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Review Article

Relative Assessment of Fertilizer Application Techniques for Enhancing Nutrient Use Efficiency, Crop Productivity, Soil Health and Environmental Sustainability: A Review

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Abstract

Enhancing fertilizer application strategies is a critical lever for addressing the multidimensional challenges confronting modern agriculture, including food security, resource sustainability, and environmental health. While the evolution from conventional broadcasting to advanced placement techniques-such as banding, deep placement, fertigation, and foliar application, led to measurable gains in Nutrient Use Efficiency (NUE) and yield, substantial research gaps and contradictions persist, particularly regarding their long-term, context-specific impacts. This review synthesizes comparative studies and quantitative meta-analyses, revealing that precision methods can increase crop yields by 10% – 40% and reduce nitrogen losses by up to 25% - 40% compared to broadcasting, but their performance varies significantly across crops, soils, and socio-economic settings. Key concerns remain, especially in India, regarding persistent imbalance in fertilizer use (notably excess nitrogen relative to phosphorus and potassium), declining soil organic matter, depletion of micronutrients, and insufficient adoption of precision technologies by smallholders. Globally, indiscriminate fertilizer application continues to drive soil degradation, greenhouse gas emissions, and water pollution, while policies often lag behind scientific advancements. Contradictions in the literature highlight that while certain placement methods outperform others in specific agro-ecological conditions, their scalability is limited by infrastructure, cost, and knowledge barriers. Future perspectives emphasize the urgency of developing adaptive nutrient management frameworks tailored to local realities, supported by soil testing infrastructure, policy incentives, digital agriculture tools, and strong farmer education. For policymakers, integrating the 4R framework-right source, rate, time, and place-into national resource strategies, reorienting subsidies toward balanced nutrients, and promoting the inclusion of small and marginal farmers in technological transitions are imperative. Coordinated global and national efforts are needed to foster equitable access to efficient fertilizer technologies, build resilience against climate variability, and ensure the sustainability of food systems. Only a systems-based, inclusive approach will enable sustainable intensification and secure agricultural productivity for present and future generations.

Introduction

Agriculture has persistently anchored global civilization by ensuring food security [1], economic prosperity, and sustainable livelihoods for billions [2], but the sector faces momentous challenges as the global population escalates and environmental pressures, especially those rooted in climate change, intensify. The judicious and effective use of fertilizers underpins the drive for optimal crop production, making the scrutiny of fertilizer application methods a pillar of modern agricultural science [3]. While substantial advancements have been made in nutrient management, including the transition from conventional broadcasting techniques to precision methods such as fertigation, foliar spraying, banding, and deep placement, significant research gaps persist within this domain [4]. Central among these is

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the absence of comprehensive, context-sensitive comparative studies that assess the long-term agronomic, environmental, and socioeconomic impacts of diversified fertilizer application techniques across varying agroecological zones and cropping systems. Most available literature concentrates on short-term yield increments or isolated environmental outcomes, thereby inadequately addressing the multidimensional sustainability of these methods or their integration into holistic nutrient stewardship strategies. Furthermore, research is limited regarding the synergistic or antagonistic interactions between fertilizer application methods and key variables such as climate adaptation [5], changing soil biogeochemistry, the emergence of multi-nutritional deficiencies, and evolving pest or disease dynamics given intensifying monoculture practices and land-use changes. There is a scarcity of long-term, field-based empirical data evaluating how modern fertilizer approaches impact soil organic matter dynamics, microbial ecosystem services critical for nutrient cycling, and overall soil health, as well as their effects on water quality over multiple growing seasons. This research gap extends to the domain of socioeconomic adoption barriers, including policy constraints, farmer education levels, resource inequities, and the cost-effectiveness of transitioning from traditional methods to innovative precision agriculture. While the agroeconomic benefits of efficient fertilizer use are well documented in short-term frameworks, the lack of longitudinal studies leaves critical questions concerning their consequences for cumulative soil nutrient balances, potential build-up of residual compounds, risk of chronic groundwater and surface water contamination, and trajectory of farm profitability and ecosystem resilience unanswered. These gaps are particularly concerning given the projected need to increase global food production by approximately 60% [6] to meet the demands of the estimated 9.7 billion world population by 2050.

The long-term impacts of fertilizer application methods transcend immediate crop yield responses and venture into the realms of ecological balance, agricultural sustainability, and socio-economic welfare. In the absence of robust long-term management, indiscriminate surface broadcasting and excessive fertilizer applications are known to exacerbate nutrient runoff, leaching, greenhouse gas emissions, and degradation of both terrestrial and aquatic ecosystems. Over time, such practices contribute to the acidification of soils, depletion of soil organic matter, decline in beneficial microbial populations, and adverse alterations to soil structure, each of which undermines not only productivity but also the resilience of cropping systems to climate anomalies and pest outbreaks. Moreover, the choices farmers make regarding placement techniques and timing influence cumulative Nutrient Use Efficiency (NUE), resource use optimization, and the persistence of nutrient imbalances or multi-nutritional deficiencies—all crucial for ensuring that soil fertility is sustained for future generations. Adoption of precision approaches, such as fertigation and banding, has been shown to augment NUE, mitigate environmental loss pathways, and improve profit margins, yet their long-term effects on soil carbon sequestration [7], the buildup of salinity, and potential risks related to over-concentration of certain nutrients remain under-investigated. In the broader societal context, the adoption trajectory of innovative application methods significantly impacts rural livelihoods, governance of natural resources, and the regulatory landscape concerning nutrient management. Regions where policies and farmer education lag behind technological innovation may experience exacerbated economic disparities and environmental degradation, challenging sustainable development goals.

