industry, India still depends heavily on imports for finished products and essential raw materials. Approximately 20% of urea, nearly 50% of DAP, and almost all MOP are imported. If we include feedstocks and intermediates, India's reliance on global fertiliser supply chains is about 68–70%. The risk is further heightened because nearly 85% of the natural gas used for urea production is imported. The phosphatic fertiliser sector also relies on imports for 90–95% of rock phosphate and about half of its phosphoric acid requirements, making fertiliser production and supply highly sensitive to changes in global energy and commodity markets.

Indian agriculture faces a major challenge due to an imbalance in fertiliser use. Nitrogenous fertilisers, especially urea, account for almost 55% of total fertiliser consumption, whereas phosphatic and potassic fertilisers are used at substantially lower levels, with DAP at about 13% and MOP at only about 3%. This skewed nutrient application has resulted in an imbalanced N:P:K ratio and a significant decline in nutrient-use efficiency, especially nitrogen-use efficiency (NUE), which has decreased from approximately 60–70% during the early Green Revolution to nearly 30–35% in recent years. Government policies and pricing have further intensified this imbalance, since urea is heavily subsidised and sold at a government-controlled price well below production and import costs. Consequently, urea alone accounts for nearly 60–65% of the total fertiliser subsidy, encouraging disproportionate N use while discouraging balanced application of phosphatic, potassic, and micronutrient fertilisers. These practices contribute to soil nutrient depletion, declining soil organic matter, groundwater contamination, soil acidification, greenhouse gas emissions, and deterioration of long-term agricultural sustainability. Recent global events, including geopolitical conflicts in major exporting regions, export restrictions, disruptions to trade routes such as the Strait of Hormuz, and volatility in energy markets, have further heightened risks to fertiliser availability, affordability, and subsidy burdens, potentially affecting the timely supply of fertiliser during critical crop growth stages.

Improving fertiliser-use efficiency (FUE) and promoting balanced nutrient management have therefore become major priorities for both farmers and policy makers. Modern intensive agriculture relies heavily on external mineral nutrient inputs, particularly N, P, and K, with N remaining the most yield-limiting nutrient in many agroecosystems. However, FUE, especially NUE, remains low, with crops generally recovering less than half of the applied N under field conditions. A substantial proportion of applied nutrients is lost from the soil–plant system through multiple physical, chemical, and biological pathways, resulting in considerable economic losses and environmental degradation. Addressing these challenges requires a transition from conventional input intensification to efficiency intensification, with greater emphasis on maximising the proportion of applied nutrients effectively absorbed and converted into economic yield. Achieving this objective will require integrated approaches, including balanced fertiliser application, soil testing, site-specific nutrient management, enhanced-efficiency fertilisers, biological nutrient mobilisation, crop improvement for enhanced FUE, and the integration of precision agriculture and digital technologies.

2. Major pathways of nutrient loss and their agronomic implications

One of the major constraints to improving FUE, particularly NUE, is nutrient loss through multiple processes operating within the soil–plant system. Nitrate leaching represents one of the dominant pathways of N loss because nitrate is highly soluble and poorly retained in soil, particularly under excessive rainfall or irrigation in coarse-textured soils with low organic matter content. Ammonia volatilisation is another important loss mechanism, especially in alkaline and high-temperature environments, where surface-applied urea rapidly hydrolyses, releasing ammonia gas into the atmosphere. Under poorly aerated or waterlogged soil conditions, denitrification is the dominant process, converting nitrate into gaseous forms such as dinitrogen (N_2) and nitrous oxide (N_2O), thereby reducing plant-available N. Nutrients may also be lost through surface runoff and soil erosion, which transport dissolved and particulate nutrients, particularly P, into nearby water bodies. In addition, P fixation through reactions with Ca, Fe, and Al compounds can substantially reduce P availability to plants, whereas microbial immobilisation may temporarily sequester nutrients within organic biomass, restricting their immediate availability. Collectively, these nutrient-loss pathways can account for approximately 40–70% of applied N losses in intensive agricultural systems.



Major pathways of nutrient loss and their agronomic implications

3. Conceptual basis of fertiliser use efficiency

Fertiliser use efficiency (FUE) measures how efficiently applied nutrients are converted into economic yield. It includes the plant's ability to absorb nutrients from the soil and convert them into biomass and grain. FUE consists of three components: agronomic efficiency (AE), recovery efficiency (RE), and physiological efficiency (PE).

3.1. Agronomic efficiency

Agronomic efficiency (AE) refers to the increase in crop yield per unit of nutrient applied.

$$AE = \frac{Y_f - Y_o}{F}$$

where Y_f is the yield in the fertilised plot, Y_o is the yield in the unfertilized plot, and F is the amount of nutrient applied.

In a cereal production system, nitrogen AE usually ranges from 10 to 30 kg of grain per kg of N applied. This varies with environmental conditions, soil properties, and crop management. AE is the product of recovery efficiency and physiological efficiency, suggesting that improvements in either nutrient uptake or internal utilisation can improve agronomic performance.

3.2. Recovery efficiency

Recovery efficiency (RE) measures the proportion of fertiliser nutrients absorbed by the crop.

$$RE = \frac{U_f - U_o}{F}$$

where U_f is nutrient uptake in the fertilised plot, U_o is nutrient uptake in the unfertilized plot, and F is the amount of nutrient applied.

Under field conditions, nitrogen RE typically ranges from 30% to 50%, indicating that a significant portion of the applied fertiliser is not taken up by crops. RE is strongly affected by soil properties, climate, crop type, and management practices, so it is the part of FUE that can be improved most quickly with changes in agricultural practices.

3.2.1. Factors influencing RE

3.2.1.1. Fertiliser placement and timing

Applying nutrients at the right place and time to match crop needs is essential for efficient resource use. Placing nutrients below the surface or in bands concentrates them within the root zone, helping prevent losses from volatilisation, runoff, and fixation. Splitting N applications also helps by matching with the times when crops need it most and reducing the risk of nutrient loss early in the season.

3.2.1.2. Soil properties

Soil texture, organic matter content, and pH are major factors regulating nutrient retention and availability. Coarse-textured soils tend to lose nutrients through leaching, while fine-textured soils may retain nutrients more effectively but can promote denitrification if poorly aerated. Adding more organic matter helps the soil hold onto nutrients, improves its structure, and increases its ability to buffer nutrients.

3.2.1.3. Moisture and hydrology

Soil moisture affects nutrient mobility, transformation, and root uptake. When moisture is sufficient, nutrients reach roots more easily via diffusion and mass flow, while drought limits nutrient movement and root activity. Excessive rainfall, irrigation, or waterlogging can cause nutrient loss through leaching and denitrification.

3.2.1.4. Root and rhizosphere traits

Root architecture, rhizosphere chemistry, and microbial interactions determine the crop's capacity for nutrient uptake. Traits such as increased rooting depth, higher root length density, extensive lateral branching, and root hair development enhance exploration of the soil profile. Additionally, root exudates and beneficial microbial associations, such as mycorrhizae, further improve nutrient solubilization and acquisition, particularly under low-input conditions.

3.3. Physiological efficiency

Physiological efficiency (PE) refers to the ability of a crop to convert absorbed nutrients into economic yield. It is defined as:

$$PE = \frac{Y_f - Y_0}{U_f - U_0}$$

Where Y_f is the yield in the fertilised plot, Y_0 is the yield in the unfertilized plot, U_f is nutrient uptake in the fertilised plot, U_0 is nutrient uptake in the unfertilized plot.

In cereal cropping systems, nitrogen PE typically ranges from 30 to 60 kg of grain per kg of N absorbed. These values vary depending on genotype, environmental factors, and management practices.

3.3.1. Physiological basis of PE

3.3.1.1. Photosynthesis and canopy function

Photosynthetic performance plays a key role in determining PE because nutrient-dependent biochemical processes drive assimilate production. Nitrogen is essential for chlorophyll, Rubisco, and thylakoid proteins, so the amount of N in leaves is closely related to photosynthetic capacity. Genotypes with high PE typically exhibit higher photosynthetic NUE, improved canopy structure, and extended green leaf area during grain filling.

3.3.1.2. Assimilate partitioning

PE also depends on the efficient allocation of assimilates to the plants' harvestable parts. When the harvest index is high and stable, sink demand is strong, and the source-sink relationship is balanced, plants convert nutrients into grain yield more effectively. On the other hand, excessive vegetative growth can reduce the efficiency with which plants convert absorbed nutrients into usable yield.

3.3.1.3. Nutrient assimilation and remobilisation

Plants take up nitrate and ammonium and convert them into amino acids. Later, they move stored N to developing grains, which is another important factor for PE. In cereals, a substantial proportion of grain N comes from N remobilised from older plant tissues during reproductive development. Efficient remobilisation requires coordinated senescence, effective phloem transport, and sustained photosynthetic activity throughout grain filling.

3.3.1.4. Metabolic efficiency

PE also depends on the efficiency of metabolic pathways that convert assimilated nutrients into structural and storage compounds. Factors such as C-N balance, respiratory costs, ATP availability, and enzyme activity contribute to genotypic variation in internal nutrient utilisation. This helps explain why cultivars with similar nutrient uptake can have different yields.

3.3.1.5. Genetic control and breeding implications

PE is more influenced by genetic factors than RE. This makes PE an important target for crop improvement, particularly through selection for traits such as photosynthetic capacity, N remobilisation efficiency, harvest index, sink strength, and stay-green behaviour. Contemporary breeding strategies use physiological phenotyping, molecular markers, and genomic selection to enhance these traits.

Improving PE, however, involves trade-offs. Higher efficiency can sometimes lead to lower grain protein concentration due to dilution, and stronger remobilisation may accelerate senescence if it is not balanced by continued assimilate production. In addition, PE remains environmentally modulated, with temperature, light, water availability, and nutrient balance all affecting the expression of genetically determined potential.

4. Conventional agronomic strategies

Conventional agronomic practices form the operational basis for improving FUE. They directly influence nutrient availability, nutrient losses, and crop demand at the field scale. Most of these practices primarily enhance recovery efficiency, while some also improve agronomic and physiological efficiency by enhancing soil function and crop performance. When properly implemented, these practices can substantially reduce fertiliser losses and help match nutrient supply and plant uptake.

4.1. 4R nutrient management

The 4R nutrient management system provides a practical basis for applying FUE principles in the field. Its four dimensions—right source, right rate, right time, and right place—help match the type, amount, timing, and placement of nutrients with crop demand and prevailing soil conditions. The right source means selecting fertiliser types that fit the crop, soil, and environment. The right rate is determined by soil testing, anticipated yield, and nutrient budgeting. Applying nutrients at the right time and place ensures they are available when and where roots can absorb them most effectively.

