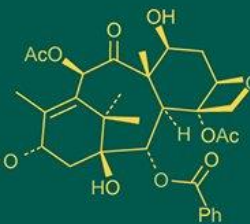
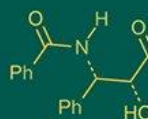


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Emerging trends and future perspectives of slow-release fertilizers for sustainable maize production

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Abstract

Maize (*Zea mays* L.) is one of the world's most important cereal crops and requires substantial nutrient inputs, particularly nitrogen, to achieve high productivity. However, conventional fertilizers often exhibit low nutrient-use efficiency because of losses through leaching, volatilization, runoff, and denitrification, resulting in economic losses and environmental degradation. Slow-release fertilizers (SRFs) have become a powerful tool for synchronising nutrient release with crop demand, thereby increasing fertiliser use efficiency and minimising nutrient loss. This review covers recent developments in slow-release fertilizer technologies for maize production including neem-coated urea, sulphur-coated urea, polymer-coated fertilizers, nano This paper discusses the impact of these factors on maize growth, physiology, yield attributes, soil fertility and nutrient recovery. It also talks about the environmental benefits of SRFs, including reduced nitrate leaching, lower GHG emissions and improved soil health, which support climate-resilient sustainable agriculture. Also, the economic benefits of less frequent fertiliser application, lower labour requirements, and increased profitability were considered. Although these benefits have been realized, widespread adoption is hindered by high initial costs, limited farmer awareness, variable nutrient release under different environmental conditions and the need for long-term evaluation of biodegradable coating materials. Future research should focus on cost-effective, environmentally safe formulations and integration of SRFs with precision-nutrient-management technologies. In summary, overall, slow-release fertilizers are a promising strategy to improve maize productivity while also optimizing resource use and sustainability.

Keywords: Maize, slow-release fertilizers, nitrogen use efficiency, coated urea, nano fertilizers, nutrient management, sustainable agriculture, greenhouse gas emissions

Introduction

During 2023-24, India produced 37.66 million tonnes of maize and Bihar accounted for almost 5.71 million tonnes, becoming one of the country's top maize-producing states (Minister of Agriculture & Farmers Welfare, For 2024-25 crop year, national maize production is expected to rise to 42.28 million tonnes with Bihar likely to produce about 4.90 million tonnes due to the increasing demand from the ethanol and livestock feed industries (Ministry of Agriculture & Farmers Welfare, 2024) ^[12]. Because of its high yield, versatility and many uses, maize has been called the Queen of Cereals. It is a crop of human consumption, animal feed, fodder, and a raw material for starch, edible oil, ethanol, and agro-industries (ICAR-Indian Institute of Maize Research, 2024) ^[5].

Nitrogen is the most important nutrient for maize growth and development, involved in chlorophyll synthesis, photosynthesis, protein synthesis, enzyme activation, and biomass production (Razaq *et al.*, 2017) ^[16]. The crop's high nitrogen requirements are met mainly by the application of conventional nitrogen fertilizers such as urea. However, these fertilizers have relatively low nitrogen use efficiency (NUE) since a large amount of the applied nitrogen is leached, volatilized, runoff, and denitrified (Zhang *et al.*, 2015) ^[25]. These nutrient losses not only decrease fertilizer effectiveness and increase production costs, but also contribute to environmental issues such as nitrate contamination of groundwater, eutrophication, and greenhouse gas emissions (Synder, 2017) ^[20]. In response to these challenges, slow-release fertilizers (SRFs) have become an innovative nutrient-management strategy. By providing nutrients in sync with crop nutrient demand, SRFs increase nitrogen use efficiency, minimize environmental loss, and provide a sustained nutrient supply, thereby improving crop productivity and sustainable maize production (Trenkel, 2010; Guo *et al.*, 2021) ^[3, 21].

2. Concept of Slow-Release Fertilizers

Slow-release fertilizers (SRFs) are advanced nutrient formulations designed to supply essential plant nutrients gradually over an extended period, thereby synchronizing nutrient availability with crop demand and improving nutrient-use efficiency (Shaviv, 2005) ^[17]. Unlike conventional fertilizers, which dissolve rapidly after soil application, they are not susceptible to substantial nutrient losses through leaching, runoff, volatilization, and denitrification. SRFs regulate nutrient release and minimize losses, resulting in improved fertilizer efficiency and reduced environmental impact (Mikkelsen, 2018) ^[11].

The controlled release of nutrients is achieved through various technologies, including sulphur coating, polymer coating, neem coating, encapsulation, nanotechnology-based formulations, and biodegradable organic coatings. These materials form a protective barrier around fertilizer granules, thereby delaying nutrient dissolution and ensuring their gradual release into the soil (Azeem *et al.*, 2014; Duhan *et al.*, 2017) ^[1, 2]. In addition to coated fertilizers, certain chemical additives and encapsulation techniques have been employed to further regulate nutrient availability and prolong fertilizer effectiveness.

The rate of nutrient release from SRFs is governed by several environmental and physicochemical factors, including soil moisture, temperature, pH, microbial activity, coating composition, and coating thickness (Azeem *et al.*, 2014) ^[1]. Nutrients are subsequently released into the soil through mechanisms such as diffusion, osmotic pressure, gradual degradation of the coating material, and microbial decomposition (Shaviv, 2005) ^[17]. Consequently, nutrients remain available throughout the critical growth stages of the crop, ensuring a sustained supply that closely matches the plant nutrient requirements.