Against this backdrop, the need for research that rigorously evaluates not only the immediate but also the prolonged consequences of fertilizer application strategies becomes urgent. The development of adaptive, site-specific nutrient management frameworks—built upon longitudinal field experiments, interdisciplinary research, and participatory farmer engagement—is critical for navigating the trade-offs between yield maximization, resource conservation, environmental stewardship, and economic viability. This perspective underpins the present exploration, which seeks to consolidate existing knowledge, identify pivotal research lacunae, and chart a course for future investigations geared towards reconciling production imperatives with the imperatives of planetary health. The complexity of contemporary nutrient management, interwoven with challenges such as climate variability, resource limitations, and the imperative of social equity, reinforces the necessity of integrating scientific innovation, technology adoption, and effective policy frameworks. Only with such a comprehensive, evidence-driven approach can the agricultural sector hope to not just meet the burgeoning demands of humanity but do so in ways that are resilient, equitable, and harmonious with the ecosystems upon which all life depends (Alnaass, et al. 2023).

Major concern in crop production

The major concerns in crop production, such as depleting soil organic matter, imbalance in fertilizer use, emerging multi-nutritional deficiency, declining nutrient use efficiency, declining crop response rate, declining fertilizer response rate, and negative soil nutrient balance [8-10], can be attributed to a combination of factors:

a. **Intensive agricultural practices:** Modern agriculture often relies on intensive practices that prioritize high crop yields and quick returns on investment. These practices can lead to overuse of synthetic fertilizers, neglect of organic matter incorporation, and imbalanced nutrient management.

b. **Excessive fertilizer use:** In pursuit of maximizing yields, some farmers apply excessive amounts of synthetic fertilizers without considering the nutrient needs of specific crops or soil conditions. This can lead to nutrient imbalances and nutrient runoff, which contributes to soil degradation and water pollution.

c. **Monoculture farming:** The extensive cultivation of a single crop, known as monoculture farming, depletes specific nutrients from the soil while also making the crop more susceptible to pests and diseases. This necessitates increased fertilizer use to maintain yields.

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d. **Inadequate soil management:** Poor soil management practices, such as inadequate crop rotation, minimal use of cover crops, and failure to replenish organic matter through organic inputs, result in declining soil health and decreased nutrient retention capacity.

e. **Climate change:** Climate change-related factors, such as altered precipitation patterns and increased temperatures, can exacerbate nutrient losses from the soil, affecting both nutrient use efficiency and crop response rates.

f. **Emerging nutrient deficiencies:** Changing agricultural practices and climate conditions can lead to emerging nutrient deficiencies in crops, as certain essential nutrients may become less available in the soil.

g. **Soil erosion:** Soil erosion, often exacerbated by improper land management, can lead to the loss of topsoil, which is rich in organic matter and nutrients, further depleting soil quality.

h. **Lack of precision agriculture:** Insufficient adoption of precision agriculture techniques that optimize nutrient application based on soil testing and crop needs can contribute to imbalances and inefficiencies in fertilizer use.

i. **Socio-economic factors:** Economic constraints and lack of access to resources and knowledge can limit farmers' ability to adopt sustainable soil and nutrient management practices.

j. **Policy and education gaps:** Inadequate policies, lack of extension services, and limited farmer education on sustainable agricultural practices can hinder the adoption of soil and nutrient management best practices.

Nutrient management planning

Adoption of Best Management Practices (BMPs) for nutrients should increase plant productivity (yield and quality), increase profitability, maintain or improve soil fertility and productivity, and avoid damage to the environment (Havlin, et al. 2016) [11] The basic requirements of good soil fertility, nutrient availability, and efficient plant use of applied nutrients include:

a. Optimal soil pH for the specific plant grown

b. Sufficient soil OM for improved soil structure, H_2O holding capacity, nutrient supply, and microbial activity

- Porous soil structure with no limits to root growth, infiltration, or drainage
- Removal or neutralization of toxic elements (Al in strongly acidic soil, Na in saline/ alkali soils, or heavy metal contaminants)

Implementation of BMPs for plant nutrients can be challenging due to many uncontrollable variables; however, efficient nutrient management should start by avoiding common mistakes

a. Less than optimum soil pH, OM, and soil structure reduce nutrient supply, plant growth, and Nutrient Use Efficiency (NUE).

b. Unrealistic yield goals may cause overapplication of nutrients, reducing NUE and increasing the risk of nutrient loss from the root zone.

c. Not using or misuse of readily available soil and plant nutrient diagnostic techniques

d. Failure to recognize the high nutrient requirements of selected plants

e. Unbalanced nutrient availability may cause hidden hunger that reduces plant yield

f. While nutrient additions may be recognized, optimum nutrient response and NUE will be realized only with the optimum rate, source, placement, and/or application timing of recommended nutrients

A nutrient management plan must be developed for each field and includes the following information

a. **Field and soil map:** A field map illustrating field boundaries, soil types, and elevation enables assessment of crop land areas, proximity to water bodies, water wells, residences, and other objects. The yield history of each manageable subfield area is essential to identifying potential productivity that influences nutrient availability, retention, and need.

b. **Soil testing and plant analysis:** Accurate soil test information depends on a quality soil sampling plan guided by the field and soil map. This information provides the foundation for assessing the soil's ability to supply plant-available nutrients and establishing nutrient recommendations. Plant analysis information from previous crops should be reviewed for areas with nutrient levels below or above their critical range.

c. **Crop and crop rotation:** Previous crop and yield level are important information, especially with legumes. Low legume yield in the previous year will provide less legume available N than a high-yielding legume crop. Surface residue condition and specific crop will guide nutrient placement decisions. The intended crop will determine the general nutrient requirements. Recognize specific plants with high requirements for certain nutrients.

d. **Yield expectation:** Realistic yield expectations are essential to estimating nutrient needs. Historical yield records for each field provide the best record for determining the expected yield level. Overestimating yield results in overapplication of nutrients with

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potential negative impacts on the environment, while underestimating yields results in underapplication of nutrients and loss of yield and profitability.

e. **Nutrient sources:** If soil physical conditions are not optimum, increasing soil OM may be warranted. Quantifying nutrient content (and mineralization rate) of organic amendments is essential to balanced nutrient supply and meeting the projected nutrient needs of the plant. Selection of fertilizer sources is based on crop needs, soil properties, and cost. Selected nutrient sources should optimize nutrient supply just ahead of peak nutrient demand.