4.2. Soil testing and site-specific nutrient management

Site-specific nutrient management recognises that soil fertility can vary significantly within and across fields. Blanket fertiliser recommendations do not account for differences in soil texture, organic matter, topography, or past management, leading to nutrient over-application in some areas and under-application in others. Soil testing thus provides the analytical basis for more precise fertiliser decision-making. A site-specific approach typically integrates soil testing, nutrient budgeting, and decision-support tools to match fertiliser inputs with localised crop requirements. More advanced methods might use grid sampling, fertility maps, or sensors such as chlorophyll meters and vegetation indices. By refining nutrient recommendations, this approach helps balance nutrients, improve efficiency, maintain yields, and reduce unnecessary fertiliser use.

4.3. Balanced fertiliser application

Balanced fertiliser application is important because crops need all essential nutrients, not just N. Deficiencies of P, K, S, Zn, Fe, or other nutrients can restrict plant growth and reduce the efficiency with which applied N is absorbed and utilised. Thus, nutrient imbalance weakens both recovery efficiency and physiological efficiency, even when total fertiliser input is high.

A balanced nutrient supply supports root development, stomatal regulation, enzyme activation, and metabolic coordination. For instance, P enhances root growth and facilitates N uptake, while K is essential for stomatal function and N assimilation. This balanced approach improves agronomic efficiency by preventing any single nutrient deficiency from limiting crop response to fertiliser.

4.4. Split application of nitrogen

Split N application is among the most effective conventional strategies for enhancing NUE. Because N moves easily through soil and can be lost in various ways, a single large application often results in a mismatch between nutrient supply and crop demand, particularly early in the season when uptake is limited. By splitting the total amount into applications at the basal, vegetative, and



A farmer applying urea during the vegetative stage of wheat growth

reproductive stages, the nutrient supply matches more closely with crop demand.

This approach reduces nitrate accumulation in soil during periods of low crop demand, thereby reducing the risk of N loss through leaching, volatilisation, and denitrification. It also enhances N recovery and often stabilises yield under variable field conditions. In cereals such as wheat and rice, split application has consistently demonstrated improved NUE compared to single-dose application.

4.5. Crop rotation and diversification

Crop rotation and diversification enhance nutrient use efficiency at the system level by promoting nutrient cycling and reducing the need for external inputs. Rotating with legumes is especially helpful because these plants fix atmospheric N, which can reduce fertiliser needs for subsequent crops. Rotational diversity also improves soil structure, organic matter, and biological activity.

In addition to improving nutrient supply, diverse cropping systems help break pest and disease cycles and increase resilience to climatic and management stresses. Intercropping and sequential cropping further optimise the complementary use of resources and nutrient uptake. These advantages make diversification an important strategy for better nutrient management, healthier soil, and long-term sustainability.



A typical view of sequential cropping of sugarcane after wheat

4.6. Organic amendments

Organic amendments such as FYM, compost, green manure, and crop residues help improve FUE by enhancing nutrient retention and supporting soil biology. They offer both nutritional and structural benefits by raising soil organic carbon, improving aggregation, increasing water-holding capacity, and raising cation exchange capacity (CEC). These changes help reduce nutrient losses and promote more stable nutrient release.



A typical view of FYM application in the field

Since nutrients in organic materials are released slowly, they complement mineral fertilisers by making them available over a longer period. Organic amendments also boost microbial activity and rhizosphere processes, which help with nutrient cycling. This makes them especially useful in integrated nutrient management systems aimed at improving both recovery efficiency and physiological performance.

4.7. Conservation agriculture

Conservation agriculture enhances nutrient efficiency by promoting minimal soil disturbance, maintaining permanent soil cover, and encouraging crop diversification. These practices improve soil structure, facilitate residue recycling, increase infiltration, and control erosion. Over time, they enhance soil biological activity and reduce losses from runoff, erosion, and structural degradation.



A typical view of maize residue recycling in the field

The benefits of conservation agriculture are most evident in long-term systems, where residue retention and reduced tillage progressively enhance soil organic matter (SOM) and physical condition. These changes gradually improve nutrient use efficiency, particularly in rainfed environments. Conservation agriculture thus complements input-focused practices by improving soil conditions for nutrient management.

5. Soil and microbial-based strategies

Soil- and microbe-mediated strategies enhance the biological basis of FUE by improving the internal functioning of the soil-plant system. Rather than relying primarily on external nutrient inputs, these approaches strengthen nutrient retention, transformation, and delivery through mechanisms such as SOM dynamics, microbial activity, and rhizosphere processes. Consequently, soil and microbial processes serve as the biogeochemical engine of agroecosystems, regulating nutrient cycling, buffering capacity, and nutrient availability to plants.

One important benefit of these strategies is that they reinforce each other. When SOM increases, it boosts microbial activity, which accelerates nutrient cycling. Improved nutrient cycling leads to stronger root growth and helps plants take up nutrients more

effectively. Over time, these improvements help plants use fertiliser more efficiently, reduce nutrient loss, and create more resilient and self-sustaining production systems.

5.1. Management of soil organic matter

Soil organic matter (SOM) plays a key role in soil fertility. It acts as a nutrient reservoir and regulates nutrient movement through the soil. SOM affects physical, chemical, and biological processes, which makes it essential for nutrient recovery and plant growth. By regulating nutrient retention, water relations, soil structure, and microbial activity, SOM links the short-term effects of fertiliser use to the long-term productivity of the soil.

Functional mechanisms

1. SOM contains negatively charged functional groups, such as carboxyl and phenolic groups, which enhance CEC. This increases the retention of nutrient cations, including NH_4^+ , K^+ , Ca^{2+} , and Mg^{2+} , thereby reducing leaching losses and maintaining a readily exchangeable nutrient pool in the rhizosphere.



Soil organic management and its agronomic implications

3. SOM functions as a dynamic nutrient buffer, moderating fluctuations in nutrient availability. Microbial mineralisation enables the gradual release of nutrients, thereby helping to better match nutrient availability with crop needs.
4. SOM provides carbon and energy for soil microorganisms. When microbial biomass and activity increase, key nutrient processes such as N mineralisation, nitrification, P solubilisation, and organic matter decomposition are enhanced.

5.2. Biofertilizers and microbial inoculants

Biofertilizers are composed of beneficial microorganisms that enhance nutrient

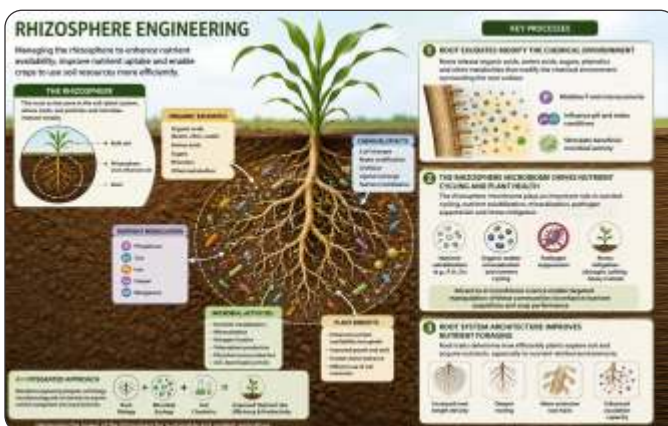
availability through biological processes rather than direct nutrient supplementation. Their primary function is to complement mineral fertilisers by increasing nutrient acquisition efficiency, mobilising otherwise inaccessible nutrient pools, and lowering the need for external inputs. Biofertilizers are especially useful in situations where a significant amount of nutrients is lost or when chemically applied nutrients are rapidly immobilised or fixed in the soil.

Functional groups and roles

1. Organisms such as *Rhizobium* form symbiotic associations with legumes, resulting in root nodules where atmospheric N is converted to ammonia. This process supplies significant quantities of N to cropping systems.
2. *Azotobacter* acts as a free-living aerobic N fixer, while *Azospirillum* establishes associative relationships with cereals and grasses. Beyond N fixation, these microorganisms frequently stimulate root growth through phytohormone production.
3. Phosphate-solubilising bacteria (PSB) and fungi transform insoluble P compounds into plant-available forms through mechanisms such as organic acid production, proton extrusion, and chelation. This function is especially critical in soils where a large proportion of applied P becomes fixed and is not readily available to plants.
4. AMF establish symbiotic associations with plant roots and expand the effective absorptive area via external hyphal networks. This significantly improves the uptake of relatively immobile nutrients, particularly P and various micronutrients, and also supports water acquisition and stress tolerance.

5.3. Rhizosphere engineering

The rhizosphere is the most active area in the soil-plant system, where roots, soil particles, and microbes interact closely. Rhizosphere engineering focuses on managing this zone to boost nutrient availability, improve plant nutrient uptake, and enable crops to use soil resources more efficiently. This method brings together root biology, microbial ecology, and soil chemistry to improve nutrient management.



Rhizosphere engineering and its agronomic implications

Key processes

1. Roots release organic acids, amino acids, sugars, phenolics, and other metabolites that modify the chemical environment surrounding the root surface. These compounds mobilise P and micronutrients, influence pH and redox conditions, and stimulate beneficial microbial activity.
2. The rhizosphere microbiome plays an important role in nutrient cycling, nutrient solubilization, mineralisation, pathogen suppression, and stress mitigation. Recent advances in microbiome science enable targeted manipulation of these communities to enhance nutrient acquisition and crop performance.
3. Root system architecture plays the most important role in nutrient foraging. Traits including increased root length density, deeper rooting, more extensive root hairs, and enhanced exudation capacity improve soil exploration and nutrient absorption, especially in nutrient-limited environments.

5.4. Agroforestry systems

Agroforestry systems integrate trees with crops and, in some cases, livestock to create a multilayered production system that recycles nutrients more effectively than monocultures. Trees access deeper soil layers and add biomass year-round, helping capture nutrients over a longer period and across a larger area. Consequently, agroforestry is especially useful when nutrient losses, soil degradation, or climatic stress limit fertilizer efficiency.



A typical view of agroforestry

Mechanisms enhancing FUE

1. Deep-rooted trees access nutrients from subsoil layers unavailable to annual crop roots and return them to the surface through litter fall, pruning residues, and root turnover.
2. Ongoing inputs of leaf litter and root biomass increase SOM, thereby enhancing nutrient retention, soil aggregation, and biological activity.
3. Tree cover helps protect the soil from heavy rain, slows runoff, and prevents nutrients from washing away.

4. Leguminous trees contribute additional N via symbiotic fixation.
5. Trees modify wind speed, temperature, radiation, and soil moisture, creating a more favourable environment for root activity, microbial processes, and nutrient uptake.

6. Advanced fertiliser technologies

Soil- and microbe-based methods help improve the environment for nutrient cycling and capture, while advanced fertiliser technologies directly influence fertiliser behaviour. These technologies aim to control nutrient release, deliver nutrients more precisely, and reduce losses. Unlike regular fertilisers, which often release nutrients rapidly, not when crops need them, advanced fertilisers are designed to match nutrient availability more closely with plant uptake.

