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Review Article

A Review on Challenges and Opportunities of Fertilizer Use Efficiency and Their Role in Sustainable Agriculture with Future Prospects and Recommendations

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ABSTRACT

The efficient use of fertilizers is a critical component of sustainable agriculture, ensuring optimal nutrient supply to crops while minimizing environmental impacts. This comprehensive review examines the various aspects of fertilizer use efficiency and its implications for sustainable agricultural practices. This review discussed the factors influencing fertilizer use efficiency, including soil properties, crop types, climate conditions, and management practices. The role of different fertilizer types, such as organic and inorganic fertilizers, and their interactions with soil microbial communities are explored. Additionally, environmental consequences of fertilizer application assessed which including nutrient leaching, greenhouse gas emissions, and potential strategies to mitigate these effects. Furthermore, this review emphasizes the importance of integrated nutrient management approaches and innovative technologies to enhance fertilizer use efficiency and promote sustainable agriculture in a changing global landscape.

Keywords: *Fertilizer, greenhouse gases, nutrient management, environmental changes, microbial interaction, sustainable agriculture*

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INTRODUCTION

Efficient use of fertilizers is crucial in modern agriculture, as it impacts crop productivity, resource management and environmental sustainability. By using fertilizers judiciously, the right amount of nutrients can be supplied to crops, reducing losses and optimizing nutrient uptake, while also minimizing potential negative environmental impacts. Throughout history, the use of fertilizers has been a common practice that dates back thousands of years. Ancient civilizations like the Babylonians and Romans utilized organic materials such as animal manure and compost to improve soil fertility and increase crop yields (Bender, 2013). In the 20th century, the introduction of synthetic fertilizers brought about a major change in agricultural practices. Chemical fertilizers including nitrogen (N), phosphorus (P), and potassium (K) fertilizers, became widely available, leading to a significant boost in global food production (Ali et al., 2023). This contributed to the "Green Revolution" and helped sustain a growing human population.

Using fertilizers efficiently is important to ensure that plants get the right amount of nutrients they need to grow strong and produce a high yield. Fertilizers are essential for providing the necessary nutrients to the soil and promoting plant growth. By using fertilizers efficiently, crops can receive the right amount of nutrients at the right time, which can help increase crop productivity and yield. Fertilizer use efficiency helps in increasing agricultural productivity, ensuring an adequate food supply, and addressing global nutrition needs. Efficient use of fertilizers reduces unnecessary nutrient losses, minimizing environmental pollution and conserving valuable resources. It also contributes to cost-effectiveness in agricultural practices by optimizing input use. Excessive fertilizer application can lead to nutrient leaching, contributing to water pollution and eutrophication (Riaz et al., 2022a).

1. Factors Influencing Fertilizer Use Efficiency

2.1. Soil properties and fertility status

The effectiveness of fertilizer use is greatly affected by the physio-chemical characteristics of the soil. In acidic soils, certain nutrients like phosphorus (P), iron (Fe), and zinc (Zn) may become less available to plants. On the other hand, in alkaline soils, micronutrients like iron (Fe), manganese (Mn), and boron (B) may be less accessible. Maintaining an appropriate soil pH through lime application can optimize nutrient availability (Marschner, 2012).

Soil organic matter enhances soil structure, water retention, and CEC. It acts as a nutrient reservoir and source of slow-release nutrients, improving nutrient retention and availability. High organic matter content positively influences fertilizer use efficiency. Soils can fix or immobilize certain nutrients, making them less available for plant uptake. Nutrient fixation occurs when elements react with soil minerals, reducing their solubility. Conversely, under favorable conditions, these nutrients may be released back into the soil solution for plant uptake. Soil with higher CEC can retain more nutrients and provide a reservoir for nutrients to be gradually released to plants, enhancing fertilizer use efficiency. Soil moisture content affects nutrient availability and movement. Adequate soil moisture is necessary for nutrient dissolution and transport towards plant roots, ensuring efficient nutrient uptake (White, 2006).

2.2. Crop types and nutrient requirements

Each crop has unique nutrient requirements based on its growth stage and physiological processes. For example, cereals like rice and wheat have higher nitrogen (N) requirements during the vegetative stage, while fruiting crops like tomatoes and peppers have higher potassium (K) requirements during the fruiting stage. Tailoring fertilizer application to meet these specific nutrient demands enhances nutrient uptake and minimizes wastage (Xue et al., 2017). The way crops are rotated and succeeded can impact the availability and cycling of nutrients in the soil.