f. **Recommended rates:** Recommended rates are determined through evaluation of expected yield potential, native soil nutrient supply, and efficiencies of crop recovery of applied nutrients. Most soil testing laboratories provide recommended nutrient rates. While these recommendations are good guides, adjustments should be made to satisfy requirements for specific field conditions. Match the nutrient rate to the crop's needs. Excess nutrients may enhance losses to the environment, while too little reduces yield and/or quality. Utilize appropriate diagnostic tools (crop scouting, soil and plant analysis, field tests, variable rate technology, record keeping, etc) to evaluate nutrient sufficiency. Documenting the nutrient response of previous crops is essential to quantify the most efficient nutrient rate for the intended crop.

g. **Application timing:** Nutrient application timing depends on the specific nutrient and the crop growth pattern. Mobile nutrients should be applied just before the maximum uptake or growth period. This may require in-season split applications or controlled release sources (N) to maximize nutrient use efficiency. With immobile nutrients, preplant applications are generally recommended.

h. **Placement method:** Many placement options exist that greatly influence nutrient availability and crop recovery of applied nutrients. For example, broadcasting N with surface residue cover reduces N recovery by the crop. Band-applied P can substantially increase yield in low P soils compared to broadcast P. Placement decisions are based on specific nutrient and intended crop.

i. **Proximity to nutrient-sensitive areas:** Assessment of the field and potential nutrient transport will help prevent nutrients from entering unwanted areas (e.g., streams, ponds, groundwater, and water wells). Use of riparian buffers, grassed waterways, conservation tillage, and other management practices reduces potential nutrient transport off the field.

j. **Assessment and revision:** After each crop season, the nutrient management plan should be evaluated relative to crop productivity and profitability. Adjustments should be made with any nutrient-related decrease in yield or quality. Regardless of the nutrient source (organic or fertilizer), adopting nutrient BMPs will help ensure efficient nutrient supply to the target crop, which should minimize off-site impacts of nutrient use. While recycling and the use of all available organic nutrient sources are beneficial to both the supplier and user, fertilizer nutrients are essential to meet the growing global population demand for food, fiber, feed, and other products generated from plant materials [12].

Principles and practices of 4R nutrient stewardship

4R Nutrient Stewardship is an approach to nutrient management [13] in agriculture that focuses on using the right source of nutrients, at the right rate, at the right time, and in the right place to optimize nutrient use efficiency, crop yields, and environmental sustainability. The 4R framework is based on key scientific principles and associated practices. Here are the principles and practices of 4R Nutrient Stewardship:

a. **Right source:** Select the appropriate fertilizer source that matches the nutrient needs of the crop and the specific nutrient deficiencies in the soil. Conduct soil tests to determine nutrient deficiencies. Choose fertilizers that provide the required nutrients in forms that are readily available to the plants. Consider alternative nutrient sources, such as organic materials or crop residues, when appropriate.

b. **Right rate:** To determine the correct amount of nutrients (rate) to apply based on crop nutrient requirements, soil nutrient levels, and expected crop yield. Calculate nutrient recommendations based on soil tests and crop nutrient requirements. Use nutrient management planning tools to adjust fertilizer rates based on specific field conditions. Avoid over-application of nutrients to minimize waste and environmental impact.

c. **Right time:** Apply nutrients when the crop needs them most, taking into account the timing of nutrient uptake and crop growth stages. Time fertilizer applications to coincide with periods of peak nutrient demand by the crop. Avoid applying nutrients during sensitive periods, such as early spring or late fall, when there is a higher risk of nutrient loss. Consider split applications of nutrients for crops with multiple nutrient uptake stages.

d. **Right place:** Apply nutrients where they will be most effectively taken up by the crop and minimize the potential for nutrient losses to the environment. Use precision agriculture techniques, such as variable rate application, to apply nutrients where they are needed most. Avoid broadcasting nutrients on the soil surface when possible, as this can lead to nutrient runoff and leaching. Incorporate nutrients into the soil through methods like injection or banding to improve nutrient placement.

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By following these 4R principles and associated practices, farmers and land managers aim to achieve several goals [14]:

a. **Optimized crop production:** By supplying the right nutrients in the right way, crops can achieve their full yield potential.

b. **Reduced environmental impact:** Precision nutrient management helps minimize nutrient runoff, leaching, and emissions of greenhouse gases, reducing the environmental impact of agriculture.

c. **Improved nutrient use efficiency:** Using nutrients efficiently reduces waste, saves costs for farmers, and reduces the need for excess nutrient application.

d. **Sustainable Agriculture:** 4R Nutrient Stewardship promotes sustainable agricultural practices that balance crop production with environmental and economic concerns.

Factors considered with fertilizer placement methods

Nutrient placement decisions in agriculture are critical for optimizing nutrient use efficiency, crop performance, and environmental sustainability (Singh, et al. 2018). Various factors should be considered when determining the placement of nutrients in the soil. Here are the factors you've mentioned and how they influence nutrient placement decisions:

a. **Optimum nutrient availability from emergence to maturity:** This factor emphasizes providing nutrients to the crop at the right time and in the right location to meet its changing nutrient demands throughout its growth stages. Nutrient placement methods should ensure that nutrients are available to the crop when it needs them most.

b. **Preventing salt injury to the seedling:** Nutrient placement methods should avoid placing concentrated sources of salts (e.g. fertilizers) too close to the seedling or young plant, as excessive salt levels can harm young seedlings. Ensuring proper spacing between the nutrient source and the seedling can help prevent salt injury.

c. **Convenience to the grower:** Growers may consider practicality and ease of nutrient application methods when making placement decisions. Balanced with other factors, convenient application methods can lead to better adoption of recommended nutrient management practices.

d. **Soil characteristics:** Soil texture, structure, pH, and nutrient levels influence nutrient placement decisions. Knowledge of soil properties helps determine the most suitable placement method to ensure nutrient availability and minimize losses due to factors like leaching or fixation.

e. **Crop and crop rotation:** Different crops have varying nutrient uptake patterns and placement requirements. Crop rotation practices may also influence nutrient placement, as certain crops can leave residual nutrients for subsequent crops.

f. **Crop nutrient requirements:** Understanding the specific nutrient needs of the crop at various growth stages is crucial. Nutrient placement should align with the crop's requirements to maximize yield potential.

g. **Nutrient mobility:** The mobility of nutrients in the soil (e.g., nitrate nitrogen, potassium) influences their placement. Highly mobile nutrients may require different placement methods to minimize leaching.

h. **Nutrient source:** Different nutrient sources (e.g., synthetic fertilizers, organic matter) have varying release rates and availability. Nutrient placement should match the characteristics of the chosen nutrient source.

i. **Environmental impact:** Minimizing nutrient losses to the environment is a key consideration. Proper nutrient placement can reduce the risk of nutrient runoff, leaching, and emissions that can negatively impact water quality and ecosystems.