This shift is especially important in situations where nutrient recovery remains low, even with the best agricultural practices. Advanced fertilisers help reduce losses from volatilisation, leaching, denitrification, and poor targeting. This improves both crop efficiency and environmental outcomes. As a result, these technologies are an important step between traditional nutrient management and precision agriculture.

6.1. Enhanced efficiency fertilisers

Concept and classification

Enhanced-efficiency fertilisers (EEFs) are specialised formulations designed to increase nutrient availability to plants and minimise nutrient losses to the environment. These outcomes are achieved by either modifying the timing of nutrient release or suppressing specific soil biochemical transformations that accelerate nutrient loss.

The major categories include the following:

1. Controlled-release fertilisers: These are designed to release nutrients at a steady rate. They usually use special coatings or barriers that regulate water ingress and nutrient egress.

2. Slow-release fertilisers: These fertilisers release nutrients slowly over time through chemical breakdown or the action of microbes. Examples are urea-formaldehyde and isobutylidene diurea (IBDU).

3. Stabilised fertilisers: These formulations incorporate additives that delay key N transformations in soil, thereby extending the retention of plant-available N forms.

Key additives

Urease inhibitors like NBPT slow the hydrolysis of urea, thereby reducing ammonia loss to the air. Nitrification inhibitors such as DCD and DMPP slow the conversion of ammonium

to nitrate, reducing the risk of nitrate leaching and nitrous oxide emissions while prolonging N retention as ammonium.

6.1.1. Coated and modified fertilisers

Coated and modified fertilisers use physical or chemical coatings to control water ingress into fertiliser granules and nutrient egress from them. These coatings act as barriers, slowing dissolution and diffusion. This leads to a slower and more predictable release of nutrients over time.

Major types of coated and modified fertilisers

1. Sulfur-coated urea: Urea granules are coated with S and usually sealed with wax or polymer materials. The S layer delays dissolution while supplying S as a secondary nutrient.

2. Polymer-coated fertilisers: Nutrients are encapsulated within polymer membranes, and their release is governed by diffusion driven by osmotic and physical gradients. The release of nutrients is regulated by modifying the thickness and composition of the polymer coating.

6.1.2. Nano-fertilisers

Nano-fertilisers are a new type of nutrient delivery system that uses materials at the nanometre scale to modify nutrient behaviour at the molecular and cellular levels. Because nanoparticles have a high surface area relative to their volume, they often react, disperse, and interact more readily with plant tissues.

Key features and modes of action

Nano-fertilisers are thought to offer three main benefits: improved solubility and dispersion, more precise nutrient delivery, and greater control over nutrient release. Depending on their formulation, nano-fertilisers can help plants absorb nutrients through their leaves, improve root nutrient uptake, or release nutrients slowly via nano-encapsulation. Some examples of nano-fertilisers are nano-urea, nano-zinc, nano-iron, and nano-encapsulated NPK blends.

7. Precision agriculture approaches

While advanced fertilisers enhance the efficiency of nutrient inputs, precision agriculture takes input management a step further. It uses sensors, geospatial analysis, remote imagery, and decision algorithms to manage differences within fields and match nutrient supply to crop needs over time and space. The main idea is to move from applying inputs the same way everywhere to using data for targeted, site-specific actions.

This change is especially important for improving FUE, since nutrient needs often differ within a field and change during the season. By diagnosing crop status in real time, spotting differences across the field, and providing adaptive recommendations, precision agriculture helps crops use nutrients more efficiently, reduces over-application, and matches nutrient supply to crops' needs as they grow.

7.1. Sensor-based nutrient management

Sensor-based nutrient management employs proximal or canopy-based measurements to check nutrient levels during the growing season and guide fertiliser application. Common tools are optical canopy sensors, which estimate crop health and N levels by measuring vegetation reflectance indices, and handheld chlorophyll meters like SPAD, which check leaf chlorophyll to indicate N content.

Scientific basis

Nitrogen status is closely linked to chlorophyll levels, and the green colour of plant canopies. Because of this, vegetation indices and chlorophyll readings are often used as proxies to assess nutrient sufficiency. Although these methods do not completely replace direct nutrient analysis, they provide practical, quick, and consistent ways to help guide nutrient management during the growing season.

Operational approaches

Two common methods are the sufficiency index, which compares field readings to those of a well-fertilised reference strip, and threshold-based management, in which fertiliser is added if readings fall below set values for a given crop stage. Both approaches improve FUE by allowing nutrient application to respond to plant needs instead of following a fixed schedule.

7.2. Variable rate technology

Variable rate technology (VRT) enables farmers to apply fertiliser at different rates across a field. Instead of treating the whole field the same, VRT accounts for variations in soil, crop growth, and plant responses to nutrients.

Types and rationale

Map-based VRT uses prescription maps derived from sources like soil samples, yield data, topography, or remote sensing. Sensor-based VRT, on the other hand, changes fertiliser rates on the spot using real-time crop measurements. The reason for this approach is simple. When there is significant variation within a field, applying the same fertiliser rate everywhere can mean too much in some areas and too little in others. Adjusting the application by location helps users use inputs more efficiently and leads to more consistent crop results.

Implementation logic

Effective VRT usually follows three main steps: identifying management zones; creating rate prescriptions; and applying them in the field using GPS. This method helps use fertiliser more efficiently by matching nutrient supply with actual crop demand and response potential.

7.3. Remote sensing and GIS

Remote sensing helps manage nutrients by enabling crops to be monitored across large areas using satellite, UAV, or aerial imagery. When combined with geographic information systems (GIS), this approach connects crop conditions to soil properties, topography, past yields, and management history.

Data sources and indices

Satellites like Sentinel-2 and Landsat can capture repeated images with moderate detail, while UAVs can collect higher-resolution images and are easier to deploy. Tools such as NDVI, NDRE, EVI, red-edge indices, and thermal indices each reveal different aspects of crop health, nutrient stress, and the interaction between water and nutrients.



A typical view of a drone capturing images of crop growth

Role in FUE improvement

Remote sensing and GIS help improve FUE by enabling early detection of stress, analysis of specific areas, and the creation of maps for targeted actions. These tools are especially useful for regularly monitoring large fields and guiding nutrient management decisions that depend on temporal changes and spatial differences.

7.4. Decision support systems

Decision support systems (DSS) integrate field observations, weather data, soil information, and predictive models to provide practical advice on nutrient management. They help turn complex data into clear decisions about how much fertiliser to use, when to apply it, where to place it, and sometimes which type to choose.

Major types

- 1. Rule-based and empirical systems:** These systems use set thresholds, observed relationships, or decision rules. These are particularly effective in agricultural extension contexts.
- 2. Process-based crop models:** Platforms such as DSSAT and APSIM simulate crop growth, soil processes, and nutrient dynamics to predict fertiliser requirements across diverse environmental and management scenarios.
- 3. AI and machine learning systems:** These systems use large datasets, including information from remote sensing, weather, soil, and past yields, to provide recommendations that become more accurate and data-driven over time.

8. Genetic and molecular approaches

While agronomic and technological interventions enhance external nutrient management, genetic improvement modifies the crop's intrinsic capacity to acquire, assimilate, remobilise, and use nutrients efficiently. Genetic and molecular approaches are therefore uniquely important, as they offer a durable pathway to improved FUE embedded within the plant, rather than relying solely on repeated external interventions. These strategies aim to increase nutrient-use efficiency at the plant level while maintaining or improving yield under both optimal and input-constrained conditions.

These methods are based on the two main parts of nutrient use efficiency. A nutrient-efficient genotype must first acquire nutrients effectively from the soil and then convert them into harvestable yield with high efficiency. Genetic improvement integrates root traits, transport processes, metabolic pathways, and source-sink relationships to enhance long-term FUE.

8.1. Breeding for nutrient use efficiency

Breeding for nutrient use efficiency addresses two fundamental components: nutrient acquisition efficiency and nutrient utilisation efficiency. Nutrient acquisition efficiency refers to the effectiveness with which roots explore soil and absorb available nutrients. Nutrient utilisation efficiency describes how efficiently absorbed nutrients are assimilated, redistributed, and converted into economic yield. Comprehensive breeding programs seek to enhance both components concurrently rather than considering them as independent objectives.

Key target traits

- 1. Root architecture:** Deep and extensive root systems facilitate comprehensive soil

exploration. Increased root length density, lateral branching, and root hair proliferation enhance contact with nutrient-rich microsites and improve nutrient interception efficiency.

- 2. Nutrient uptake kinetics:** High-affinity transporter systems enable efficient nutrient acquisition at low soil nutrient concentrations. This mechanism is particularly important under reduced-input agricultural conditions.
- 3. Internal nutrient utilisation:** Efficient assimilation pathways, enhanced nutrient remobilisation from vegetative tissues to grains, and optimised biomass partitioning collectively contribute to increased yield per unit of nutrient absorbed.

8.2. Molecular breeding and genomics

Recent advances in genomics have enabled the dissection of NUE into measurable genetic components, such as QTLs, candidate genes, and regulatory pathways related to nutrient uptake, signalling, root development, and nutrient remobilisation. As a result, breeding has shifted from relying primarily on visible traits to using more predictive, detailed genetic information.

Key approaches

Marker-assisted selection facilitates the rapid introgression of favourable alleles associated with nutrient-efficient traits into elite genetic backgrounds. Genomic selection further enhances this process by employing genome-wide markers to predict breeding values for complex traits governed by multiple loci. Together, these approaches accelerate breeding cycles and increase the precision with which nutrient-efficient genotypes are identified and combined.

Key gene targets

Commonly targeted gene families include nitrate transporters (NRT), ammonium transporters (AMT), and phosphate transporters (PHT), along with regulatory genes involved in root development, nutrient signalling, and stress-responsive nutrient utilisation. These genes are significant not only for direct nutrient transport but also for coordinating whole-plant responses to nutrient availability.

8.3. Transgenic and gene editing approaches

Conventional and molecular breeding rely on selection and recombination, whereas transgenic and gene-editing approaches enable direct manipulation of genes associated with nutrient uptake, assimilation, signalling, and root development. These advanced methods are especially advantageous when target alleles are absent, rare, or challenging to combine using traditional breeding techniques.

Strategic applications

Transgenic approaches may include overexpressing nutrient transporter genes, modifying assimilation pathways to enhance metabolic efficiency, or introducing traits that improve nutrient mobilisation. Gene editing, particularly with CRISPR/Cas systems, enables precise changes to genes that control nutrient uptake, root architecture, and N metabolism through knockout, knock-in, or adjustment of gene expression.