When leguminous crops are used in rotation, they can fix nitrogen from the atmosphere, which reduces the need for nitrogenous fertilizers in the following non-legume crops. Organic and inorganic fertilizers have distinct nutrient release dynamics. Evaluating crop responses to various fertilizers helps select the most suitable ones for specific crops and ensures efficient nutrient utilization (El-Mahrouk et al., 2019). Different crops may have different nutrient requirements in terms of ratios. For instance, leafy vegetables may require a higher N to P ratio, while fruiting crops may need a higher K to N ratio.

2.3. Climate and weather conditions

The efficiency of fertilizer use in agriculture is greatly influenced by the climate and weather conditions. Changes in temperature, rainfall patterns, and humidity can influence nutrient availability, losses, and the effectiveness of fertilizers. When there is heavy and intense rainfall, it can cause nutrient leaching and runoff from agricultural fields to increase. Too much water can carry soluble nutrients, like nitrates and phosphates, beyond the root zone. This can make them less available to crops and increase the chances of water pollution. When temperatures and humidity are high, it can cause ammonia (NH_3) to be released from urea-based fertilizers more quickly. This can also speed up denitrification, which means that nitrate (NO_3^-) is converted into nitrogen gas (N_2), leading to a loss of nitrogen from the soil (Yuan et al., 2005).

2.4. Management practices and timing of fertilizer application

By supplying nutrients when the crop needs them most, this method avoids excessive nutrient availability during periods when the plant's demand is low, thus reducing nutrient losses through leaching or runoff. For example, a portion of nitrogen (N) fertilizer can be applied during planting to support early growth, while the remaining amount is applied during the vegetative or reproductive stages when the crop has a higher N demand. This practice ensures that the nutrients are optimally utilized by the crop during critical growth phases, leading to enhanced nutrient uptake and improved overall fertilizer use efficiency "Controlled-release fertilizers (CRFs)" are designed to release nutrients gradually over an extended period, providing a steady and continuous supply to plants. These fertilizers are formulated with special coatings or matrices that control nutrient release, allowing nutrients to be available to plants based on their growth requirements.

CRFs are particularly beneficial in situations where a single application can meet the crop's nutrient needs for an extended period. Most of the soil contaminated by the generic and anthropogenic activities and in anthropogenic activities indiscriminate use of fertilizers is one of them (Ali et al., 2022a). High concentrations of heavy metals in soil adversely affect plant growth and their different biochemical processes such as metabolism, stomata opening, and photosynthesis (Ali et al., 2022c). By releasing nutrients slowly, CRFs reduce the risk of nutrient leaching, volatilization, and excessive nutrient availability, which can lead to environmental pollution. As a result, controlled-release fertilizers improve nutrient use efficiency by ensuring that nutrients are delivered to plants in a controlled and timely manner, matching their growth demands.

2.5. Soil microbial interactions

Nitrification and denitrification are essential nitrogen (N) transformation processes facilitated by soil microorganisms. Nitrification converts ammonium (NH_4^+) to nitrate (NO_3^-), a form that is readily taken up by plants but is also susceptible to leaching. Denitrification, on the other hand, converts nitrate back to gaseous forms, such as nitrogen oxides (N_2O) and nitrogen gas (N_2), which can be lost to the atmosphere.