Methods of fertilizer application

The application rates of fertilizer depend on the soil fertility. The fertility of a soil is usually measured by a soil test according to the particular crop. The method of applying fertilizers depends on the nature of crop plants, their nutrient needs, and the soil Fertilizers are applied to crops both in the form of solids and liquids. Most of the fertilizers are applied in the form of solids (e.g., urea, di-ammonium phosphate, and potassium chloride). Solid fertilizer is typically used in granulated or powdered form. It is also available in the form of prills or solid globules [15]. Liquid fertilizers comprise anhydrous ammonia, aqueous solutions of ammonia, and aqueous solutions of ammonium nitrate or urea. The concentrated liquid fertilizers can be diluted with water (e.g., UAN). Its more rapid effects and easier coverage are the advantages of liquid fertilizer.

Application of solid fertilizers

Broadcasting: The spreading of fertilizer all over the field in a uniform manner is known as broadcasting. A separate operation in addition to seeding is required in the broadcasting mode of fertilizer application. The fertilizer may be spread on the surface of the soil itself, with or without incorporation into the soil, or it may be placed below the soil surface in closely spaced rows by the use of a fertilizer drill [15]. Normally the fertilizer used for this kind of application is in an insoluble form; especially, insoluble phosphatic fertilizer such as rock phosphate is used for broadcasting mode of application. This method is suitable for crops with dense stand. The plant roots will permeate the whole volume of the soil. Large doses of fertilizers are needed for the application. There are two methods of broadcasting method of application, namely broadcasting at sowing or planting (basal application) and top dressing (Figure 1).

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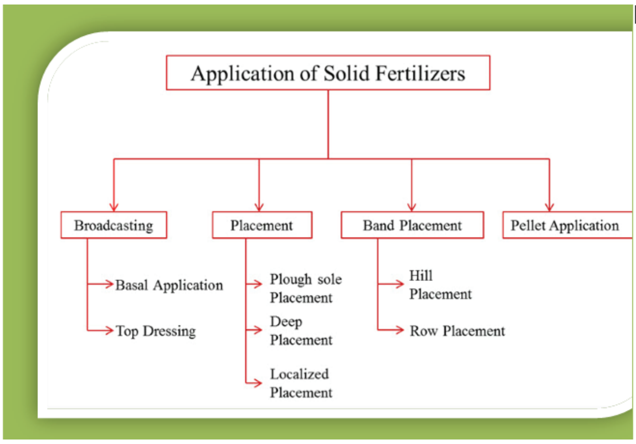

Figure 1: Methods of application of solid and granular fertilizers.

a. **Broadcasting at sowing or planting (basal application):** The main objective of the basal application is the application of fertilizers at sowing time for a uniform distribution. Thus the fertilizer will be spread over the entire field and completely mix with soil. Boron fertilizers are generally applied by broadcast method. Normally they are incorporated prior to seeding for crops not planted in rows. Boron is applied by broadcast method in plants such as legumes and grasses and broadcast methods are more effective in trees and grape vines and also in the cases of coarser-textured soils [16].

b. **Top dressing:** The nitrogenous fertilizers are normally applied closely in crops like paddy and wheat, to supply nitrogen in a readily available form to growing plants. This kind of application of nitrogen fertilizer is known as top dressing. To improve rice yield and the nitrogen availability to the plants, top dressing is recommended for the lower soil layer for Japonica rice, new high-yielding rice varieties such as Indica type, and large grain type varieties [15]. Fukushima, et al. [17] suggested that the new type rice variety Bekoaoba will increase its sink size and the rice yield by top dressing at 30 DBH or early top dressing, leading to short culms and erect leaves. In Bangladesh, crystal urea is normally applied as top dressing. It decreases yield by misbalancing the yield components. Usually, this problem is prevented by the application of super granules of urea (USG); since the USG can minimize the loss of N from soil, thus effectively increasing up to 20% - 25% [18].

Disadvantages of broadcasting: The plants in the field cannot fully utilize the fertilizers as they move laterally over long distances. Due to the presence of fertilizer all over the field, the weeds also absorb the nutrients, and the weed growth is also stimulated by the fertilizer. A large amount of the fertilizer is needed, and nutrients are fixed in the soil. They may come in contact with a large mass of soil.

Placement: The placement of the fertilizer in soil at a specific place with or without reference to the position of the seed is referred to as the placement method of fertilizer application. The placement method is normally recommended in conditions where the quantity of the fertilizer is small and the soil has low fertility. It can also be applied in the case of plants with poorly developed roots. The phosphatic and potassic fertilizers are normally applied by the placement method. The commonly used methods of placement methods are plow sole placement, deep placement, and localized placement.

a. **Plough sole placement:** During the process of ploughing, the fertilizer is placed at the bottom of the plough furrow in the form of a continuous band so that every band is covered as the next furrow is turned. This method is suitable for dry land where the surface soils become quite dry up to a few centimetres from the bottom soil and have a heavy clay pan just below the plough sole layer.

