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Assessing Grain Yield and Achieving Enhanced Quality in Maize by Next Generation Fertilizer: A Review

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Authors' contributions

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ABSTRACT

It explores the potential of advanced fertilizers in improving maize yield and quality while addressing environmental and socioeconomic concerns. Investigating the innovations in fertilizer technologies and their impact on maize cultivation, identifying research gaps and suggesting policy recommendations. The potential of advanced fertilizers for enhancing maize yield and quality while tackling environmental and socioeconomic issues: Advanced fertilizers, marked by enhanced nutrient use efficiency and targeted nutrient delivery, present valuable prospects for sustainable corn farming. This includes progress in fertilizer technologies, combined management strategies, and the effects of these cutting-edge products on corn yield and quality. Additionally, we explore research gaps, areas requiring further study, and policy suggestions to support the adoption of advanced fertilizers in corn production systems. By seizing these opportunities and addressing the related challenges, the global agricultural community can strive for more sustainable, efficient, and productive corn farming practices that contribute to improved food security and nutrition.

Keywords: Next-generation fertilizers; maize production; grain yield; grain quality; sustainable agriculture.

1. INTRODUCTION

Maize (*Zea mays* L.), also known as corn, is one of the most important cereal crops globally, serving as a staple food for more than one billion people [1]. It is cultivated in various agro-ecological zones across the world, with the United States, China, Brazil, and Mexico being the largest producers [2]. Apart from its significance as a food source for humans, maize is also a crucial feedstock for livestock and an essential raw material in industrial applications, such as biofuel and biodegradable plastics production [3]. Given the increasing global population and changing dietary preferences, there is a growing demand for maize, necessitating the enhancement of its yield and quality [4]. Yield improvements are vital for ensuring food security and minimizing the need for additional agricultural land expansion, which can result in deforestation and loss of biodiversity [5]. Enhancing maize grain quality is equally important, as it directly affects human nutrition and health, livestock productivity, and the value of industrial products derived from maize [6]. Various factors, including climate change, soil degradation, and pests, have been reported to negatively affect maize yield and quality [7,8]. Additionally, the excessive use of conventional fertilizers has led to environmental issues, such as eutrophication, soil and groundwater contamination, and greenhouse gas emissions [9]. Therefore, innovative and sustainable agricultural practices are necessary to address these challenges.

Next-generation fertilizers, also referred to as advanced or controlled-release fertilizers, are a group of innovative products designed to improve nutrient use efficiency and minimize environmental impacts [10]. These fertilizers can be broadly classified into two categories: (1) controlled-release fertilizers, which encapsulate nutrients in polymer coatings or matrix materials to regulate their release over time [11]; and (2) stabilized fertilizers, which incorporate chemical or biological agents that reduce nutrient loss through volatilization, leaching, or other processes [12]. The use of next-generation fertilizers has been demonstrated to increase crop yield and quality by providing plants with a more consistent supply of nutrients, which can enhance photosynthesis, stress tolerance, and other physiological processes [13,14]. Moreover, these fertilizers can help mitigate environmental problems associated with conventional fertilizers by reducing nutrient losses and promoting more efficient nutrient utilization [15,16]. We examine the potential of next-generation fertilizers for assessing grain yield and achieving enhanced quality in maize production. We will discuss the types and mechanisms of next-generation fertilizers, their impact on grain yield and quality, the environmental and socioeconomic implications of their use, and future directions for research and policy. (Table 1) shows a comparative snapshot of agricultural productivity across several countries. Despite having a smaller cultivation area, the United States leads in total production due to its high productivity per hectare, indicating advanced farming techniques and efficient land use. Conversely, China, despite having the largest cultivation area, exhibits less efficiency. Countries like Brazil, Argentina, and India demonstrate varying levels of productivity, influenced by factors like

Table 1. Global area, production, and productivity of maize in major countries, [17]

Country	Area (million hectares)	Production (million tonnes)	Productivity (tonnes/hectare)
United States	33.1	380.1	11.5
China	42.7	262.4	6.1
Brazil	18.3	102.0	5.6
Argentina	6.4	51.0	7.9
India	9.2	29.9	3.2
Mexico	7.5	27.1	3.6
Ukraine	5.5	35.0	6.3
South Africa	2.6	16.8	6.5
Indonesia	3.2	14.3	4.5
Russia	3.5	16.8	4.8
World Total	196.0	1,164.7	5.9

agricultural policies, technology use, and land quality. The overall global productivity stands at 5.9 tonnes per hectare, pointing towards a need for enhanced efficiency worldwide.