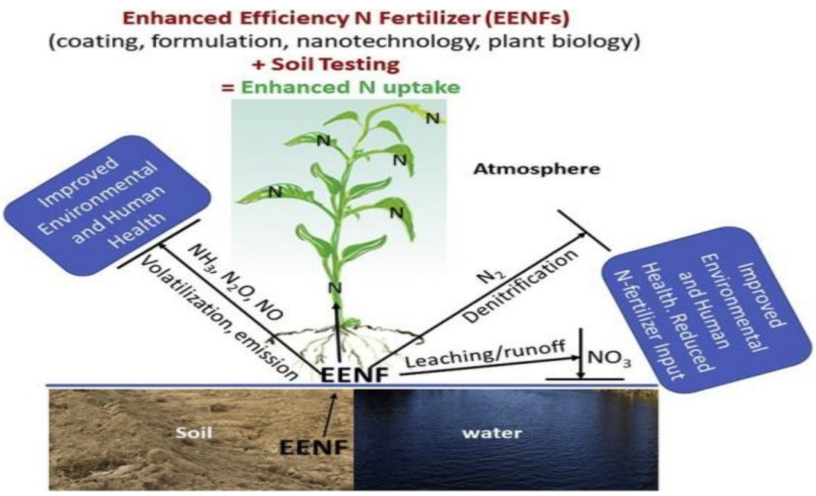
3. Types of Fertilizers

3.1. Organic Fertilizers and In-organic fertilizers

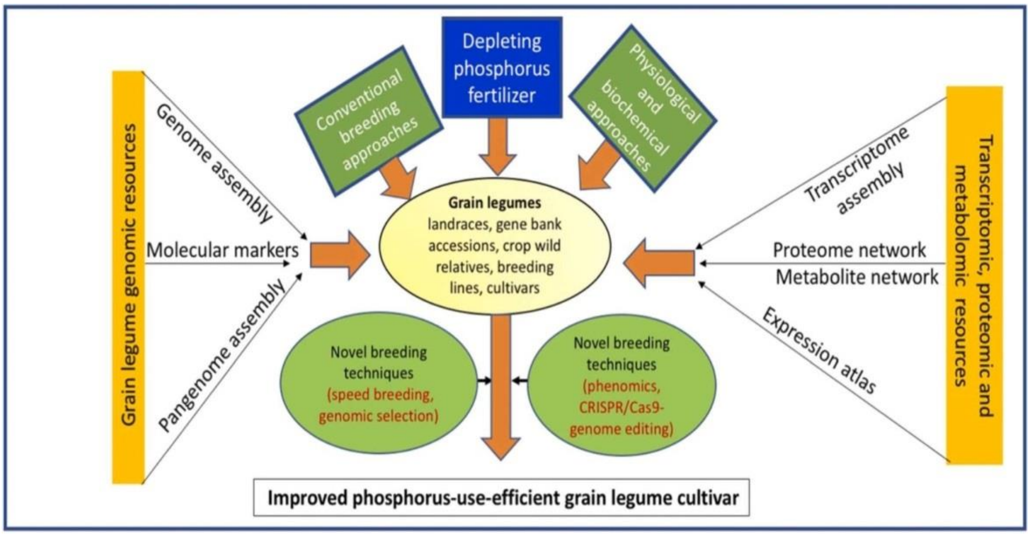
They can be derived from various sources, such as crop residues, animal manures, compost, and green manure cover crops, all of which are abundant in organic matter and essential nutrients like nitrogen (N), phosphorus (P), potassium (K), and micronutrients. Using organic fertilizers can help enhance the soil structure by increasing the aggregation of soil particles and promoting the formation of stable organic matter. The use of organic fertilizers helps increase the number of helpful soil microorganisms like mycorrhizal fungi and beneficial bacteria. These microorganisms assist in the cycling of nutrients and enhance the availability of nutrients to plants (Singh et al., 2011).

Additionally, they can boost the content of organic matter in the soil, leading to better soil fertility, increased microbial activity, and overall soil health. Organic fertilizers provide a habitat for beneficial soil microorganisms, fostering their growth and activity. These microorganisms play essential roles in nutrient cycling, nitrogen fixation, and disease suppression, benefiting plant health. Organic fertilizers have lower environmental impacts compared to synthetic fertilizers. They are less likely to contribute to nutrient runoff and groundwater pollution, thus helping to protect water quality and ecosystems. Organic fertilizers provide a valuable alternative to synthetic fertilizers, promoting soil health, sustainability, and improved nutrient management in agriculture. Their slow-release nutrient supply, soil-improving properties, and positive effects on beneficial soil organisms make them an essential component of sustainable agricultural practices (Tejada et al., 2006). Here's an explanation of the types of inorganic fertilizers commonly used in agriculture:

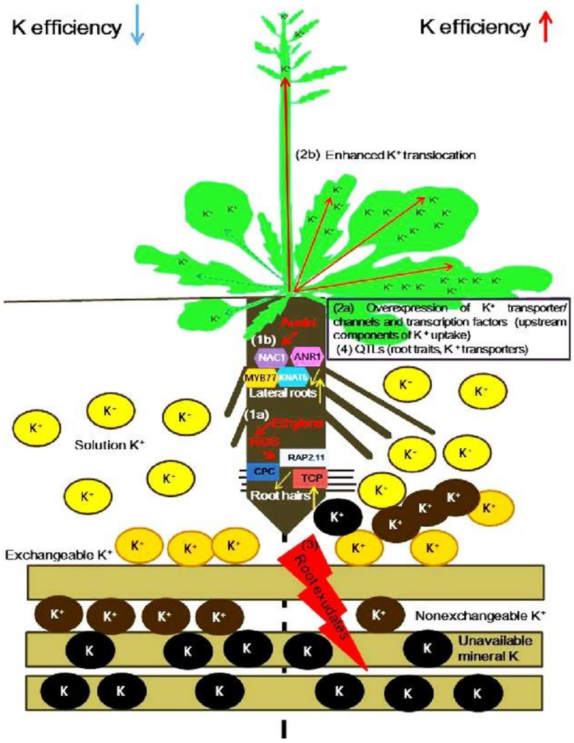
Nitrogen (N): Nitrogen (N) fertilizers are essential for promoting vegetative growth and overall plant development. They come in various forms, including; Ammonium Nitrate (NH_4NO_3): A common quick-release nitrogen fertilizer with high solubility; Urea ($CO(NH_2)_2$): A widely used solid nitrogen fertilizer that is rapidly converted to ammonium in the soil and Ammonium Sulfate [$(NH_4)_2SO_4$]: A nitrogen fertilizer with additional sulfur, suitable for acidic soils (Raun and Johnson, 1999).



Phosphorus (P): Phosphorus (P) is vital for root development, seed formation, and energy transfer within plants. Common inorganic phosphorus fertilizers include; Superphosphate: A partially soluble fertilizer, typically produced by reacting phosphate rock with sulfuric acid; Triple Superphosphate (TSP): A concentrated form of superphosphate with higher P content; Monoammonium Phosphate (MAP) and Diammonium Phosphate (DAP): Fertilizers containing both nitrogen and phosphorus, suitable for various crops (Bünemann et al., 2011).



Potassium (K): Potassium (K) fertilizers play a vital role in improving plant stress tolerance and promoting fruit and seed development. Common inorganic potassium fertilizers include; Potassium Chloride (KCl): The most widely used potassium fertilizer, easily soluble in water; Potassium Sulfate (K_2SO_4): A source of potassium with additional sulfur, suitable for potassium-deficient soils (Schachtman et al., 1998).



Calcium (Ca), Magnesium (Mg) and Sulphur (S): Calcium (Ca), magnesium (Mg) and sulphur (S) are secondary nutrients important for plant cell structure and photosynthesis. Inorganic fertilizers containing calcium and magnesium include; Calcium Nitrate [Ca $(NO_3)_2$]: A nitrogen and calcium source, often used in hydroponic systems; Magnesium Sulfate (MgSO4): Known as Epsom salt, a soluble magnesium fertilizer (Marschner, 2012). Sulphur containing fertilizers are the ammonium sulphate, single super phosphate (SSP), ammonium phosphate sulphate, potassium magnesium sulphate, potassium sulphate, magnesium sulphate and other sulphate of nutrients.

Inorganic fertilizers offer precise control over nutrient composition and are readily available for plant uptake. However, proper management is essential to prevent overuse and minimize environmental impacts.

3.1.1 Formulations

Inorganic fertilizers, also known as synthetic or mineral fertilizers, are manufactured from mineral salts that contain essential nutrients for plant growth. Single-nutrient fertilizers contain only one of the essential nutrients. Common examples include ammonium nitrate (NH_4NO_3) for nitrogen, superphosphate (Ca $(H_2PO_4)_2$) for phosphorus, and potassium chloride (KCl) for potassium. Compound fertilizers are blends of two or more primary nutrients, typically N, P, and K. These formulations are designed to provide a balanced nutrient ratio for specific crops or growth stages. Common examples include 20-20-10 (N-P-K) and 15-15-15 (N-P-K) compound fertilizers. These fertilizers can include secondary nutrients like calcium (Ca), magnesium (Mg), and sulfur (S), as well as micronutrients like iron (Fe), zinc (Zn), manganese (Mn), copper (Cu), boron (B), and molybdenum (Mo).