A typical view of gene editing

8.4. Omics approaches

Omics technologies help us better understand nutrient efficiency by showing how plants respond to nutrient stress at different biological levels. Instead of looking at single genes, these methods reveal networks that connect nutrient sensing, signalling, metabolism, and growth regulation. This shift makes nutrient-use efficiency a clearer, more measurable trait, improving our understanding and supporting more precise breeding strategies.

Major platforms and applications

Transcriptomics helps find genes and regulatory modules that respond to nutrient deficiency or sufficiency. Proteomics shows which proteins are involved in transport, signalling, and assimilation. Metabolomics tracks biochemical intermediates that reveal how nutrient stress changes plant metabolism. Together, these methods help identify biomarkers of nutrient efficiency, clarify regulatory networks, and identify new targets for breeding and biotechnology.

9. Root system engineering

Although root traits are part of genetic improvement strategies, their primary role in nutrient absorption requires focused attention. Root system architecture determines recovery efficiency by shaping the spatial reach, intensity, and selectivity of nutrient foraging. Improving root systems through breeding, molecular methods, or targeted phenotyping offers a direct way to enhance nutrient capture, especially in low-input or variable soil environments.

Key traits are deep rooting to access subsoil nutrients and moisture, high root length density for broad soil exploration, root hair development for better uptake of immobile nutrients such as P, and root exudation capacity for chemical mobilisation in the rhizosphere. Enhancing these traits together, rather than individually, increases nutrient foraging and recovery efficiency while reducing dependence on external fertilisers.

10. Water-nutrient interactions

Plants need water to absorb nutrients, since most nutrients move to the roots via mass flow driven by transpiration or by diffusion along concentration gradients. Consequently, optimising fertiliser efficiency requires careful water management, since both nutrient movement in soil and root uptake capacity are strongly influenced by soil moisture dynamics.

Water-nutrient interactions are bidirectional. Insufficient water limits nutrient mobility and root activity, while excessive water increases runoff, leaching, and denitrification losses. Efficient irrigation improves FUE not only by reducing drought stress but also by stabilising the physical conditions necessary for nutrient transport and uptake.

Irrigation management strategies

1. Drip irrigation and fertigation:

These methods deliver water and nutrients directly to the root zone, maintain favourable nutrient concentrations around active roots, and reduce the volume of soil exposed to nutrient loss pathways.

2. Controlled irrigation scheduling:

Matching irrigation timing and quantity with crop requirements reduces excessive drainage, runoff, and nutrient displacement, while enhancing synchrony between nutrient availability and uptake.



A typical view of drip irrigation in wheat field

11. Integrated nutrient management

Integrated nutrient management (INM) brings together different FUE strategies into a single, practical system for the field. The central principle involves the careful integration of mineral fertilisers, organic amendments, and biological nutrient sources to meet

immediate crop requirements while preserving long-term soil fertility.

The scientific foundation of INM is complementarity among nutrient sources. Mineral fertilisers supply immediately available nutrients; organic inputs enhance soil structure and nutrient buffering while releasing nutrients gradually; and biofertilisers promote nutrient mobilisation and biological cycling. When managed collectively, these sources improve nutrient synchrony, minimise losses, and sustain essential soil functions for long-term productivity.

Core components

- Mineral fertilisers that supply N, P, and K for immediate nutrient availability.
- Organic amendments, including FYM, compost, green manures, and crop residues, which rebuild soil fertility and provide gradual nutrient release.
- Biofertilizers and microbial inoculants that facilitate nutrient mobilisation, biological N fixation, and enhancement of rhizosphere activity.

12. Cropping system intensification

Fertiliser efficiency is determined not only by the type and amount of fertiliser applied, but also by the spatial and temporal organisation of the cropping system. Intensification of cropping systems enhances FUE when system design promotes complementarity in nutrient capture, strengthens nutrient cycling, and optimises biological interactions among crops.



A typical view of cropping system intensification

Intercropping and relay cropping play important roles in intensified

systems. Intercropping means growing different crops together that have different root depths, nutrient needs, or growth times, which helps them use nutrients more efficiently. Relay cropping lets one crop start growing before another finishes, so the land is used for longer and fewer nutrients are lost.

In systems that include legumes, these methods can boost natural N fixation and improve overall nutrient use. As a result, the system produces more, requires fewer external inputs, and becomes more resilient to environmental changes.

13. Phosphorus and potassium efficiency strategies

While N is often the primary focus in discussions of FUE, sustainable nutrient management also requires optimising the use of P and K. These nutrients pose unique challenges due to their distinct behaviors in soil. Phosphorus is susceptible to fixation and exhibits low mobility, whereas K availability is largely influenced by residue cycling, cation exchange, and mineral weathering processes.

13.1. Phosphorus efficiency

The primary limitations to P efficiency include fixation by Fe and Al in acidic soils and by Ca in alkaline soils, as well as restricted mobility within the soil profile. Consequently, even when total P levels are adequate, a significant portion may remain inaccessible to plant roots.

Effective strategies involve managing soil pH to enhance P availability, promoting mycorrhizal associations to expand the root absorptive network, and applying rock phosphate alongside microbial inoculants that facilitate solubilization. These methods increase P recovery by enhancing the proportion that becomes accessible to plants, rather than solely relying on increased fertiliser application.

13.2. Potassium efficiency

Potassium efficiency is largely determined by internal nutrient cycling and the gradual release of K from soil minerals through weathering. Residue management is therefore critical, as a considerable proportion of the crop's K remains in the vegetative biomass rather than being removed with the harvested grain.

Practices such as residue retention, application of K-solubilising microorganisms, and soil management techniques that promote mineral weathering and cation exchange collectively enhance K efficiency. These strategies maintain a more readily available K pool and reduce the necessity for frequent corrective fertilisation.

14. Climate-smart nutrient management strategies

Because weather and climate have an enormous impact on nutrient behaviour, it is important to consider FUE in a climate-smart way. Changes in temperature, rainfall, drought, flooding, and other extreme events can alter nutrient transformation, transport, plant demand, and loss pathways. Consequently, climate variability affects not only the quantity of fertiliser required but also the timing and form in which it can be applied efficiently.

Climate-smart nutrient management helps address this variability by encouraging flexible, careful decisions about nutrient use. Key strategies include adjusting fertilisation schedules based on weather forecasts, using stabilised fertilisers to reduce weather-

driven emissions and losses, and combining nutrient management with climate-resilient crops and varieties that can withstand stress.

These approaches enhance system resilience and contribute to environmental sustainability. Specifically, they can reduce greenhouse gas emissions such as nitrous oxide, decrease nutrient loss during erratic rainfall or drought, and sustain improved nutrient-use performance under increasingly variable growing conditions.

15. Policy and economic strategies

The impact of FUE-enhancing practices remains limited without enabling policies and viable economic incentives. Policy and economic strategies provide the structure needed to expand technical knowledge beyond individual experiments or farms.

15.1. Role of policy

Public policy can accelerate adoption by supporting precision agriculture technologies, reforming fertiliser subsidies to reward efficiency over input volume, and promoting biofertilisers, organic inputs, and soil health programmes. These interventions are essential, as many high-efficiency practices require an initial investment, technical support, or risk-sharing mechanisms before they can be widely adopted by farmers.

15.2. Carbon and environmental markets

Carbon credit systems and payments for ecosystem services offer financial rewards for actions that lower greenhouse gas emissions, increase soil carbon storage, or reduce nutrient runoff into water bodies. These tools help farmers make choices that support wider environmental goals and can make nutrient efficiency more appealing, even if it is not immediately profitable.

15.3. Economic implications

At the farm level, higher FUE helps cut unnecessary input costs and often boosts profits by getting more value from each unit of fertiliser. Across the whole system, it helps reduce environmental impacts and encourages more sustainable growth. The economic and agronomic reasons for FUE are closely linked, demonstrating that efficiency intensification is a practical strategy for development, not merely a scientific idea.

CHAPTER 2

1. Imbalanced fertiliser application and soil health in the Indo-Gangetic Plains of India

The Indo-Gangetic Plains (IGP) are among the world's most intensively cultivated agroecosystems. The region extends from northwestern to eastern India, supporting the highly productive rice–wheat system established during the Green Revolution. Although irrigation, high-yielding varieties, and increased fertiliser use substantially boosted cereal production, the long-term ecological impacts are now evident. Major concerns include declining soil fertility, reduced nutrient-use efficiency, and emerging multi-nutrient deficiencies.

Fertiliser consumption in the IGP is heavily skewed toward nitrogenous fertilisers, particularly urea, whereas the application of P, K, S, and micronutrients remains comparatively low and often insufficient. This imbalance has been reinforced by fertiliser pricing and subsidy structures that have historically favoured N fertilisers, thereby influencing farmer practices and input economics. As a result, soils in major agricultural states such as Haryana, Punjab, and Uttar Pradesh are increasingly affected by K depletion, secondary nutrient deficiencies, declining organic carbon levels, nutrient mining, and deterioration of physical soil properties.

2. Economics of fertiliser use and nutrient affordability

Fertiliser economics play a key role in farmers' nutrient-use decisions. In input-intensive systems such as the rice–wheat system of IGP, nutrient management depends not only on agronomic recommendations but also on the affordability and availability of fertilisers. **Table 1** presents the quantities of paddy and wheat grain required to purchase 1 kg of major nutrients from different fertiliser sources between 2018–19 and 2023–24, providing a useful indicator of nutrient affordability under prevailing market and subsidy conditions.

A consistent decline in the quantity of grain required to purchase one kg of N was observed for both paddy and wheat during the study period. For paddy, the grain equivalent decreased from 0.70 kg in 2018–19 to 0.56 kg in 2023–24, while for wheat it declined from 0.66 to 0.54 kg over the same period. This trend indicates that N remained the most economically accessible nutrient for farmers, primarily due to continued government support for urea and other nitrogenous fertilisers, which protected farmers

from global fertiliser price fluctuations. Consequently, the low cost of N has encouraged excessive and often indiscriminate urea application across the IGP.

In contrast, P and K demonstrated substantially greater price volatility. The quantity of paddy required to purchase one kg of P_2O_5 through single super phosphate (SSP) increased sharply to 3.12 kg in 2023–24, compared with 2.42–2.77 kg in previous years. Diammonium phosphate (DAP) remained relatively stable, requiring 2.48 kg of paddy grain in 2023–24. These trends help explain the historical preference for DAP over SSP in the IGP, despite the agronomic advantage of SSP in supplying both S and P. Farmer preferences have therefore been shaped by nutrient composition, relative price stability, and perceived economic returns.

The sharp rise in K fertiliser costs after 2021 has important agronomic implications. For paddy, the grain required to purchase 1 kg of K_2O increased from 1.68 kg in 2021–22 to 2.78 kg in 2022–23, and remained elevated at 2.60 kg in 2023–24. Similar trends were observed for wheat. Rising K costs often discourage farmers in the rice–wheat system from applying potassic fertilisers, particularly in regions where visible deficiency symptoms are not immediately apparent. Such practices accelerate K depletion in soils and contribute to hidden hunger and long-term yield stagnation.