2. OVERVIEW OF NEXT GENERATION FERTILIZERS

Next-generation fertilizers, also known as advanced or controlled-release fertilizers, are innovative products designed to enhance nutrient use efficiency while minimizing environmental impacts [10]. These fertilizers can be broadly classified into two categories: (1) controlled-release fertilizers, which encapsulate nutrients in polymer coatings or matrix materials to regulate their release over time [11]; and (2) stabilized fertilizers, which incorporate chemical or biological agents that reduce nutrient loss through volatilization, leaching, or other processes [12]. The data in (Table 2) describes different types of fertilizers and their benefits. Slow-release fertilizers improve nutrient use efficiency by gradually providing nutrients. Biofertilizers, containing live microorganisms, enhance soil fertility and plant growth. Nutrient-use efficiency enhancers facilitate better nutrient absorption by plants, reducing the need for excessive fertilization. Silicon-based fertilizers, containing silicon, boost plant growth and stress tolerance. These fertilizers each provide unique advantages, improving soil health and plant productivity.

2.1 Comparison between Conventional and Next-generation Fertilizers

Conventional fertilizers, such as urea, ammonium nitrate, and diammonium phosphate, are widely used in agriculture to supply essential nutrients to crops. However, these fertilizers often have low nutrient use efficiency, leading to nutrient losses through leaching, volatilization, and runoff, which can cause environmental

Table 2. Types of next-generation fertilizers for maize production [18]

Type of fertilizer	Description	Examples
Slow-release fertilizers	These fertilizers release nutrients slowly over an extended period, reducing nutrient losses and increasing nutrient use efficiency.	Polymer-coated urea, slow-release nitrogen, controlled-release potassium
Biofertilizers	These fertilizers contain living microorganisms that enhance soil fertility and plant growth.	Rhizobia, mycorrhizal fungi, plant-growth-promoting rhizobacteria
Nutrient-use efficiency enhancers	These fertilizers improve the ability of plants to take up and use nutrients more efficiently, thereby reducing the need for higher fertilizer application rates.	Chelated micronutrients, amino acids, plant extracts
Silicon-based fertilizers	These fertilizers contain silicon, which can enhance plant growth and stress tolerance.	Calcium silicate, potassium silicate, sodium silicate

problems [9]. In contrast, next-generation fertilizers are designed to improve nutrient use efficiency by providing a more controlled and targeted release of nutrients. Controlled-release fertilizers can gradually release nutrients over an extended period, synchronizing nutrient availability with plant uptake, which can lead to improved crop growth and reduced nutrient losses [11]. Stabilized fertilizers reduce nutrient losses by using chemical or biological agents to control the transformation and mobility of nutrients in the soil, promoting more efficient nutrient utilization by plants [12]. The comparison highlights in (Table 3) Shows the evolution from conventional to next-generation fertilizers. Traditional fertilizers contain primary nutrients (NPK), are rapidly released leading to nutrient losses, have lower efficiency, and a significant environmental impact. Next-generation fertilizers, while costlier, offer additional nutrients, controlled-release, higher efficiency, and reduced environmental contamination, showcasing improvements in sustainable agriculture.

2.2 Mechanisms of Action in Enhancing Crop Yield and Quality

The improved nutrient use efficiency of next-generation fertilizers has been linked to several mechanisms that can enhance crop yield and quality. For example, a controlled release of nutrients can provide plants with a consistent supply of essential elements, resulting in better photosynthesis, stress tolerance, and overall growth [13,14]. This consistent supply can also reduce the risk of nutrient deficiencies or toxicities that could limit crop development and yield potential.

Moreover, next-generation fertilizers can improve crop quality by modulating plant metabolism and physiological processes. For instance, an adequate supply of nitrogen (N) from controlled-release or stabilized fertilizers can improve protein synthesis and grain protein content, leading to higher nutritional quality [6]. Additionally, a more efficient uptake of nutrients can also promote the accumulation of desirable compounds, such as antioxidants and vitamins, further enhancing the quality of maize grains [14].