Complete fertilizers are formulations that contain a balanced combination of three primary nutrients: nitrogen (N), phosphorus (P), and potassium (K). Complete fertilizers are commonly used for general-purpose fertilization (Singh and Gaur, 2012). Controlled-release fertilizers are designed to gradually release nutrients over an extended period. These formulations may be coated or encapsulated to regulate nutrient release rates. Controlled-release fertilizers reduce nutrient leaching and enhance nutrient use efficiency (Jiao et al., 2018).

Inorganic fertilizers provide essential nutrients to plants, contributing to improved crop yields and agricultural productivity. However, their application should be judiciously managed to prevent environmental issues like nutrient runoff and groundwater contamination.

3.1.1. Nutrient Availability

3.1.2.1 Nitrogen (N) Fertilizers

Inorganic nitrogen fertilizers, such as ammonium nitrate (NH_4NO_3), ammonium sulfate ($(NH_4)_2SO_4$), and urea (CO $(NH_2)_2$), provide readily available nitrogen to plants. These fertilizers quickly dissolve in soil water, and the ammonium (NH_4^+) and nitrate (NO_3^-) ions are readily taken up by plant roots. However, the availability of nitrogen can be affected by soil pH, microbial activity, and environmental factors such as temperature and moisture (Mengel and Kirkby, 2001).

3.1.2.2. Phosphorus (P) Fertilizers

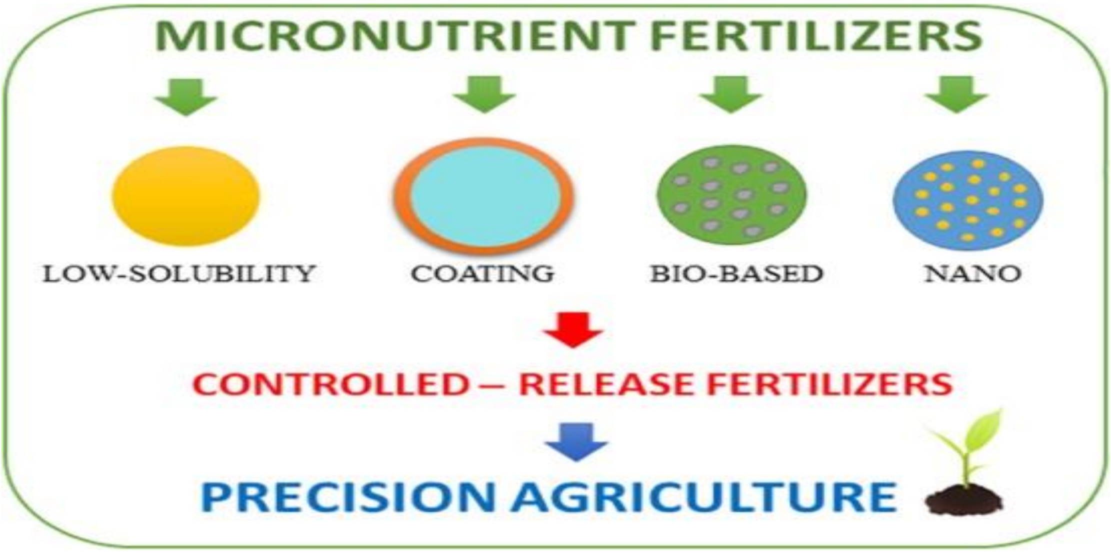
Inorganic phosphorus fertilizers, like diammonium phosphate (DAP) [$(NH_4)_2$ HPO_4], superphosphate, and triple superphosphate, contain water-soluble phosphate compounds. These fertilizers provide an immediate source of phosphorus to plants. However, the availability of phosphorus is influenced by soil pH and the presence of phosphate-fixing compounds, leading to potential immobilization of phosphate in certain soil types (Mengel and Kirkby, 2001).

3.1.2.3. Potassium (K) Fertilizers:

Inorganic potassium fertilizers, such as potassium chloride (KCl) and potassium sulfate (K_2SO_4), are readily soluble in water, providing available potassium ions to plants. Soil properties, such as cation exchange capacity (CEC) and clay content, influence potassium availability and retention.