b. **Deep placement:** It is used for the placement of ammoniacal nitrogenous fertilizers in the reduction zone of the soil, particularly in the root zone. This method is especially suitable for paddy fields. The main advantage of this method is to prevent the loss of nutrients by run-off. The Japanese used different methods of N fertilizer application to minimize the loss of N through volatization, denitrification, leaching, etc. Based on the Japanese concept of deep point placement of fertilizer N in transplanted rice, IFDC (International Fertilizer Development Center) implemented the use of super granules of urea (USG) to achieve the same agronomic benefits in 1975 [19]. The loss of nitrogen is greater in rice (*Oryza sativa* L.) fields, especially in the irrigated rice cropping systems with very poor water control. Bandaogo, et al. [20] conducted field experiments in Sourou Valley, Burkina Faso, during the 2012 wet season and 2013 dry season. They studied the impact of fertilizer N, including prilled urea (broadcasted) and briquettes in the form of USG (applied via FDP - fertilizer deep point placement). Results showed that FDP is genotype and season-specific and could be an alternative method for farmers to enhance nitrogen use efficiency (NUE) in irrigated rice farming. Nitrogen is found to be an essential nutrient for the growth of rice plants. Usually, prilled urea (PU) was applied by broadcasting because it is considered a fast-releasing source of nitrogen. But in flooded rice fields, it can be lost by ammonia volatization, immobilization, denitrification, and surface runoff [35]. To overcome this problem, the USG can be applied by deep placement. USG is a slow-releasing nitrogenous fertilizer, and it reduces the N loss and also improves the N use efficiency of wetland rice (Hasan, et al. 2002).

c. **Localized placement:** To supply the nutrients, an adequate amount of fertilizer is applied to the soil close to the seed or the roots of growing plants. The common methods used for the placement of fertilizers or nutrients are: Drilling: In this method, a seed-cum-fertilizer mode of drilling is used for the application of fertilizer during the sowing time itself. The fertilizer and the seed are placed in the same row, but the depth

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is different. The method is suitable in the case of cereal crops, especially for the application of phosphatic and potassic fertilizers. Due to the higher concentration of the soluble salts, the germinated seeds and young plants may get damaged. This is the greatest disadvantage of this method. Side dressing: The fertilizers are spread between the rows and around plants. In the case of crops like maize, sugarcane, cotton, etc., the fertilizer is applied by hand in between the rows. But the fertilizers are placed around the trees like mango, apple, grapes, papaya, etc. Adiaha and Agba [21] out that among the four methods used (broadcasting, ring application, hole application, and liquid application) for the cultivation of maize plants (*Zea mays* L.), the ring method seems to be appropriate for maize production at 1 m spacing between plants on a bed.

Advantages of the placement of fertilizers:

- There is minimal contact between the soil and the fertilizer.
- The fixation of nutrients is greatly reduced.
- The nutrients are available only for the crop plants, and the weeds all over the field cannot make use of the fertilizers.
- Higher residual response of fertilizers.
- Higher utilization of fertilizers by the plants.
- Loss of fertilizer, for example, loss of nitrogen, by leaching, is reduced.
- Immobile phosphates are better utilized when placed.

Band placement: The band placement refers to the fertilizer placement in the form of bands. In the case of band placement, the fertilizers can be applied by the hill placement method or by row placement method.

a. **Hill placement:** The fertilizer is applied close to the plants on one or both sides of the plants as bands, but the length and the breadth of the band vary with the nature of the crop. This method is common for the application of fertilizers in orchards. Ibrahim, et al. [22] reported that the hill placement of manure and fertilizers like DAP (diammonium phosphate) and NPK improved the yield and efficiency of millets in the Sahelian agro-ecological area of Niger.

b. **Row placement:** The fertilizer is applied in continuous bands on one or both sides of the row in which the plants are planted. This method is common in the case of crops like sugarcane, potato, maize, cereals, etc. There will be a fertilizer attachment on the planter in cases of hill or row placement. So there is no need for a separate operation. These methods are labor-saving, and in some rare cases, the seeds and the fertilizer will be incorporated into the soil separately by using a machine or by hand. Under drier conditions, small grains of fertilizers have a better response to band applications (Randall and Hoeft, 1988). Chaudhary and Prihar [23] observed that if the fertilizer was placed 20 cm below the seeds, the nutrient uptake was found to be increased, and the seedling growth was also found to be faster and resulting in higher grain yield in the case of maize (*Zea mays* L.) and wheat (*Triticum aestivum* L.). This result indicates that the band placement is more effective than the broadcast mode of fertilizer application. If the growths of the roots are found only in the surface layers, it is advised that the fertilizer should not be broadcast to avoid surface drying.

Pellet application: It is mainly used for the placement of nitrogenous fertilizers in the paddy fields. The fertilizers are applied in the form of pellets about 2.5-5 cm deep between the crops. The small pellets of convenient sizes of fertilizers are made and mixed with the soil in the ratio of 1:10. The pellets are deposited in the mud of paddy fields. Schnier, et al. (1990) conducted a study in transplanted rice and direct-seeded flooded rice to evaluate the effect of time and method of fertilizer N application on grain yield and N-use efficiency by using 15N-labeled urea. The N application in the form of a pellet releases its content slowly, and due to continuous nutrient release, the plant can uptake N at different stages of its growth.

Application of liquid and water-soluble fertilizers

a. **Starter solution:** A solution of N, P_2O_5, and K_2O in the ratio of 1:2:1 and 1:1:2 applied to young vegetable plantlets, particularly at the time of transplantation, is normally referred to as a starter solution. This method helps in the rapid establishment and quick growth of the seedlings. The additional labor and higher fixation rate of phosphates are the two major disadvantages of the starter solution method of fertilizer application. During the time of transplantation of plants, the plants get "shocked" due to the damaged or broken roots. As a result, the uptake of water and nutrients by the roots will be restricted, and stunted growth or death of the plants may occur. Replacing the use of pure water with dilute solutions containing plant nutrients often reduces the shock of transplanted plants, resulting in faster establishment of plants [24]. Gordon and Pierzynski [25] found that the use of starter solutions containing N and P consistently increased grain yields, reduced the number of thermal units required for plant emergence to maturity, decreased grain moisture content at the time of harvest, and increased total P uptake of corn.

b. **Foliar application:** The application of liquid fertilizers directly to the leaf surface by using the spraying method is known as foliar application (Figure 2). The leaves can easily and directly absorb the nutrients through their stomatal openings and also through the epidermis. This will be an effective method of fertilization. The fertilizer solutions containing one or more nutrients will be applied to the foliage of the growing plants. Since the nutrients are sprayed only after dissolving