3. ASSESSING GRAIN YIELD IN MAIZE

3.1 Traditional Methods of Measuring Grain Yield

3.1.1 Plot-based assessments

Plot-based assessments are the conventional method for measuring grain yield in maize and other crops. This approach involves establishing experimental plots with different treatments, such as varying fertilizer types or application rates. After the growing season, the maize plants are harvested, and the grain yield is measured, typically in terms of weight per unit area (e.g., kilograms per hectare) (Lobell *et al*., 2009). Plot-based assessments provide reliable and accurate yield data, but they can be labor-intensive, time-consuming, and limited in spatial scale.

3.1.2 Remote sensing techniques

Remote sensing techniques have been increasingly used in agriculture to assess crop growth and yield. These techniques involve the use of satellite or aerial imagery to capture information on various crop attributes, such as vegetation cover, biomass, and spectral reflectance, which can be used to estimate grain yield [19]. Remote sensing offers several advantages over plot-based assessments,

Table 3. Comparison between conventional and next-generation fertilizers [18]

Parameter	Conventional fertilizers	Next-generation fertilizers
Nutrient content	Typically, only NPK	Can include additional micronutrients and/or beneficial compounds
Release rate	Rapid release, leading to leaching and volatilization losses	Slow and/or controlled-release, reducing nutrient losses
Efficiency	Lower nutrient use efficiency, requiring higher application rates	Higher nutrient use efficiency, requiring lower application rates
Environmental impact	High potential for leaching, volatilization, and eutrophication	Lower potential for environmental contamination
Cost	Generally lower cost per unit of nutrient	Higher cost per unit of nutrient

including the ability to cover large areas and monitor crop growth throughout the season. However, the accuracy of remote sensing-based yield estimates can be affected by factors such as atmospheric conditions, sensor characteristics, and data processing algorithms [20].

3.2 Innovations in Yield Assessment

3.2.1 Precision agriculture technologies

Precision agriculture technologies have emerged as a promising approach to improve the assessment and management of crop yield. These technologies include global positioning systems (GPS), geographic information systems (GIS), variable rate technology (VRT), and unmanned aerial vehicles (UAVs) [21]. Precision agriculture allows for the collection of high-resolution data on crop growth, soil properties, and environmental factors at a fine spatial scale, enabling the development of site-specific management practices that can enhance grain yield and resource use efficiency [22]. For example, yield monitors mounted on combine harvesters can provide real-time, georeferenced yield data, which can be used to create yield maps and identify areas of low or high productivity within a field [23]. This information can then be used to guide targeted applications of next-generation fertilizers and other inputs, optimizing their effectiveness in enhancing maize grain yield.

3.2.2 Integration of data-driven techniques

The growing availability of large and diverse datasets in agriculture has led to the development of data-driven techniques for yield assessment and management. These techniques involve the use of advanced statistical and machine learning methods to analyze data from various sources, such as field measurements, remote sensing, and weather records, and generate insights into the factors affecting crop yield [24]. Data-driven techniques can help improve the accuracy of yield estimates and identify the optimal management practices for maximizing grain yield under different conditions. For example, Zhang et al. [25] used a combination of remote sensing, weather data, and machine learning algorithms to develop a yield prediction model for maize that accounted for the effects of next-generation fertilizers and other management factors. The model provided accurate yield predictions and enabled the identification of the most effective fertilizer strategies for different maize-growing regions.

3.3 Impact of Next-generation Fertilizers on Grain Yield

3.3.1 Case studies and experimental evidence

Several studies have investigated the impact of next-generation fertilizers on maize grain yield under various agro-ecological conditions. For example, Chen et al. [13] conducted a field experiment in the Huang-Huai-Hai Plain of China and found that the use of coated urea, a controlled-release fertilizer, resulted in a 9.3% increase in maize grain yield compared to conventional urea. The coated urea also improved nitrogen use efficiency by 17 .8% and reduced soil nitrate accumulation, suggesting potential benefits for both productivity and environmental sustainability. In another study, Giro et al. [14] evaluated the effects of winter cover crops and nitrogen fertilization on maize yield in a long-term no-till system in Brazil. They found that the use of polymer-coated urea, combined with cover crops, increased maize grain yield by up to 20% compared to conventional urea. The improved yield was attributed to better synchronization of nitrogen release with crop demand and reduced nitrogen losses from the soil. These studies and others [11,12] provide evidence that next-generation fertilizers can enhance maize grain yield under various conditions, likely due to their ability to improve nutrient use efficiency and match nutrient availability with crop requirements. However, the magnitude of the yield response to next-generation fertilizers can be influenced by several factors, such as soil properties, climate, and management practices.