Table 1 Economics of application of fertilisers on paddy and wheat in India (2018–19 to 2023–24)

Particulars	2018-2019	2019-2020	2020-2021	2021-2022	2022-2023	2023-2024
Quantity of paddy required to buy						
1 kg of N	0.70	0.67	0.65	0.63	0.60	0.56
1 kg of P_2O_5						
as SSP	2.77	2.70	2.76	2.42	2.60	3.12
as DAP	3.09	2.62	2.55	2.45	2.65	2.48
1 kg of K_2O	1.52	1.74	1.56	1.68	2.78	2.60
Quantity of wheat required to buy						
1 kg of N	0.66	0.64	0.62	0.61	0.58	0.54
1 kg of P_2O_5						
as SSP	2.63	2.55	2.61	2.33	2.50	2.99
as DAP	2.94	2.47	2.41	2.36	2.55	2.38
1 kg of K_2O	1.45	1.65	1.48	1.61	2.67	2.49

3. Nutrient-based subsidy policy and fertiliser pricing dynamics

The nutrient-based subsidy (NBS) policy was introduced in India to promote balanced fertiliser use by linking subsidies to nutrient content rather than to individual fertiliser products. Under this system, fixed per-kg subsidies are provided for N, P, K, and S, with the

objective of improving nutrient-use balance while reducing distortions associated with product-specific subsidies. **Table 2** presents the subsidy rates for major nutrients from 2015–16 to 2025–26 and reflects how global fertiliser markets, import dependence, geopolitical disruptions, and domestic policy interventions affect nutrient affordability.

Subsidy trends indicate a major increase in government support during the global fertiliser crisis of 2021–2023. Nitrogen subsidy rates increased sharply, reaching 99.27 per kg during the 2022–23 rabi season, with comparable increases observed for P and K. These interventions were primarily intended to protect Indian farmers from unprecedented increases in international fertiliser prices driven by supply chain disruptions, rising energy costs, and geopolitical instability.

The post-crisis subsidy structure reveals important policy shifts with significant implications for fertiliser balance in the IGP. Nitrogen subsidy rates stabilised at 43.02 per kg by Kharif 2025, reflecting partial normalisation of global N markets and increased emphasis on domestic N production technologies, including nano urea and indigenous manufacturing. In contrast, K subsidy rates declined sharply and remained comparatively low at 2.38 per kg from late 2023 onward. Reduced subsidy support for potassic fertilisers increases the retail cost burden on farmers and discourages K application, particularly in cereal-based systems where visually responsive nutrients such as N are preferentially applied. Consequently, continuous K removal without adequate replenishment accelerates depletion of soil K reserves. In intensively cultivated states such as Haryana and Punjab, where crop nutrient extraction rates are high, inadequate K replenishment can progressively disturb soil cation balance, reduce stress tolerance, impair water-use efficiency, and increase vulnerability to abiotic stresses.

Table 2 Per kg nutrient-based subsidy (NBS) rates for N, P, K, and S during 2015–16 to 2025–26

Nutrients	2015-16	2016-17	2017-18	2018-19	2019-20	2020-21	2021-22	2022 (Kharif)	2022 (Rabi) Oct. 01- Dec. 31, 2022	2022 (Rabi) Oct. 01- Dec. 31, 2023	2023 (Kharif)	2023-24 (Rabi)	2024-25 (Kharif)	2024-25 (Rabi)	Kharif 2025
N	20.87	15.85	18.98	18.90	18.90	18.78	18.78	91.96	98.02	99.27	76.49	47.02	47.02	43.02	43.02
P	18.67	13.24	11.99	15.21	15.21	14.88	45.32	72.74	66.93	49.94	41.03	20.82	28.72	30.80	43.60
K	15.50	15.47	12.39	11.12	11.12	10.11	10.11	25.31	23.65	25.70	15.91	2.38	2.38	2.38	2.38
S	1.67	2.04	2.24	2.72	3.56	2.37	2.37	6.94	6.12	2.84	2.80	1.89	1.89	1.76	2.61

Source: Ministry of Agriculture & Farmers' Welfare, Govt. of India

Phosphorus subsidy trends represent an intermediate pattern. The renewed increase in P subsidy during Kharif 2025, reaching 43.60 per kg, reflects policy efforts to stabilise phosphatic fertiliser use and sustain productivity in cereal-based systems. However, continued dependence on DAP has also contributed to nutrient imbalance because DAP supplies N in addition to P, often resulting in unintended excess N application.

4. Formulation-wise fertiliser subsidies and their agronomic implications

Although nutrient-based subsidy rates determine the broader economics of fertiliser use, formulation-specific subsidies directly influence the market competitiveness and adoption of individual fertiliser products. **Table 3** presents government subsidy support per metric tonne for major phosphatic and potassic fertilisers from 2023–24 to 2025–26, highlighting how formulation-level subsidies shape nutrient-use patterns.

It indicates the continued dominance of DAP within India's fertiliser subsidy regime. Among all fertiliser formulations, DAP received the highest subsidy support, increasing to ₹27,799 per metric tonne during Kharif 2025. The consistently high subsidy allocation reflects the strategic importance of DAP in sustaining cereal productivity within the rice–wheat system. However, prolonged dependence on DAP has also contributed to nutrient imbalance because DAP supplies N in addition to P, often leading to excessive N application.

The increasing subsidy support for SSP is agronomically important. SSP subsidy increased from ₹3,540 per metric tonne during the 2023–24 rabi season to ₹7,263 per metric tonne during Kharif 2025. Unlike DAP, SSP supplies S along with P, making it particularly valuable in regions experiencing S deficiency due to prolonged intensive cultivation and declining organic matter recycling. The enhanced subsidy support for SSP may therefore represent a strategic policy effort to encourage more balanced nutrient application and diversify phosphorus fertiliser sources.

In contrast, persistently low subsidy support for muriate of potash (MOP) raises concerns regarding long-term soil fertility. Although MOP remains the principal source of potassic fertiliser, its subsidy remained nearly stagnant at approximately ₹1,427–1,428 per metric tonne after 2023. Limited subsidy support increases the relative cost of potassic fertilisers and discourages K application, particularly in high-input cereal systems, where farmers tend to apply less expensive N fertilisers. Such practices accelerate the depletion of soil K reserves and further aggravate nutrient imbalance in intensively cultivated production systems.

The inclusion of complex fertilisers, including Urea–SSP complexes, indicates emerging efforts to promote balanced fertilisation strategies through multi-nutrient formulations. These fertilisers are designed to supply multiple nutrients simultaneously and reduce the risk of imbalanced nutrient application. However, their adoption remains dependent on market availability, farmer awareness, and the effectiveness of extension services.

Table 3 Per metric tonne subsidy on different phosphatic and potassic fertilisers during 2023–24 to 2025–26

S. No.	Fertiliser Grades (FG) (N P K S nutrients)	2023 (kharif)	2023-24 (rabi)	2024 (kharif)	2024-25 (rabi)	2025 (kharif)
1.	DAP (18-46-0-0)	32641	22541	21676	21911	27799
2.	MAP (11-52-0-0)	29748	15999	20108	20748	27404
3.	TSP (0-46-0-0)	18872	9578	1321.2	14168	20056
4.	MOP (0-0-60-0)	9547	1427	1427	1427	1428
5.	SSP (0-16-0-11)	6872	3540	4804	5121	7263
6.	28-28-0-0	32906	18995	21208	20670	24253
7.	16-16-16-0	30177	27986	21349	11235	12499
8.	Ammonium sulphate (20.6-0-0.23)	16325	10074	10075	9224	9419
9.	PDM (0-0-14.5-0)	2307	345	345	345	345
10.	Urea-SSP complex (5-15.0-10)	NA	NA	6849	6947	8952

*NA means not covered under NBS regime, Source: Ministry of Agriculture & Farmers' Welfare, Govt. of India

5. State-wise fertiliser consumption patterns and nutrient imbalance in the IGP

State-level fertiliser consumption data provide direct evidence of regional nutrient-use intensity and emerging patterns of nutrient imbalance. **Table 4** presents the state-wise consumption of N, P, and K fertilisers across India.

The data show that states within the IGP are among the largest fertiliser consumers in the country because of intensive cereal cultivation and extensive irrigation. Uttar Pradesh recorded the highest overall nutrient consumption due to its large cultivated area, followed by Maharashtra, Madhya Pradesh, Punjab, and Haryana. However, total fertiliser consumption does not fully represent nutrient-use intensity. Haryana and Punjab exhibit highly intensive fertiliser-use systems characterised by disproportionately high N consumption relative to K use.

Haryana consumed 1,151.40 thousand tonnes of N compared with only 39.43 thousand tonnes of K, resulting in an approximate N:P:K consumption ratio of 29:7:1. This ratio is substantially distorted relative to the recommended 4:2:1 ratio for balanced fertilisation

in cereal-based systems and reflects chronic under-application of K together with excessive dependence on N fertilisers.

Comparative analysis further highlights the severity of K neglect in Haryana. Despite intensive agricultural production, K consumption in Haryana remains considerably lower than in states such as West Bengal and Karnataka, where relatively balanced fertilisation practices are more common. These observations suggest that the traditional assumption of inherently “potassium-rich” alluvial soils in the IGP may no longer remain agronomically sustainable under modern high-yielding production systems.