3.1.2.4. Micronutrient Fertilizers

Inorganic fertilizers for micronutrients, such as iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu), typically contain water-soluble forms of these elements. These fertilizers can address specific micronutrient deficiencies in crops such as zinc and iron biofortification in cereals (Ali et al., 2021; 2022b). The availability of micronutrients is influenced by soil pH and the presence of other compounds that may form complexes with these elements (Marschner, 2012).



3.1.2.5. Fertilizer Formulations and Slow-Release Fertilizers

Fertilizer formulations, such as coated and slow-release fertilizers, affect nutrient availability over an extended period. Slow-release fertilizers provide nutrients gradually, reducing the risk of nutrient leaching and improving nutrient use efficiency (Marschner, 2012).

3.2. Slow release fertilizers; mechanisms and applications

3.2.1. Mechanisms of Slow-Release Fertilizers

3.2.1.1. Coating and Encapsulation

Slow-release fertilizers are coated or encapsulated with materials that control the rate of nutrient release. The coatings can be made from materials such as sulfur, polymers, or resin, which gradually break down in response to environmental factors like temperature, moisture, and microbial activity (Li et al., 2008).

3.2.1.2. Nutrient Complexation

Slow-release fertilizers utilize nutrient complexation, where nutrients are chemically bound to a carrier material. The release is controlled by the gradual decomposition or solubilization of the complex, making nutrients available to plants at a controlled rate (Liu et al., 2013).

3.2.2. Applications of Slow-Release Fertilizers

3.2.2.1. Agricultural Crops

Slow-release fertilizers find extensive application in agricultural crop production. They can be used for various crops, including cereals, vegetables, and fruit trees. Slow-release formulations cater to the specific nutrient needs of crops during different growth stages, reducing the frequency of fertilizer applications (Ganeshamurthy et al., 2021).

3.2.2.2. Turf grass and Ornamental Plants

Slow-release fertilizers are commonly employed in turf grass management and landscaping to promote steady growth and reduce the risk of nutrient leaching and burning (Branham et al., 2017).

3.2.2.3. Nursery and Greenhouse Production

Slow-release fertilizers are widely used in nursery and greenhouse settings to provide a continuous supply of nutrients for young plants and seedlings, enhancing their growth and development (Galvis et al., 2012).

3.2.2.4. Environmental Restoration and Land Reclamation

Slow-release fertilizers are employed in environmental restoration projects, such as wetland reclamation, to support vegetation establishment and reduce nutrient runoff (Kim et al., 2018).

4. Interactions with Soil Microbial Communities

Fertilizer application provides additional nutrients to the soil, which can stimulate microbial growth and activity. Microbes, such as nitrogen-fixing bacteria and mycorrhizal fungi, which help in nutrient cycling can benefit from the higher nutrient availability. The use of various fertilizers can affect the quantity and variety of microbes in soil. Research indicates that changes in nutrient levels and pH levels brought about by fertilizer application can alter the composition of microbial communities (Xiong et al., 2015).

PGPR are beneficial bacteria that colonize the rhizosphere (root zone) and promote plant growth through various mechanisms. Some fertilizers, especially organic amendments, can provide a favorable environment for PGPR proliferation. Organic fertilizers enhance soil organic matter content and microbial diversity, creating a conductive habitat for PGPR activity. Mycorrhizal fungi create mutually beneficial relationships with plant roots, resulting in enhanced nutrient absorption, especially phosphorus and micronutrients.

Fertilizer application can indeed influence the decomposition of soil organic matter, with some fertilizers, especially those high in nitrogen (N), potentially accelerating the decomposition process. This has implications for soil carbon dynamics and can affect soil fertility and nutrient cycling. Nitrogen is a vital nutrient for soil microorganisms, which play a crucial role in organic matter decomposition. Nitrogen fertilizers, particularly those in the form of ammonium (NH_4^+) and nitrate (NO_3^-), can provide an immediate and readily available nitrogen source to soil microbes. This increased availability of nitrogen can stimulate microbial activity, leading to higher rates of organic matter decomposition (Geisseler and Horwath, 2014).