3.3.2 Factors influencing the effectiveness of next-generation fertilizers on yield

The impact of next-generation fertilizers on maize grain yield can be influenced by various factors, including soil properties, climatic conditions, and crop management practices. Soil properties, such as texture, organic matter content, and pH, can affect the release of nutrients from controlled-release fertilizers and the efficacy of stabilized fertilizers in reducing nutrient losses [15]. For example, soils with high clay content or low pH may slow down the release of nutrients from polymer-coated fertilizers, potentially limiting their effectiveness in enhancing yield [13]. Climatic conditions, such as temperature and precipitation, can also influence the performance of next-generation fertilizers. High temperatures can accelerate the release of nutrients from controlled-release fertilizers, while excessive rainfall can increase the risk of nutrient losses through leaching or runoff, potentially reducing the yield benefits of these fertilizers [11].

Crop management practices, such as tillage, crop rotation, and irrigation, can interact with next-generation fertilizers to affect maize grain yield. For example, no-till systems can help maintain soil moisture and nutrient availability, potentially enhancing the effectiveness of controlled-release or stabilized fertilizers in improving yield [14]. Similarly, the use of cover crops or intercropping can improve soil fertility and nutrient cycling, complementing the benefits of next-generation fertilizers for yield enhancement [12].

4. ENHANCING MAIZE GRAIN QUALITY

4.1 Factors Affecting Grain Quality

4.1.1 Genetic factors

Grain quality in maize is influenced by several genetic factors, including kernel size, shape, and composition, as well as the presence of desirable or undesirable traits, such as high protein content or low levels of anti-nutritional factors [6]. Breeding programs have developed various maize cultivars with improved grain quality characteristics, such as quality protein maize (QPM), which has higher levels of essential amino acids, particularly lysine and tryptophan, compared to conventional maize [26]. Advances in genomics and molecular breeding techniques are further enhancing the potential to develop maize cultivars with superior grain quality traits [27].

4.1.2 Environmental factors

Environmental factors, such as temperature, precipitation, and solar radiation, can also affect maize grain quality by influencing crop growth, development, and physiological processes [28]. For example, high temperatures during grain filling can reduce kernel size and weight, while drought stress can reduce starch accumulation and increase protein concentration in the grain [29]. These environmental factors can interact with genetic factors and agronomic practices to determine the final grain quality attributes of maize.

4.1.3 Agronomic practices

Agronomic practices, such as fertilizer management, irrigation, and pest control, can also influence maize grain quality by affecting the availability of nutrients and other resources for crop growth and development [30]. Adequate and balanced fertilization is essential for ensuring optimal grain quality, as nutrient deficiencies or imbalances can lead to reduced kernel size, altered nutrient composition, or increased susceptibility to pests and diseases [31]. Next-generation fertilizers have the potential to improve grain quality by enhancing nutrient availability and uptake, as well as modulating plant metabolism and physiological processes related to grain development.

4.2 Role of Next-generation Fertilizers in Improving Grain Quality

4.2.1 Improved nutrient availability and uptake

Next-generation fertilizers can improve grain quality in maize by ensuring a consistent and targeted supply of essential nutrients, such as nitrogen, phosphorus, and potassium, as well as micronutrients, such as zinc and iron [10]. By improving nutrient use efficiency and reducing nutrient losses, these fertilizers can enhance the availability and uptake of nutrients by maize plants, leading to increased kernel size, weight, and nutrient content [12]. For example, controlled-release fertilizers can release nutrients in a gradual and controlled manner, synchronizing nutrient release with crop demand and reducing the risk of nutrient deficiencies or imbalances during critical stages of grain development [11].