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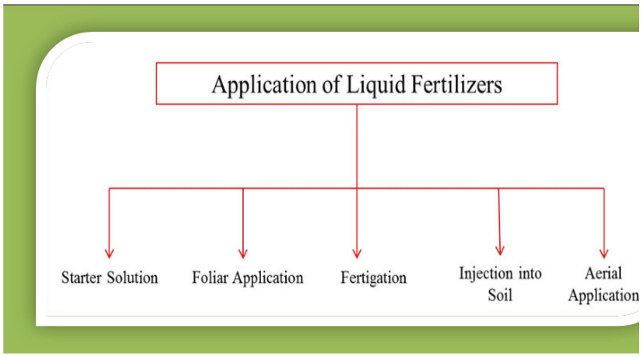

Figure 2: Methods of application of liquid and soluble fertilizers.

them in water, the leaves can easily absorb several nutrient elements. The concentration of the fertilizer solution can be controlled manually, and this will reduce the damaging and scorching of the leaves. The minor nutrients, such as iron, copper, boron, zinc, and manganese, can be easily applied by foliar application.

The foliar applied urea induces a positive effect in the wheat cultivation by increasing the photosynthetic rate and urease enzyme activities. But in the case of soybeans, the yields were inconsistent depending on the year and cultivar used by the foliar application. The results concluded that (a) the foliar applied urea can supply the required N to sustain the growth of the seedlings, (b) to alleviate the N deprivation, the applied urea is absorbed by the seedlings as fast as possible, (c) the failure in the promotion of rapid growth by urea is probably due to phytotoxicity. Heumann, et al. [26] prepared a sustained-release fertilizer composition.

c. **Injection into soil/plants:** The liquid fertilizers can be injected into the soil by either pressure or non-pressure types. Non-pressure solutions may be applied on the surface or in furrows. The loss of plant nutrients can be prevented by the injection of liquid fertilizers into the soil. For example, anhydrous ammonia placed in narrow furrows at a depth of 12-15 cm will be covered suddenly to prevent loss of ammonia. The plant roots take up only a very small portion of the soil-added fertilizers. In most cases, high soil permeability allows the loss of nutrients, especially by fast leaching of the fertilizers to the underground water. The fertilizers are also lost by volatilization, especially N. The addition of nutrients like phosphorus and micronutrients in the form of dissolved compounds also prevents the absorption of added fertilizers by the roots. The fertilizers can also be directly applied to the tree trunk. The main advantage of the injection of fertilizers directly into the plant trunk is that the treatments used for controlling or eradicating the weeds can be avoided because the weeds cannot compete with the crop plants for the available nutrients. Shaaban [27] recommended the application of injection fertilization, especially directly to the trunks of mango and grapevine. It is a very effective method for the nutrient supply, as well as being found to be safer for the underground water in terms of contamination, and causes fewer health hazards.

d. **Aerial application:** The application of liquid fertilizer using aircraft in areas where ground application is not possible is known as aerial application; for example, in hilly areas, forest lands, grasslands, sugarcane fields, etc. The loss of fertilizer is considerably lower in this method. The aerial application of superphosphate in Pinus radiata of the Forest Research Institute in New Zealand recommended that the application of fertilizers by airplane is an accepted tool of management of P. radiata on phosphate-deficient soils and has the benefits of optimum time, rate, and frequency of application.

e. **Fertigation:** There are two types of irrigation practices used for the application of fertilizers along with irrigation, i.e., pressurized irrigation and drip irrigation. The major disadvantage of normal irrigation practice is that the efficiency of water use in this mode is low. But pressurized irrigation practices normally have higher water use efficiency, less nutrient loss, and are well controlled. The initial cost and maintenance costs, and expertise are the major constraints of the pressurized irrigation practices. The most appropriate method of water and nutrient application is drip irrigation or fertigation. Both the water-soluble solid and liquid fertilizers can be applied along with irrigation water. The combined application of water-soluble solid or liquid fertilizers with irrigation water through a pressurized irrigation system is known as fertigation. The nitrogenous fertilizers, such as urea and other ammoniac fertilizers, which are easily soluble in water, are applied along with irrigation water. The application of fertigation will increase yield and minimize soil and water pollution. The loss of fertilizer is considerably lower in this method. The nutrient addition by fertigation is determined by the concentration of the nutrients in irrigation water, the nutrient absorption by the plant, the rate of evapotranspiration, and the reaction (precipitation or fixation) by the growth medium. Hebbar, et al. [28] studied the effect of fertigation and evaluated the sources and level of fertilizer application on growth, yield, and fertilizer use efficiency of hybrid tomato in red sandy loam soil. The data showed a significantly higher production of Total Dry Matter (TDM) and Leaf Area Index (LAI). The chlorophyll concentration was significantly higher in fertigation treatments and also resulted in lesser leaching of NO_3-N and K. Root growth and uptake of NPK were also increased by WSF (water-soluble fertilizer) fertigation. The commonly used fertigation systems are pressure differential, the Venturi (vacuum), and the injection pump. In California, in the late 1960s, about 5% of the nitrogen fertilizers were applied with irrigation water. A chemigation survey in the USA conducted by Threadgill [29] showed that only 3.5% of them used nitrogen fertilizers along with irrigation water. Sixty-one percent used micro-irrigation systems and 43% used sprinkler systems.