4.1. Role of soil microorganisms in nutrient cycling and fertilizer transformation

During this decomposition process, nutrients like nitrogen (N), phosphorus (P), and sulfur (S) are released from organic matter and made available for plant uptake. Certain soil bacteria, such as Rhizobium species and free-living diastrophic bacteria are capable of biological nitrogen fixation. They convert atmospheric nitrogen (N_2) into ammonium (NH_4^+), a form that plants can use for growth. This process enriches the soil with available nitrogen, benefiting both plants and other soil organisms. Nitrifying bacteria are responsible for converting ammonium (NH_4^+) into nitrate (NO_3^-) through nitrification. On the other hand, denitrifying bacteria facilitate the conversion of nitrate back into nitrogen gas (N_2) under anaerobic conditions, reducing nitrogen losses to the atmosphere.

Phosphorus mineralization is the process by which soil microorganisms release phosphorus from organic matter or inorganic complexes, making it available for plant uptake. Phosphorus-mobilizing microorganisms, such as mycorrhizal fungi, play a significant role in enhancing phosphorus availability to plants. Soil microorganisms contribute to sulfur cycling by mineralizing organic sulfur compounds, converting them into sulfate (SO42-), and facilitating sulfur transformations in the soil. Microorganisms are involved in the decomposition of organic carbon and the subsequent stabilization of carbon in soil aggregates, contributing to carbon sequestration and soil organic matter formation (Lal, 2010).

4.2. The influence of fertilizer application on soil microbial diversity and function

Fertilizer application provides an external source of nutrients, which can stimulate the growth of certain microbial populations. Microbes that can utilize the added nutrients may experience increased abundance and activity. Different fertilizers may favor the growth of specific microbial groups. For example, nitrogen fertilizers can promote the proliferation of nitrogen-fixing bacteria, while phosphorus fertilizers may influence the abundance of phosphate-solubilizing microorganisms (Shen et al., 2010). Fertilizers can affect beneficial soil microbes, such as mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR). Excessive fertilizer application may reduce the dependency of plants on these beneficial microbes, potentially affecting plant health and nutrient uptake (Kaur et al., 2018). Fertilizer-induced changes in microbial activity can alter the rate of microbial respiration, leading to fluctuations in carbon dioxide emission from the soil (Kuzyakov et al., 2000).

5. Environmental impacts and mitigation strategies

5.1. Nutrient leaching and water quality concerns

Nutrient leaching is a significant environmental concern that affects water quality in various ecosystems, including agricultural lands, urban areas, and natural environments. It occurs when excess nutrients, such as nitrogen and phosphorus, are washed away from the soil surface by rainwater or irrigation, eventually reaching groundwater, streams, rivers, and lakes. One of the most prevalent water quality concerns related to nutrient leaching is eutrophication. Oxygen depletion can harm aquatic life, leading to fish kills and negatively impacting entire aquatic ecosystems (Smith and Schindler, 2009).

5.2. Greenhouse gas emissions and climate change feedbacks

Greenhouse gas (GHG) emissions from fertilizer use and the associated climate change feedbacks are significant environmental concerns. The production and transportation of synthetic fertilizers, particularly nitrogen fertilizers, require significant energy inputs, leading to CO_2 emissions. Additionally, nitrogen fertilization can alter soil carbon dynamics, potentially increasing CO_2 emissions from soil. Greenhouse gas emissions from fertilizers contribute to climate change, which, in turn, can affect agricultural productivity and nutrient cycling in the soil. Changes in temperature and precipitation patterns due to climate change can influence the efficiency of nutrient use, potentially impacting crop yields (Lobell et al., 2011).

5.3. Best Management Practices (BMPs) for reducing environmental impacts

Best Management Practices (BMPs) for reducing the environmental impacts of fertilizers are essential to promote sustainable agriculture and protect the environment. Applying fertilizers at the right time, in the right amount, and in the right place is crucial for optimizing nutrient use efficiency and minimizing nutrient losses. Precision agriculture techniques, such as soil testing, variable rate application, and remote sensing, can help tailor fertilizer application to the specific needs of each field. Slow-release or controlled-release fertilizers release nutrients gradually over an extended period, matching plant demand. These fertilizers reduce nutrient leaching and runoff, minimizing environmental impacts. Planting cover crops or using green manure can capture excess nutrients, prevent soil erosion, and improve soil health.