4.2.2 Modulation of plant metabolism and physiological processes

Next-generation fertilizers can also affect maize grain quality by modulating plant metabolism and physiological processes related to grain development, such as photosynthesis, assimilate partitioning, and storage product synthesis [31]. For example, some nitrification inhibitors and urease inhibitors, which are used in stabilized fertilizers, can influence the forms and concentrations of nitrogen in the soil and plant tissues, potentially affecting nitrogen metabolism and the synthesis of proteins and other nitrogen-containing compounds in the grain [32]. Similarly, some controlled-release

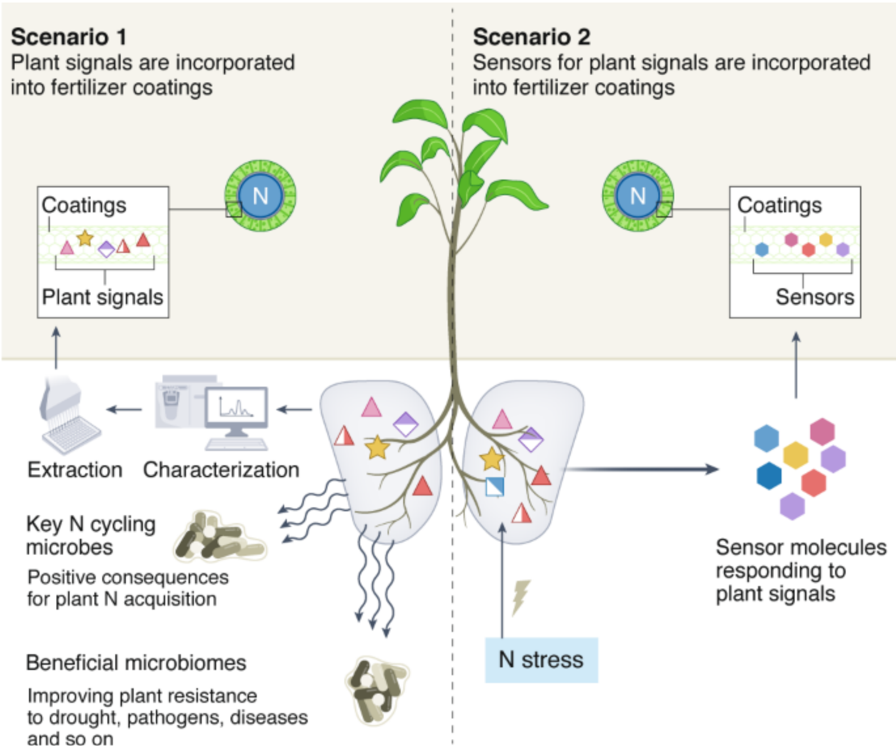

Fig. 1. Next-generation enhanced-efficiency fertilizers for sustained food security

fertilizers and micronutrient fertilizers can affect the uptake and metabolism of other nutrients, such as phosphorus and potassium, which can influence grain composition and quality [12].

4.3 Case Studies and Experimental Evidence on Grain Quality Enhancement

Several studies have investigated the effects of next-generation fertilizers on maize grain quality, providing evidence for their potential benefits in improving various quality attributes, such as kernel size, weight, and nutrient composition. In a study by Li et al. [11], the application of controlled-release urea in paddy fields in southern China increased maize kernel weight by 5.2% compared to conventional urea, while also improving nitrogen use efficiency. The researchers attributed the enhanced kernel weight to the improved availability and uptake of nitrogen by maize plants, as well as the synchronization of nitrogen release with crop demand during the critical stages of grain development. Another study by Wang et al. [12] evaluated the effects of a polymer-coated compound fertilizer containing nitrogen, phosphorus, potassium, and zinc on maize grain yield and quality in northern China. The results showed that the coated fertilizer increased kernel size and weight by 8.1% and 7.6%, respectively, compared to a non-coated fertilizer. Moreover, the coated fertilizer improved the concentrations of nitrogen, phosphorus, potassium, and zinc in the grain, indicating enhanced nutrient uptake and assimilation by maize plants. Similarly, Zhang et al. [10] reported that the application of a controlled-release micronutrient fertilizer containing zinc, manganese, and boron improved maize grain quality in terms of kernel size, weight, and nutrient composition. The controlled-release fertilizer increased kernel size and weight by 7.4% and 6.9%, respectively, and increased the concentrations of zinc, manganese, and boron in the grain by 12.6%, 8.7%, and 11.3%, respectively, compared to a conventional micronutrient fertilizer. These studies and others [30,31] demonstrate the potential of next-generation fertilizers to enhance maize grain quality by improving nutrient availability and uptake, as well as modulating plant metabolism and physiological processes related to grain development. However, the magnitude of the grain quality response to next-generation fertilizers can be influenced by various factors, such as soil properties, climate, and management practices, as well as the specific formulations and application rates of the fertilizers.