Table 4 State-wise consumption of fertiliser nutrients in India

States/UTS	Nitrogen (in 000 Tonne)	Phosphorus (in 000 Tonne)	Potassium (in 000 Tonne)	Total (in 000 Tonne)
Andaman & Nicobar Islands	0.01	0.01	0.02	0.04
Andhra Pradesh	1102.36	571.32	180.52	1854.20
Arunachal Pradesh	0.61	0.07	0.11	0.79
Assam	207.42	55.84	36.33	299.58
Bihar	1385.77	416.42	125.51	1927.69
Chhattisgarh	577.42	264.96	51.67	894.05
Dadra and Nagar Maya and Daman and Diu	0.21	0.07	0.00	0.28
Delhi	19.01	2.08	0.07	21.15
Goa	1.17	0.60	0.67	2.43
Gujarat	1362.93	422.22	92.65	1877.80
Haryana	1151.40	286.76	39.43	1477.59
Himachal Pradesh	34.78	10.87	6.91	52.57
Jammu & Kashmir	70.45	19.99	8.50	98.94
Jharkhand	200.68	58.95	5.38	265.01
Karnataka	1352.53	690.33	282.17	2325.04
Kerala	79.02	34.20	58.17	171.39
Madhya Pradesh	2118.56	946.54	138.22	3203.31
Maharashtra	1798.09	1048.39	427.70	3274.17
Manipur	6.78	2.41	0.97	10.16
Meghalaya	1.73	0.41	0.00	2.13
Mizoram	9.41	0.13	0.02	9.55
Nagaland	0.61	0.04	0.01	0.65
Odisha	426.31	199.35	51.29	676.94
Puducherry	8.70	2.34	0.75	11.78
Punjab	1631.06	356.27	54.76	2042.09

States/UTS	Nitrogen (in 000 Tonne)	Phosphorus (in 000 Tonne)	Potassium (in 000 Tonne)	Total (in 000 Tonne)
Rajasthan	1378.72	453.43	30.19	1862.34
Tamil Nadu	709.61	284.93	144.52	1139.06
Telangana	1287.07	489.70	102.26	1879.02
Tripura	8.56	4.52	2.75	15.83
Uttar Pradesh	4151.08	1229.97	182.76	5563.82
Uttarakhand	115.93	26.84	5.22	147.99
West Bengal	949.95	515.84	354.36	1820.15
India	22147.90	8395.77	2383.85	32927.52

Source: Ministry of Agriculture & Farmers' Welfare, Govt. of India

6. Factors affecting fertiliser adoption and nutrient imbalance in the IGP

Fertiliser-use behaviour in the IGP is influenced by interacting economic, institutional, agronomic, and socio-psychological factors. Although fertiliser use played a central role in enhancing crop productivity during the Green Revolution, current fertiliser-use patterns are increasingly shaped by input economics, policy incentives, and farmer risk perceptions rather than by scientifically balanced nutrient management.

Economic factors remain major drivers of fertiliser adoption. Differential pricing and subsidy structures have historically reduced the relative cost of N fertilisers relative to P- and K-based fertilisers, encouraging greater reliance on urea in intensive cereal production systems. This trend is particularly evident in irrigated regions of Haryana and Punjab, where high cropping intensity and assured irrigation support intensive fertiliser use.

Variation in soil fertility status across districts and agroecological zones also influences fertiliser-use decisions. However, fertiliser recommendations are often based on generalised schedules rather than field-specific nutrient requirements, resulting in inefficient nutrient application and low nutrient-use efficiency. Limited adoption of site-specific nutrient management further contributes to imbalanced fertilisation in the region.

Irrigation availability strongly affects fertiliser application intensity. Crop response to fertilisers is generally greater under irrigated conditions, leading farmers in canal- and tube-well-irrigated areas to apply higher fertiliser rates. Under such conditions, excessive N application combined with intensive irrigation increases the likelihood of nutrient leaching and environmental losses.

Farmer education, technical awareness, and extension support also play important roles in nutrient management decisions. Access to agricultural advisory services, farmer

discussion networks, and information on balanced fertilisation can improve nutrient management practices. Nevertheless, fertiliser-use decisions in many farming systems continue to be influenced by the perception that higher N application directly translates into higher productivity, despite evidence of diminishing returns under excessive N use.

Household socio-economic characteristics further affect fertiliser adoption behaviour. Larger landholdings, higher household income, and greater market integration are often associated with higher fertiliser consumption, whereas farmers located farther from input supply networks may apply lower fertiliser doses due to limited access and higher transaction costs.

Policy interventions, including soil testing programs and nutrient management schemes, can influence fertiliser-use behaviour; however, the adoption of improved nutrient management practices depends largely on farmers' awareness, access to technical support, ease of implementation, and confidence in the economic benefits. Therefore, fertiliser-use patterns in the IGP must be interpreted within a broader socio-economic and institutional framework rather than solely through agronomic considerations.

7. Soil health implications of imbalanced fertiliser use

The long-term effects of imbalanced fertiliser use are increasingly evident across the IGP. Continuous nutrient extraction under intensive cereal cultivation, combined with inadequate replenishment of K, S, and micronutrients, has accelerated soil degradation and reduced the sustainability of high-input production systems.

Persistent nutrient imbalance adversely affects both soil biological activity and physicochemical properties. Intensively cultivated areas of the IGP increasingly exhibit declining soil organic carbon, reduced microbial diversity, greater soil compaction, and deterioration of aggregate stability. These changes impair nutrient cycling processes, reduce soil resilience, and further lower FUE, thereby creating a cycle of declining soil productivity and increasing dependence on external nutrient inputs.

Potassium depletion is of particular concern because of its role in osmotic regulation, enzyme activation, water relations, and stress tolerance. Continuous removal of K without adequate replenishment weakens crop resilience to drought, heat, and disease stress and may increase vulnerability of production systems to climatic variability. Similarly, deficiencies of S and micronutrients are becoming increasingly common under prolonged intensive cultivation and limited organic matter recycling.

The persistence of nutrient imbalance, therefore, represents not only a fertiliser management issue but also a broader challenge to long-term soil health, environmental sustainability, and agricultural resilience in the IGP. Restoring nutrient balance will require integrated nutrient management approaches that combine balanced fertiliser use, organic amendments, crop diversification, residue recycling, precision nutrient management, and evidence-based policy reforms to improve nutrient-use efficiency and sustain soil fertility.



CHAPTER 3

1. Annual crop calendar: The triple-cropping & diversification strategy

Kharif season (June – October): rice (main crop)

The focus here is on water management and nutrient efficiency.

Nursery & farm operations

- Sowing window: June 1st to June 20th.
- Seed treatment: Treat seeds with chemical fungicides like Tricyclazole or Validamycin, or biological alternatives like *Trichoderma sp.*, to prevent seed-borne diseases.
- Puddling: Perform 2-3 passes of wet tillage to create an impervious layer, reducing water percolation.
- Transplanting: Move 25-30-day-old seedlings to the main field. Use spacing of 20cm x 15cm.

Fertilizer application

Apply nutrients at a 120:60:40 (N: P₂O₅: K₂O) ratio to achieve the target yield.

- Basal: Apply 1/3rd N (urea), full P (DAP/SSP), and full K (MOP) during the last puddling.
- Top dressing: Apply the remaining N in two equal splits: one at the tillering stage (3 weeks after transplanting) and one at the panicle initiation stage.
- Zinc: Apply 25kg/ha of ZnSO₄ basally to prevent Khaira disease.

NOTE: Apply P and K only as a basal application. If mung bean was incorporated, reduce basal urea by 25 kg/acre. Apply 25 kg/ha ZnSO₄ basally.

Rabi season (November – March): wheat (main crop)

Wheat follows rice. Time is critical; every week's delay after mid-November reduces yield by 1-2%.

Farm operations

- Sowing window: November 1st to November 15th (Ideal).
- Method: Use a zero-till seed drill if rice residue is managed, or a super seeder. This saves 10 to 15 days and preserves soil moisture.
- Sowing depth: 4-5 cm.
- Irrigation: The CRI (crown root initiation) stage (21 DAS) is the most critical. Do not skip this irrigation.

Fertilization

- Ratio: 150:60:40 (N:P₂O₅:K₂O).
- Basal: Full P and K, and 1/2 N at sowing.
- Top dressing: Apply remaining N in two splits. The first after the 1st irrigation (CRI stage) and the second after the 2nd irrigation (late jointing stage).

NOTE: Apply half N and full P & K at sowing. Use a seed-cum-ferti drill to place fertiliser 2-3 cm below the seed for better uptake. Apply the remaining N in two splits timed with the first two irrigations.

Summer/Zaid season (April – June): Mungbean (gap crop)

This "Catch Crop" breaks the cereal-cereal cycle, fixes atmospheric N, and provides extra income.

Farm operations

- Sowing window: Immediately after wheat harvest (Late March to mid-April).
- Variety selection: Use short-duration varieties (60-65 days).
- Sowing: Direct drill into wheat stubble with minimal tillage.
- Niches: This crop uses the residual moisture and heat of the IGP summer.

Fertilization

- The ideal ratio is 20:40:0 (N:P:K).
- Nitrogen: Only a "starter dose" of 20kg N/ha is needed.
- Phosphorus: 40kg P₂O₅/ha (SSP is preferred as it also provides S).
- Bio-fertilizers: Treat seeds with *Rhizobium* culture to enhance nodulation and N fixation for the succeeding rice crop.

NOTE: Use SSP instead of DAP to provide essential sulphur. Treat seeds with *Rhizobium* and PSB. These microbes unlock fixed P in the soil.

Table 1 Annual crop calendar for farmers

Stage	Month	Operation	Key input
Nursery (rice)	June	Seedbed prep & sowing	ZnSO ₄ , Carbendazim
Vegetative (rice)	July-Aug	Transplanting & weeding	Urea (Split 1), Butachlor
Reproductive (rice)	Sept	Water maintenance	Urea (Split 2)
Sowing (wheat)	Nov	Zero-till sowing	DAP, MOP, Urea
Critical (wheat)	Dec	CRI stage irrigation	Urea (Split 2)
Harvest/sowing	April	Wheat harvest / Mungbean sowing	Rhizobium culture
Harvest (mung)	June	Pod picking / bio-mass incorporation	Residual moisture

Table 2 Alternate cropping pattern for extreme water scare and saline soil conditions

Pattern	Benefit	Window
Maize - wheat – mungbean	Saves 30-40% water compared to rice.	Maize: June-Sept
Pigeonpea – wheat	Deep-rooted; improves soil structure.	Pigeonpea: June-Nov
Rice - mustard – sunflower	High oilseed value; diversifies income.	Mustard: Oct-Feb