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Key reasons why fertilizer application methods are crucial

The importance of fertilizer application methods in agriculture cannot be overstated, as they are essential for maximizing crop yields, ensuring efficient nutrient utilization, reducing environmental impacts, and promoting sustainable farming practices [30]. The impact of different fertilizer application methods on field crop production is substantial, significantly influencing crop yield, quality, and overall agricultural sustainability. The choice of an appropriate application method depends on various factors, including the crop type, soil characteristics, environmental conditions, and available resources. Therefore, understanding and adopting the right fertilizer application techniques is crucial for achieving optimal agricultural outcomes.

a. **Cost savings:** Using the right application methods can save farmers money by reducing the need for excess fertilizer. Precision farming techniques, like variable rate application, enable farmers to apply nutrients only where they are needed, optimizing resource use.

b. **Crop quality:** Foliar Sprays and Fertigation allow for the precise application of nutrients directly to the plant leaves or through irrigation systems. This can enhance crop quality by addressing specific nutrient deficiencies or by promoting nutrient uptake at critical times.

c. **Crop uniformity:** Uniform nutrient distribution across the field promotes crop uniformity, making it easier to manage and harvest crops efficiently.

d. **Environmental impact:** Runoff and Water Pollution: Surface application methods can increase the risk of nutrient runoff into water bodies, potentially causing water pollution and harmful algal blooms. This can have negative ecological and environmental impacts. Air Quality: Surface-applied fertilizers, especially those containing ammonia or nitrogen, can volatilize into the air, contributing to air pollution and greenhouse gas emissions. Precision methods help reduce such emissions. Soil Health: Properly applied fertilizers can improve soil health and fertility, benefiting long-term crop production. Surface application methods that lead to nutrient imbalances or loss can harm soil health.

e. **Minimizing nutrient loss:** Inappropriate fertilizer application methods can lead to nutrient runoff and leaching, which can pollute water bodies and harm aquatic ecosystems. Correct placement and timing of fertilizers can help minimize nutrient losses, protecting the environment. Different crops have varying nutrient requirements at different growth stages. Proper application methods, such as timing, placement, and rates, ensure that plants receive the right nutrients when they need them. This increases nutrient use efficiency, reduces waste, and saves money for farmers.

f. **Nutrient use efficiency: Surface boadcasting:** Surface application methods may result in nutrient losses through runoff, volatilization, or fixation in the soil, reducing nutrient use efficiency. Nutrients applied to the surface may not be as readily available to crops, leading to lower efficiency. Incorporation and Injection: These methods place nutrients in the root zone, reducing losses and improving nutrient use efficiency. Nutrients are more accessible to crops, resulting in better utilization.

g. **Reducing environmental impact:** Improper fertilizer application can contribute to air and water pollution, greenhouse gas emissions, and soil degradation. Choosing the right application methods helps mitigate these negative environmental effects, supporting sustainable agriculture.

h. **Regulatory compliance:** Many regions have regulations governing fertilizer use, including application rates and methods. Adhering to these regulations is essential to avoid legal issues and potential fines.

i. **Resource conservation:** Proper fertilizer application methods help conserve valuable resources like water and energy. By reducing runoff and leaching, water resources are protected, and energy is saved in the production and transportation of fertilizers.

j. **Soil health:** Inadequate or excessive fertilization can harm soil health over time. Proper application methods ensure that nutrients are delivered in a way that minimizes soil nutrient imbalances and degradation.

k. **Sustainability:** Sustainable farming practices are essential to protect the long-term viability of agriculture. Fertilizer application methods that align with sustainable principles help maintain soil fertility and reduce the need for environmentally harmful practices.

l. **Sustainability: Sustainable practices:** Precision application methods and sustainable nutrient management practices align with long-term agricultural sustainability goals. They promote efficient resource use, reduce environmental impacts, and support responsible farming.

m. **Yield enhancement: Precision methods (Injection, banding and drip irrigation):** These methods provide targeted delivery of nutrients to the root zone, ensuring that crops receive the necessary nutrients when they need them. This can lead to increased crop yields due to optimized nutrient availability during critical growth stages.

n. **Variable Rate Application (VRT):** VRT allows farmers to adjust fertilizer rates based on soil nutrient levels and crop requirements within the same field. This fine-tuned approach can lead to higher yields in areas with nutrient deficiencies and reduced costs where nutrients are not needed as much. Correct application methods

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can significantly boost crop yields. Efficient nutrient delivery ensures that plants have the resources they need to grow and produce high-quality crops.

o. **Research and innovation:** Ongoing research and innovation in fertilizer application methods lead to advancements that can improve agricultural productivity and environmental stewardship.

Impact of fertilizer application method

The method of fertilizer application in agriculture has a significant impact on soil health, plant growth, and the environment. The choice of application method affects how efficiently nutrients are delivered to plants, how they interact with the soil, and whether there are potential negative consequences for the environment. Here's an overview of the impacts of different fertilizer application methods on soil, plants, and the environment:

Soil impact

a. **Nutrient distribution:** The method of application determines how evenly nutrients are distributed in the soil. Surface application may lead to uneven distribution, while precision methods like injection or incorporation ensure a more even nutrient spread.

b. **Nutrient retention:** Incorporation and injection methods reduce the risk of nutrient loss through runoff or volatilization, as nutrients are placed within the root zone, enhancing nutrient retention in the soil.

c. **Soil structure:** Excessive or improper application methods can lead to soil compaction, reduced aeration, and degradation of soil structure, affecting root growth and water infiltration.

d. **Acidification and pH:** Some fertilizers can influence soil pH. For example, ammonium-based fertilizers may acidify the soil, necessitating the use of lime to counteract pH changes.

e. **Microbial activity:** Fertilizer application methods can impact soil microbial communities. Excessive or unbalanced fertilization can harm beneficial soil microorganisms, affecting nutrient cycling and soil health.

Plant impact

a. **Nutrient availability:** Proper fertilizer placement methods, such as banding or injection, ensure that nutrients are readily available to plant roots, promoting optimal nutrient uptake and plant growth.

b. **Root development:** Fertilizer application methods that reduce soil compaction and promote good soil structure can enhance root development, leading to healthier and more productive plants.

c. **Crop uniformity:** Precision methods contribute to crop uniformity by ensuring that each plant receives the required nutrients, reducing variability in crop development.

d. **Minimized nutrient stress:** Balanced nutrient application methods help prevent nutrient stress in plants, which can result from nutrient deficiencies or toxicities.

Environmental impact

a. **Nutrient runoff:** Surface application methods increase the risk of nutrient runoff into water bodies, which can lead to water pollution, harmful algal blooms, and aquatic ecosystem damage.

b. **Groundwater contamination:** Improper application can result in nutrient leaching into groundwater, potentially contaminating drinking water sources.

c. **Greenhouse gas emissions:** Certain fertilizers, such as nitrogen-based fertilizers, can contribute to greenhouse gas emissions, particularly nitrous oxide (N_2O), which is a potent greenhouse gas

d. **Air pollution:** Ammonia volatilization from surface-applied fertilizers can contribute to air pollution and can have negative health effects.

e. **Ecological impact:** Excess nutrients in the environment can disrupt ecosystems, leading to habitat changes, biodiversity loss, and ecological imbalances [31].