5. ENVIRONMENTAL AND SOCIO-ECONOMIC IMPLICATIONS

5.1 Environmental Benefits of Next-generation Fertilizers

5.1.1 Reduced nutrient runoff and leaching

Next-generation fertilizers have the potential to reduce nutrient runoff and leaching, which are major environmental concerns associated with conventional fertilizer use [33]. Nutrient runoff and leaching can lead to water pollution, eutrophication, and the degradation of aquatic ecosystems [34]. By improving nutrient use efficiency and providing a more targeted supply of nutrients, next-generation fertilizers can minimize the loss of nutrients to the environment and reduce the risk of water pollution [10]. For example, controlled-release fertilizers can release nutrients in a gradual and controlled manner, synchronizing nutrient release with crop demand and reducing the risk of nutrient losses through runoff and leaching [11].

5.1.2 Lower greenhouse gas emissions

Next-generation fertilizers can also contribute to lower greenhouse gas emissions from agricultural systems, mainly by reducing the emissions of nitrous oxide (N_2O) from the soil [35]. Nitrous oxide is a potent greenhouse gas with a global warming potential 298 times that of carbon dioxide (CO_2) over a 100-year time horizon [36]. Agricultural activities, particularly nitrogen fertilization, are major sources of N2O emissions [37]. Next-generation fertilizers, such as stabilized fertilizers containing nitrification inhibitors or urease inhibitors, can reduce N_2O emissions by slowing down the conversion of nitrogen to nitrate (NO_3^-) and nitrite (NO_2^-) in the soil, thus reducing the substrate availability for denitrification [32]

5.2 Socioeconomic Benefits

5.2.1 Increased farmer income

The use of next-generation fertilizers can lead to increased farmer income by improving crop yields and quality, and reducing input costs associated with fertilizer application [12]. Higher crop yields can translate into higher revenues for farmers, while improved grain quality can fetch better market prices, further boosting income. Moreover, the enhanced nutrient use efficiency of next-generation fertilizers can reduce the need for additional fertilizer applications, lowering input costs and increasing the overall profitability of crop production [10].

5.2.2 Improved food security and nutrition

The improved yield and quality of maize grain achieved through the use of next-generation fertilizers can have significant implications for food security and nutrition, particularly in regions where maize is a staple crop [6]. Higher maize yields can help meet the growing demand for food, feed, and industrial products, while better grain quality, in terms of nutrient content and digestibility, can contribute to improved human and animal nutrition [26]. For example, quality protein maize (QPM) cultivars, which have higher levels of essential amino acids, particularly lysine and tryptophan, compared to conventional maize, can help address protein malnutrition in vulnerable populations [27].

5.3 Challenges and Potential Drawbacks

5.3.1 High initial costs

One of the main challenges associated with the adoption of next-generation fertilizers is their higher initial cost compared to conventional fertilizers [15]. The development and production of these advanced fertilizers often involve complex manufacturing processes and advanced materials, which can drive up the cost of the product. High initial costs may deter farmers, particularly small-scale farmers with limited resources, from adopting next-generation fertilizers, even if they offer long-term economic and environmental benefits.

5.3.2 Limited accessibility for small-scale farmers

Accessibility to next-generation fertilizers can be a challenge, particularly for small-scale farmers in developing countries, who often have limited access to agricultural inputs, credit, and extension services [6]. Limited availability and distribution networks, combined with the high initial costs, can make it difficult for these farmers to access and adopt next-generation fertilizers. To address this issue, public and private sector efforts are needed to develop and promote innovative financing mechanisms, distribution channels, and extension services that can facilitate the widespread adoption of next-generation fertilizers among small-scale farmers [12].