Table 3 High-value alternatives to improve soil health and remuneration

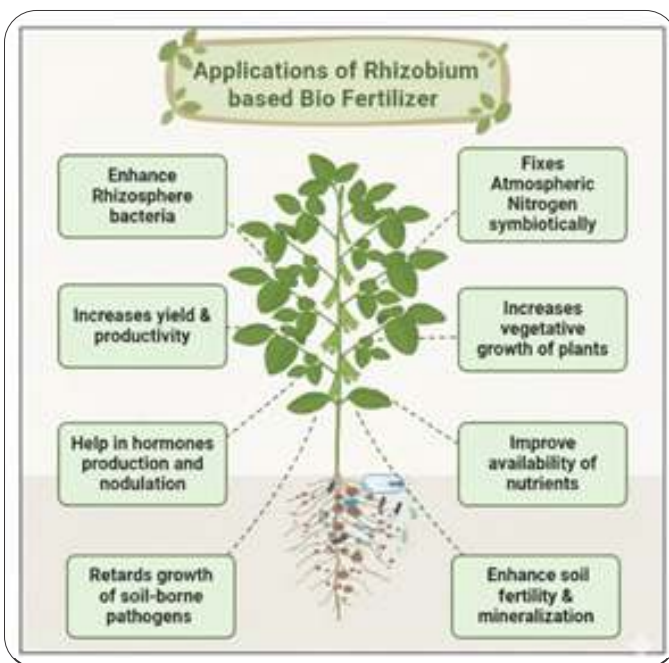
Month	Standard: rice-wheat-mung	Alternative A: diversified oilseed	Alternative B: resource saver	Key management & fertilisation
June	Rice (nursery)	Rice (Basmati)	Kharif maize	Nursery: Treat seeds with Carbendazim. Basal: 1/3 N, full P, full K + Zinc.
July	Rice (transplanting)	Rice (transplanting)	Maize (veg stage)	Weed control: Apply pre-emergence herbicide within 3 days.
Aug	Rice (tillering)	Rice (tillering)	Maize (tasselling)	Top dress: Apply 1/2 of the remaining N (Urea) at tillering.
Sept	Rice (PI stage)	Rice (booting)	Maize (cob filling)	Top dress: Final N split at Panicle Initiation (PI).
Oct	Harvest rice	Harvest Basmati	Harvest maize	Prepare the land immediately to utilise residual moisture.
Nov	Wheat (sowing)	Mustard (sowing)	Potato/peas	Wheat basal: Full P, K, and 1/2 N. Use Zero-Till drill.
Dec	Wheat (CRI stage)	Mustard (flowering)	Potato (bulking)	Critical: 1st Irrigation at 21 days (CRI). Apply 2nd N split.
Jan	Wheat (jointing)	Mustard (pod filling)	Peas (podding)	Wheat: Final N split. Mustard: Watch for aphids.
Feb	Wheat (heading)	Mustard (maturity)	Harvest potatoes/peas	Mustard: Stop irrigation 3 weeks before harvest.
Mar	Harvest wheat	Harvest mustard	Summer Maize /moong	Wheat: Stop irrigation at the dough stage.
Apr	Mungbean (sowing)	Sunflower (sowing)	Summer mung bean	Mung: Use 20kg N as a starter; treat with Rhizobium.
May	Mung (flowering)	Sunflower (heading)	Mung (podding)	Irrigation: Light, frequent irrigations to beat the summer heat.

CHAPTER 4

1. Crop-specific Rhizobium: Applications and recommendations

Rhizobium forms a symbiotic relationship with leguminous plants by infecting root nodules and fixing atmospheric N into ammonia, naturally supplying N to plants. This biological N fixation reduces dependence on synthetic N fertilisers, lowers production costs, and mitigates environmental risks from chemical fertiliser use. Rhizobium biofertilizers also enhance soil microbial diversity, increase nutrient availability, and improve resistance to biotic and abiotic stresses, leading to better crop growth and yield. Additionally, Rhizobium strains produce phytohormones and siderophores that support plant growth and nutrient uptake, including in non-leguminous crops.

Biofertilizers like Rhizobium offer several advantages, including low cost, long shelf life, ease of application in both liquid and solid forms, and reduced environmental impact. They improve soil health by increasing organic matter, enhancing water retention, and boosting nutrient exchange capacity. Applying Rhizobium biofertilizer can increase crop yields by 10 to 35 per cent in leguminous crops and enhance plant vigour, reducing reliance on costly chemical inputs.



Beneficial effects of Rhizobium-based biofertilizers

Recent research in this area has focused on Rhizobium mutants that differ from indigenous strains by exhibiting significantly enhanced symbiotic efficiency. These mutants promote increased nodulation, greater plant biomass, and ultimately higher crop yields in chickpea, field-pea, and lentil crops cultivated in Haryana.

The key differences observed are as follows:

1. Higher nodulation and plant growth: The mutants, particularly MbPrRz1,

demonstrate a significant increase ($p < 0.05$) in both nodule number and plant biomass compared to indigenous or commercial strains. Enhanced nodulation is essential for N fixation, which directly influences plant growth and yield.

- 2. Improved crop yield:** Mutant-inoculated treatments outperform uninoculated controls and commercial strains in yield per nodule. MbPrRz1, in particular, achieved yields of approximately 2.78 kg per plot for chickpea and 2.08 kg per plot for field-pea in Haryana. The mutants also significantly increased lentil yield compared to commercial strains.
- 3. Enhanced enzymatic activity:** The mutants exhibit increased hydrolytic enzyme activity, specifically pectinase and cellulase, which are vital for effective symbiotic infection of legume roots. This suggests improved biological N fixation ability compared to native isolates.
- 4. Soil fertility improvement:** Fields treated with the mutants display elevated levels of total N and other macro- and micronutrients after experimentation, indicating enhanced soil fertility compared to soils containing only indigenous rhizobial populations.
- 5. Genetic characterization:** The mutants consistently express molecular markers such as *nifH*, a gene associated with N fixation, indicating durable and efficient biological N fixation ability in contrast to the variability observed in indigenous strains.

Table 1 Crop-specific *Rhizobium* strains (including developed mutants and common strains)

Crops	Rhizobium strain / species	Function / notes
Chickpea	MbPrRz1 (<i>Mesorhizobium ciceri</i>)	Developed mutant, high nodulation and yield boost
Field-pea	MbPrRz2 (<i>Rhizobium leguminosarum</i>)	Developed mutant, enhanced N fixation
Lentil	MbPrRz3 (<i>Rhizobium leguminosarum</i>)	Developed mutant, improved crop yield
Chickpea	<i>Mesorhizobium ciceri</i> CH-21	Commercial strain, less effective than mutants
Field-pea	<i>Rhizobium leguminosarum</i> P-34	Commercial strain, native soil strain
Lentil	<i>Rhizobium leguminosarum</i> LN-65	Commercial strain, native soil strain
Common bean	<i>Rhizobium etli</i>	Effective for <i>Phaseolus vulgaris</i> (common beans)
Soybean	<i>Bradyrhizobium japonicum</i>	Widely used for soybean symbiosis
Pea (<i>Pisum sativum</i>)	<i>Rhizobium leguminosarum</i> bv. <i>viciae</i>	Standard inoculant strain
Lentil	<i>Rhizobium leguminosarum</i> bv. <i>viciae</i>	Effective for lentil symbiosis

NOTE: *Rhizobium* species form symbiosis mainly with legumes; rice and wheat do not form classic nodules with *Rhizobium* but can benefit from associative N-fixing bacteria, which are not true *Rhizobia*.

2. Bioformulations as substitutes for phosphatic fertilisers

Phosphate-rich organic manure (PROM), PSBs, and phosphate-enriched compost (PEC) help increase soil P levels. These methods are especially useful where high-quality rock phosphate is scarce, and P resources cannot be renewed.

PROM is an organic amendment enhanced with rock phosphate and additives to boost P content and availability for plants. By combining organic waste with rock phosphate, PROM provides a slow-release source of P for crops. Direct soil application supports sustainable P management and reduces reliance on expensive soluble P fertilisers. This method aligns with circular economy principles by converting agricultural residues and organic waste into valuable nutrients, improving nutrient recycling and soil health.

PSBs are beneficial microorganisms that increase P availability in soils by converting insoluble and poorly available phosphate forms into soluble forms accessible to plants. In soils, P is frequently bound to Ca, Fe, or Al, resulting in only a limited fraction (approximately 30%) being available to plants. PSBs enhance P availability primarily by secreting organic acids, such as citric, malic, oxalic, and formic acids, which solubilise rock phosphate and other mineral phosphates through acidification and chelation. Additionally, these bacteria elevate phosphatase activity and promote ion-exchange reactions, further mobilising P from soil minerals and organic matter. Numerous PSB species have been identified, including genera such as *Serratia*, *Burkholderia*, *Azotobacter*, *Rhodococcus*, *Xanthomonas*, *Enterobacter*, and *Pantoea*, as well as fungi such as *Penicillium* and *Aspergillus*. Inoculation of soils with PSBs and rock phosphate has resulted in significant yield improvements in crops such as maize, rice, wheat, soybean, cowpea, and stevia, often equalling or exceeding the performance of conventional soluble P fertilisers. This biotechnological strategy offers a cost-effective, environmentally sustainable method to improve P nutrition.

PEC is produced by enriching compost derived from crop residues, animal manure, or other organic wastes with rock phosphate, often in combination with PSBs, to increase P content and availability. The composting process mobilises P from rock phosphate and enhances nutrient balance by supplying secondary and micronutrients. Enrichment with rock phosphate reduces the C: N ratio, indicating improved compost maturity, and increases P content, particularly citrate-soluble P, thereby enhancing nutrient availability over time. Incorporation of PSBs into compost further improves P solubilization and accelerates mineralisation rates of N and S. Research indicates that PEC application significantly increases crop yields, P uptake, and PUE in crops such as black gram, cowpea, chickpea, lentil,

wheat, green gram, and rice. PEC also promotes nodule formation and growth in legumes, supporting symbiotic N fixation. Compared to chemical phosphatic fertilisers, PEC provides residual benefits, contributing to sustained soil P availability in cropping systems.

Table 2 Various species of PSBs used with rock phosphate and their effects on crop yields

S. No.	Crop/cropping system	PSB species /modification of rock phosphate	Observations
1	Potato-soybean	Rice straw enriched with rock phosphate, mica, and <i>Aspergillus awamori</i> (fungus), along with 50-75% of RDF	Yield increases up to 43.3% in potato, 21.5% over control; 27.6-46.9% increase in soybean grain yield
2	Maize-wheat	Rock phosphate treated with <i>Pantoea cyripedii</i> (PSB-3) and <i>Pseudomonas plecoglossicida</i> (PSB-5)	Higher yields in maize than DAP; wheat yields highest with RP+inoculants, on par with DAP
3	Maize-wheat	Rock phosphate treated with <i>Penicillium oxalicum</i> (fungus)	Higher yields than control and rock phosphate alone
4	Soybean-wheat	Half P from rock phosphate with <i>Pseudomonas striata</i> and <i>Glomus fasciculatum</i> (mycorrhiza)	Higher yields than control; soybean yield 3.4% higher than 100% SSP; wheat yield is almost similar
5	Rice-rapeseed-mungbean	Mussorie rock phosphate inoculated with <i>Pseudomonas striata</i>	Significantly superior rice equivalent yields, at par with DAP at the 3 rd year
6	Stevia rebaudiana	Mussorie rock phosphate with PSB (<i>Burkholderia gladioli</i> , <i>Enterobacter aerogenes</i> , <i>Serratia marcescens</i>)	136% biomass increase; stevioside and rebaudioside-A increased by 291% and 575% respectively

Table 3 Phosphate-enriched compost (PEC) for various crops and their effects

S. No.	Crop	Compost composition / PEC Details	Observations
1	Black gram	PEC prepared with rock phosphate, mica, maize straw, FYM, and PSB inoculation	Significant seed yield increase (up to 4 t/ha), 15.21% over control, at par with 6 t/ha
2	Cowpea	Rock phosphate added to biowaste per P ₂ O ₅ requirement	83% yield gain over control and 55% over soluble P fertilizer
3	Chickpea and lentil	Rock phosphate added to the composting material of fruit peels and vegetable waste	Higher nodules per plant and weight; 15% higher yield vs control
4	Wheat-green gram rotation	Rock phosphate added to rice residue, mustard leaf residue, tree leaf compost	No significant difference among composts, but rice residue PEC had the highest yields and residual effect
5	Rice	Rock phosphate added to rice straw with aerobic composting	PEC + chemical fertilizer (50:50) had numerically higher yield than chemical fertilizer alone

CHAPTER 05

1. Government flagship programmes for balanced use of fertilisers

Balanced fertilisation is critical for maintaining soil fertility, increasing crop productivity, enhancing nutrient use efficiency, and ensuring sustainable agriculture. The Government of India has implemented several flagship programmes and initiatives to promote judicious and balanced fertiliser use.