Research findings

Broadcasting, particularly surface broadcasting, involves spreading fertilizer uniformly over the field. While operationally simple and favored for dense planting systems, it frequently leads to:

a. Higher nutrient losses (especially nitrogen), due to volatilization and runoff.

b. Reduced NUE compared to targeted methods.

c. Broad-scale stimulation of weed growth and potentially higher environmental harm through eutrophication and soil degradation.

Quantitatively, nitrogen losses from broadcast urea in flooded rice systems often exceed 50% of applied N, whereas deep placement methods (e.g., using urea super granules-USG) reduce N loss by up to 20–25% and significantly increase NUE and crop yield in wetland rice.

Band and Deep Placement techniques, which position nutrients close to the root zone, consistently report:

a. Higher NUE and yield advantages under low soil fertility and moisture-limited conditions.

b. Up to 30–40% higher crop uptake of phosphorus and potassium compared to broadcasting

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c. Reduced risk of salt injury to seedlings and minimized weed competition.

Meta-analysis & quantitative synthesis

Multiple meta-analyses and large-scale field syntheses, especially on placement *vs.* broadcasting, converge on these findings:

a. Band placement of phosphorus increases maize and wheat yields by an average of 8–20% across low- to medium-fertility soils; uptake is especially improved when placed 15–20 cm below the seed zone.

b. Deep placement of USG in rice reduces N loss by up to 25% compared to prilled urea broadcast; yield gains of 10–15% are consistently reported in wetland rice.

c. Fertigation can reduce nitrate leaching by 30–40% and enhance total dry matter by 15% - 25% in tomato and other horticultural crops under controlled irrigation.

d. Foliar application of micronutrients increases yield reliably in cereals but is erratic in oilseeds and legumes, with yield changes ranging from −5% (negative effects) to +15% depending on crop and season.

Method	Yield Impact	Nutrient Loss	NUE	Notable Contradictions
Broadcasting	Baseline/variable	Higher (up to 50% N lost in rice)	Lower	In some coarse soils, more effective for boron and legumes than banding
Band Placement	8% - 20% (maize/ wheat P)	Lower	Higher	Root growth variation affects performance
Deep Placement	20% - 25% N efficiency in rice	Lowest	Highest	Genotype/season-specific response in rice
Fertigation	10% - 30% yield (vegetables)	Minimized	High	High initial/ maintenance cost; less feasible in rainfed systems
Foliar Application	Inconsistent by crop	Minimal	Moderate	Positive in wheat, variable in soybean; possible leaf toxicity

Conclusion and future prospectives

The transformation of fertilizer application practices stands at the crossroads of enhancing food security, environmental sustainability, and farmer prosperity—challenges sharply felt both globally and within India. Despite decades of improvements, major concerns such as declining nutrient use efficiency, soil degradation, imbalanced fertilizer use, and environmental externalities continue to threaten the viability of crop production worldwide. Comparative research and meta-analyses consistently show that advanced placement methods like banding, deep placement, and fertigation can improve crop yields by 10% - 40%, reduce nitrogen losses by up to 25% - 40%, and minimize environmental footprints relative to surface broadcasting. However, the benefits of these approaches are often modulated by local climatic, edaphic, and socio-economic realities, making a one-size-fits-all solution impractical. The contradictions in field outcomes, adoption rates, and cost-benefit profiles highlight an urgent need for context-specific, evidence-based strategies. For example, while fertigation and deep placement have been transformative for irrigated crops and rice systems, respectively, their adoption in rainfed or resource-limited smallholder farms—common in India and sub-Saharan Africa—remains slow due to high initial investments, technological complexity, and knowledge gaps. In India, excessive and imbalanced use of fertilizers (notably N over P and K), neglect of secondary and micronutrients, and weak enforcement of best management practices persist as core issues. The growing challenge of emerging multiple nutrient deficiencies and climate-induced nutrient losses further complicates sustained productivity.

Globally, a future-oriented approach must blend advanced agronomic science with digital technologies, such as soil health mapping, Internet-of-Things-enabled fertigation, variable-rate application, and remote sensing, to enable real-time, precise, and sustainable nutrient management. India's future perspective should prioritize a mix of policy innovation, farmer-centric knowledge dissemination, and investment in scalable, affordable precision technologies, tailored to the needs of smallholders and marginal farmers who constitute the backbone of its agriculture. Strengthening soil testing infrastructure, incentivizing balanced fertilization (through direct benefit transfers or input subsidies for P, K, and micronutrients), and integrating organic amendments and crop rotations are critical. The government and allied agencies must invest in large-scale longitudinal field trials to build robust, location-specific data, while engaging the private sector, farmer cooperatives, and extension systems in technology transfer and capacity building.

For policymakers, both in India and globally, the imperative is to frame nutrient management not only as a technical challenge but as a cornerstone of sustainable development. Policies must be rooted in the 4R Nutrient Stewardship framework—right source, right rate, right time, right place—supported by clear regulatory guidelines, incentives for sustainable practices, and strong enforcement to curb misuse. Importantly, policy must account for equity and inclusion by facilitating access for smallholders to new technologies, knowledge, and financing mechanisms. Subsidy and support schemes should be reoriented towards performance-based incentives: rewarding farmers for adopting precision methods, reducing nutrient runoff, improving soil organic matter, and enhancing ecosystem services. At the international level, knowledge exchanges, joint research programs, and harmonized standards can accelerate innovation diffusion and build global resilience against shared threats like climate change and nutritional insecurity.

In the long run, only a systems-based, multidisciplinary approach—integrating field experimentation, digital technology, grassroots education, and enlightened policy—will enable India and the global community to meet the dual challenge of producing more with less environmental impact.

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The choices made today regarding fertilizer application methods and supporting policies will determine whether agricultural systems can sustainably feed future generations while preserving the environmental foundations upon which all livelihoods ultimately depend.

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