5.3.3 Potential regulatory issues

The introduction and adoption of next-generation fertilizers may also face regulatory hurdles, particularly in countries with stringent regulations on the registration, production, and use of agricultural inputs [38]. The development and commercialization of next-generation fertilizers often involve novel materials and technologies, which may require additional safety assessments and regulatory approvals. To facilitate the approval and adoption of next-generation fertilizers, policymakers and regulatory agencies need to develop clear guidelines and frameworks that can assess the safety, efficacy, and environmental impacts of these products, while balancing the need for innovation and sustainable agricultural development [38].

6. FUTURE DIRECTIONS AND RECOMMENDATIONS

6.1 Advancements in Next-generation Fertilizer Technologies

As the global population continues to grow and the demand for food increases, there is a pressing need for more sustainable and efficient agricultural practices. Advancements in next-generation fertilizer technologies are crucial to addressing this need. Researchers and industry stakeholders should continue to innovate and develop novel fertilizer formulations that can further improve nutrient use efficiency, reduce environmental impacts, and cater to the specific needs of different crops and agroecological conditions [12]. For example, exploring the use of nanotechnology in the development of fertilizers with improved nutrient delivery systems and novel materials that can enhance nutrient availability and uptake by plants [39]. Additionally, advancements in biotechnology can lead to the development of microbial-based fertilizers that can improve plant nutrient uptake and promote growth through symbiotic relationships with the plant roots [40].

6.2 Integrated Management Approaches for Optimized Maize Production

To maximize the benefits of next-generation fertilizers in maize production, it is essential to adopt integrated management approaches that consider the interactions between various agronomic practices, such as crop rotation, tillage, pest and disease management, and irrigation [41]. Integrated management approaches can help optimize the use of next-generation fertilizers, ensuring that their potential benefits are realized in the context of broader agricultural systems. For instance, precision agriculture technologies, such as variable rate application and remote sensing, can be combined with next-generation fertilizers to deliver the right amount of nutrients at the right time and place, further enhancing nutrient use efficiency and reducing environmental impacts [31].

6.3 Research Gaps and Areas for Further Investigation

While the potential benefits of next-generation fertilizers have been demonstrated in various studies, there are still several research gaps and areas that warrant further investigation. Long-term field trials are needed to better understand the agronomic, environmental, and socioeconomic impacts of next-generation fertilizers under different climatic and soil conditions [30]. Additionally, more research is needed to explore the interactions between next-generation fertilizers and other agronomic practices, such as tillage and crop rotation, to develop integrated management recommendations that can optimize maize production. Furthermore, interdisciplinary research that combines agronomy, environmental science, economics, and social sciences can provide valuable insights into the trade-offs and synergies associated with the adoption of next-generation fertilizers and help inform policy and decision-making processes.

6.4 Policy Recommendations for Promoting Next-generation Fertilizers

To promote the widespread adoption of next-generation fertilizers and their integration into sustainable agricultural systems, policymakers and stakeholders should consider the following recommendations:

1. Develop and implement incentive schemes that encourage farmers to adopt next-generation fertilizers, such as subsidies, tax breaks, or low-interest loans, to offset the high initial costs associated with these advanced products [12].
2. Invest in agricultural research and extension services to develop and

disseminate knowledge on the benefits, best practices, and appropriate use of next-generation fertilizers, particularly for small-scale farmers who may have limited access to information and resources [6].

3. Encourage public-private partnerships and collaborations between researchers, industry stakeholders, and policymakers to accelerate the development and commercialization of next-generation fertilizers, while ensuring that regulatory frameworks adequately address safety, efficacy, and environmental concerns [38].
4. Promote the adoption of integrated management approaches, such as precision agriculture and sustainable farming practices, that can optimize the use of next-generation fertilizers and contribute to more efficient and environmentally friendly maize production systems [41,42].

7. CONCLUSION

Next-generation fertilizers hold great promise for enhancing grain yield and quality in maize production while addressing environmental and socioeconomic challenges. By leveraging advancements in fertilizer technologies, adopting integrated management approaches, and addressing research gaps and policy needs, the agricultural community can work towards more sustainable, efficient, and productive maize cultivation practices. This shift will contribute to improved food security, nutrition, and overall global well-being.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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