6. Integrated nutrient management for fertilizer efficiency

6.1. Combining organic amendments with inorganic fertilizers

Combining organic amendments with inorganic fertilizers as part of Integrated Nutrient Management (INM) is a strategic approach that aims to improve fertilizer efficiency, enhance soil health, and optimize crop productivity. This integrated approach combines the benefits of both organic and inorganic nutrient sources, resulting in balanced nutrient supply, reduced nutrient losses, and sustainable agricultural practices.

6.2. Synergistic Effects of biofertilizers and plant growth promoting rhizobacteria (PGPR)

Synergistic effects of biofertilizers and plant growth promoting rhizobacteria (PGPR) in Integrated Nutrient Management (INM) represent a powerful approach to enhance fertilizer efficiency and promote sustainable agriculture. Biofertilizers and PGPR are beneficial microorganisms that interact with plants to improve nutrient uptake, plant growth, and overall crop productivity. When used in combination, they can complement each other's functions, leading to greater benefits for crop plants. While on the other hand, different plant species provide the carbon and many other macro or micronutrients for the soil bacterial species or other decomposer in the form of the rotten leaves and root exudates, and in turn they provide the decomposed organic material which stabilized the soil structure, plays a key role in nutrients cycling, soil physical condition and nutrient improvement in soil (Ali et al., 2022d)

6.3. Precision agriculture and site-specific nutrient management

Precision Agriculture, Site-Specific Nutrient Management (SSNM), and Integrated Nutrient Management (INM) are interrelated concepts that aim to optimize fertilizer efficiency, enhance crop productivity, and minimize environmental impacts. Precision Agriculture is an advanced farming approach that utilizes technology, such as Global Positioning Systems (GPS), remote sensing, and geographic information systems (GIS), to manage fields at a fine-scale level.

7. Challenges and opportunities for sustainable fertilizer use

7.1. Challenges

Sustainable fertilizer use faces several challenges in meeting crop demand while minimizing environmental impacts. These challenges arise from various factors, including population growth, changing dietary preferences, resource constraints, and environmental concerns. In many regions, there is a mismatch between nutrient application and crop nutrient requirements, leading to imbalanced soil nutrient levels. Excessive use of fertilizers can lead to nutrient losses through leaching and runoff, polluting water bodies and contributing to eutrophication. Nutrient pollution has adverse effects on aquatic ecosystems and human health. High costs and limited availability can hinder their ability to adopt sustainable fertilization practices.

7.2. Opportunities

Sustainable fertilizer use aims to align fertilizer supply with crop demand while minimizing environmental impacts and promoting long-term agricultural productivity. Achieving this balance involves several opportunities and strategies. Precision agriculture technologies, such as remote sensing, global positioning systems (GPS), and variable rate application, allow farmers to apply fertilizers more efficiently and precisely based on crop needs and soil variability. Implementing nutrient management plans tailored to specific field conditions can optimize fertilizer use and minimize nutrient wastage. Site-specific nutrient application involves analyzing soil data and crop requirements at a micro-scale to apply fertilizers precisely where and when they are needed. This approach reduces over-application, mitigates nutrient imbalances, and increases fertilizer use efficiency (Varvel and Wilhelm, 2016).

CONCLUSION

The important role of fertilizers in increasing crop yields and ensuring global food security will likely be highlighted. The increasing demand for fertilizers due to the growing world population and the need to produce more food on limited arable land was discussed. Environmental challenges associated with fertilizer use, such as nutrient pollution, greenhouse gas emissions, and soil degradation were also covered. Improper fertilizer management can lead to nutrient runoff, eutrophication of water bodies, and negative impacts on biodiversity. Various strategies and practices aimed at improving fertilizer use efficiency will be explored. These could include precision agriculture, site-specific nutrient management, balanced fertilization, use of slow-release fertilizers, and the integration of organic and inorganic sources of nutrients. The importance of nutrient cycling in sustainable agriculture and how efficient nutrient management can reduce the need for excessive fertilizer application is our main topic of discussion.

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Conflict of Interest

There is no such evidence of conflict of interest.

Author Contribution

All authors have participated in critically revising the entire manuscript and approval of the final manuscript.

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