Soil Health Card Scheme

The Soil Health Card Scheme, launched in 2015, aims to promote soil test-based nutrient management among farmers.

Objectives

- Assess soil nutrient status
- Provide crop-wise fertiliser recommendations
- Promote balanced use of fertilizers
- Improve soil health and productivity

Major features

- Soil samples are collected and tested every two years
- Farmers receive Soil Health Cards containing nutrient status and fertiliser recommendations
- Recommendations include major nutrients (N, P, K) and micronutrients

Benefits

- Reduction in excessive fertiliser use
- Improvement in nutrient use efficiency
- Lower cultivation cost
- Better crop yield and soil fertility

National Mission for Sustainable Agriculture

The National Mission for Sustainable Agriculture (NMSA), a key component of the National Action Plan on Climate Change, promotes sustainable agricultural practices.

Key components

- Integrated nutrient management (INM)
- Soil health management

- Organic farming promotion
- Resource conservation technologies

Importance

- Encourages balanced and efficient nutrient use
- Promotes use of organic manures and biofertilizers
- Improves soil organic carbon and soil health

Neem Coated Urea Programme

The Government of India mandated complete neem coating of urea to improve N use efficiency.

Objectives

- Reduce N losses
- Improve fertiliser efficiency
- Prevent diversion and misuse of urea

Advantages

- Slow release of N
- Better nutrient uptake by crops
- Reduced fertiliser consumption
- Lower environmental pollution

Integrated Nutrient Management

Integrated Nutrient Management (INM) promotes the balanced application of chemical fertilisers alongside organic and biological nutrient sources.

Components

- Chemical fertilisers
- Farmyard manure (FYM)
- Compost and vermicompost
- Green manures
- Crop residues
- Biofertilizers

Benefits

- Maintains long-term soil fertility
- Improves soil physical, chemical and biological properties
- Sustains crop productivity

Paramparagat Krishi Vikas Yojana (PKVY)

The Paramparagat Krishi Vikas Yojana (PKVY) promotes organic farming through cluster-based approaches.

Objectives

- Reduce dependence on chemical fertilisers
- Promote organic nutrient sources
- Improve soil health and biodiversity

Major activities

- Use of compost and biofertilizers
- Organic certification
- Farmer training and awareness

Importance

- Enhances soil organic matter
- Encourages eco-friendly nutrient management

Nutrient-Based Subsidy Scheme

The Nutrient-Based Subsidy (NBS) Scheme was introduced to support the use of phosphatic and potassic fertilisers.

Objectives

- Promote balanced fertilisation
- Encourage efficient fertiliser use
- Reduce excessive use of urea

Covered nutrients

- Nitrogen (N)
- Phosphorus (P)
- Potassium (K)
- Sulphur (S)

Benefits

- Balanced NPK application
- Increased fertiliser use efficiency
- Better soil nutrient balance

PM-PRANAM Scheme

The PM Programme for Restoration, Awareness Generation, Nourishment and Amelioration of Mother Earth (PM-PRANAM) encourage states to reduce chemical fertiliser consumption.

Objectives

- Promote sustainable fertiliser use
- Encourage alternative nutrient sources
- Reduce subsidy burden on chemical fertilisers

Importance

- Supports natural and organic farming
- Encourages balanced nutrient management

National Food Security Mission

The National Food Security Mission (NFSM) promotes sustainable crop production technologies for rice, wheat, pulses, and coarse cereals.

Nutrient management components

- Demonstrations on balanced fertilisation
- Promotion of micronutrients
- Integrated nutrient management practices

Benefits

- Increased productivity
- Improved soil fertility
- Efficient nutrient utilisation

Rashtriya Krishi Vikas Yojana

The Rashtriya Krishi Vikas Yojana (RKVY) supports states in strengthening agriculture and allied sectors.

- Activities related to balanced fertilisation
- Establishment of soil testing laboratories
- Vermicompost units
- Organic manure production
- Farmer trainings on nutrient management

Importance

- Promotes location-specific nutrient management
- Enhances awareness regarding balanced fertiliser use

National Project on Organic Farming

The National Project on Organic Farming (NPOF) promotes the production and use of organic inputs.

Focus areas

- Biofertilizers
- Organic manures
- Composting technologies

Benefits

- Improves soil biological activity
- Reduces dependence on chemical fertilisers
- Promotes sustainable agriculture

City Compost Scheme

The City Compost Scheme promotes the production and marketing of compost derived from municipal solid waste.

Objectives

- Improve soil organic matter
- Reduce chemical fertiliser consumption
- Promote recycling of urban waste

Benefits

- Enhances soil fertility
- Supports integrated nutrient management

GOBAR-Dhan Scheme

The GOBAR-Dhan Scheme promotes the conversion of cattle dung and organic waste into valuable products.

Major outputs

- Biogas
- Organic manure
- Bio-slurry

Importance

- Encourages nutrient recycling
- Improves soil organic carbon
- Supports sustainable farming systems

Besides these, a large-scale program can be initiated to convert flowers and offerings (biological) in the temples into manure separately from domestic FYM and to use it exclusively for indoor plants to maintain "Aastha".

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3	जैविक कार्बन (OC)		3	जैविक कार्बन (OC)	
4	उपलब्ध नाइट्रोजन (N)		4	उपलब्ध नाइट्रोजन (N)	
5	उपलब्ध फॉस्फोरस (P)		5	उपलब्ध फॉस्फोरस (P)	
6	उपलब्ध पोटैशियम (K)		6	उपलब्ध पोटैशियम (K)	
General Recommendations			General Recommendations		
1	जैविक खाद		1	जैविक खाद	
2	जैव उर्वरक		2	जैव उर्वरक	
3	सुखा-सिंचन		3	सुखा-सिंचन	
International Year of Soils 2015			Healthy Soils for a Healthy Life		

A typical view of soil health card

CHAPTER 6

1. From input use to nutrient efficiency: the way forward

The future of Indian agriculture relies on improving FUE through balanced, science-based, and sustainable nutrient management. India's dependence on imported fertilisers and raw materials, along with excessive use of nitrogenous fertilisers, has led to nutrient imbalance, declining soil health, reduced nutrient-use efficiency, and environmental degradation. NUE has dropped from nearly 60–70% during the early Green Revolution to around 30–35% in recent years.

Balanced fertilisation should prioritise K, S, and micronutrients, guided by soil test and site-specific recommendations. Integrated approaches combining mineral fertilisers, organic amendments, crop residues, biofertilisers, rhizosphere management, conservation agriculture, and precision technologies can improve nutrient recovery, reduce losses, and sustain long-term productivity. Additionally, soil biological processes, root system efficiency, water management, and crop diversification are essential for enhancing nutrient-use efficiency and resilience under changing climatic conditions.

In the IGPs, especially in Haryana, Punjab, and Uttar Pradesh, fertiliser use is highly imbalanced, with excessive N application and insufficient K and micronutrients. These practices have accelerated nutrient mining, soil degradation, groundwater contamination, greenhouse gas emissions, and reduced crop response to fertilisers. A shift from input intensification to efficiency intensification is needed, with a focus on maximising yield and profitability per unit of nutrient applied.

Biofertilisers, phosphate-solubilising microorganisms, and INM should be considered complementary components within a broader nutrient-efficiency management system. These approaches are not substitutes for scientific fertilisation, but serve as biological tools to enhance nutrient cycling, improve soil organic matter, stimulate microbial activity, and support long-term soil health and ecological sustainability.

2. Recommendations

For farmers

- Adopt soil test-based fertilisation and apply nutrients based on field-specific recommendations instead of using uniform fertiliser rates.
- Apply a balanced mix of N, P, K, S, and micronutrients to prevent deficiencies and improve crop performance.

- Reduce reliance on urea by using split N applications and adopting efficient N management practices.
- Incorporate organic and biological inputs, including FYM, compost, crop residues, green manures, biofertilisers, and microbial inoculants, to enhance soil health and nutrient cycling.
- Adopt precision and water-efficient practices, such as leaf colour charts, sensors, fertigation, and efficient irrigation scheduling, to match nutrient supply with crop needs.
- Promote crop diversification and integrate legumes, such as pulses and mung bean, to increase biological N fixation and improve soil fertility.
- Retain crop residues and use residue incorporation and mulching to build soil organic matter, improve soil structure, enhance water retention, and support microbial activity.
- Use advanced fertiliser technologies, including enhanced-efficiency fertilisers and biofertilisers, to increase nutrient recovery and reduce environmental losses.

Policy Makers

- Redirect fertiliser subsidies to support balanced nutrient application instead of volume-based N support.
- Expand soil testing laboratories, digital soil health platforms, and real-time advisory systems to enable site-specific nutrient management.
- Support integrated nutrient management by combining mineral fertilisers, organic amendments, biofertilisers, and conservation practices.
- Increase the affordability and accessibility of potassic, sulphur, and micronutrient fertilisers to restore nutrient balance.
- Promote precision agriculture technologies, including sensors, GIS, remote sensing, decision-support systems, and variable-rate application, to improve nutrient management efficiency.
- Strengthen production, quality control, and distribution systems for biofertilisers, microbial inoculants, compost, and other organic nutrient sources.
- Integrate climate-smart nutrient management with adaptation strategies to reduce greenhouse gas emissions and increase resilience to changing weather conditions.
- Expand extension services, demonstrations, and farmer training programs focused on balanced fertilisation and nutrient use efficiency.

- Invest in research and innovation on nutrient-efficient crop varieties, root system engineering, and molecular approaches for sustainable nutrient management.
- Develop agroecology-specific nutrient management strategies, especially for high-intensity regions like the IGPs, where nutrient imbalance and soil degradation are severe.

Creating mass movement

- Jingles on soil health and balanced fertiliser use for FM/radio broadcasts
- Short social media videos depicting “Mother Earth” and the adverse effects of excessive or imbalanced fertiliser use
- Organising quiz contests through print media with awards for participants
- Nukkad nataks on balanced fertiliser use and soil health

NOTE

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NOTE

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ICAR - Indian Institute of Wheat and Barley Research
Karnal – 132 001 (Haryana)