Nitrogen is an ideal material for controlled release technologies because it is highly prone to environmental loss. By controlling nitrogen supply according to crop demand, SRFs improve NUE, reduce nutrient loss, and ensure a nitrogen supply for the entire growing season (Iqbal *et al.*, 2020) ^[6]. This sustained nutrient supply enhances nutrient uptake, crop growth and productivity, and sustainable maize production.

3. Types of Slow-Release Fertilizers

Slow-release fertilizers are available in several formulations designed to regulate nutrient release, improve nutrient-use efficiency, and minimize environmental losses. The major types of slow-release fertilizers used in maize production are described below:

3.1 Nano-fertilizers: Nano-fertilizers are nanotechnology-based nutrient formulations in which nutrients are delivered as nanoparticles or nano-sized carriers with a high surface area-to-volume ratio. Their small size allows efficient nutrient absorption through plant roots and foliage, while controlled release of nutrients improves nitrogen use efficiency, nutrient uptake and crop productivity. Nano-fertilizers have shown great promise in enhancing maize growth, reducing fertilizer losses and pollution (Duhan *et al.*, 2017; Wang *et al.*, 2023) ^[2, 23].

3.2 Neem-Coated Urea: Neem-coated urea is produced by coating urea granules with neem oil or neem-derived bioactive compounds. These compounds suppress the

activity of nitrifying microorganisms, thereby slowing the conversion of ammonium (NH_4^+) to nitrate (NO_3^-). This process reduces nitrogen losses through leaching, denitrification, and volatilization, resulting in enhanced nitrogen availability, improved nutrient use efficiency, and increased maize productivity (Prasad, 2005; Prasad & Shivay, 2021) ^[14, 15].

3.3 Sulphur-Coated Urea: Sulphur-coated urea consists of urea granules encapsulated with a layer of elemental sulphur that regulates the dissolution of urea in the soil. The gradual breakdown of the sulphur coating ensures a sustained release of nitrogen while simultaneously supplying sulphur, an essential secondary nutrient required for protein synthesis and enzyme activity. This dual nutrient supply improves fertilizer efficiency, supports balanced plant nutrition, and enhances maize growth and yields (Azeem *et al.*, 2014) ^[1].

3.4 Polymer-Coated Fertilizers: Polymer-coated fertilizers are made by wrapping fertilizer granules in semi-permeable polymer membranes that control nutrient release according to soil. These coatings allow a controlled and predictable nutrient supply throughout the crop growth period, reducing nutrient loss, improving fertilizer recovery efficiency, and enhancing crop performance in intensive agricultural production system (Guo *et al.*, 2021; Zhao *et al.*, 2021) ^[3, 26].

3.5 Biobased Slow-Release Fertilizers: Biobased slow-release fertilizers are made by mixing plant nutrients with environmentally friendly materials including biochar, compost, biodegradable polymers, and other natural organic materials. Nutrient release is slowly provided by microbial degradation of carrier materials, providing a sustained nutrient supply, improving soil organic matter, stimulating beneficial microbes, and improving soil health. These eco-friendly fertilizers are a promising strategy for sustainable nutrient management in today's maize production (Kalita *et al.*, 2024) ^[7].

4. Importance of Slow-Release Fertilizers in Maize Production

Maize is a very nutrient-intensive crop that requires large amounts of nutrients (especially nitrogen) to support optimal vegetative growth, biomass production and grain yield (ICAR-IIMR, 2024) ^[5]. Adequate nitrogen availability is critical for chlorophyll synthesis, photosynthetic activity, protein synthesis, and plant development. Slow-release fertilizers (SRFs) provide a synchronized supply of nitrogen during vegetative and reproductive stages, leading to increased photosynthesis, leaf area, root development, and biomass (Nazir *et al.*, 2022) ^[13]. One of the benefits of SRFs is their ability to enhance NUE by synchronizing nutrient release with crop physiology. This controlled nutrient release reduces nitrogen losses through leaching, volatilization, runoff and denitrification, improving fertilizer use, reducing applications and maize productivity (Iqbal *et al.*, 2020) ^[6]. Additionally, the long-term supply of nutrients during flowering and grain filling stages results in better cob development, filling, kernel weight and yield. In addition to increasing crop productivity, SRFs also contribute to soil fertility and biological activities. Their gradual nutrient release benefits beneficial soil microorganisms, enhances nutrient cycling, and reduces nutrient depletion, especially in sandy soils and areas with high rainfall (Shoji *et al.*,

2001; Liu *et al.*, 2021) ^[10, 18]. Furthermore, prolonged nutrient availability eliminates the need for frequent split-fertiliser applications, thereby reducing the need for additional Labour, minimising operational costs, and improving the returns. These agronomic, environmental, and economic benefits make slow-release fertilizers an important sustainable nutrient management option for modern maize production systems (Trenkel, 2010) ^[21].

5. Impact of Slow-Release Fertilizers on Growth Parameters of Maize

Slow-release fertilizers (SRFs) positively influence the growth and physiological performance of maize by ensuring a continuous and balanced supply of nutrients throughout the crop growth cycle. The sustained availability of nitrogen enhances several metabolic and physiological processes, including chlorophyll synthesis, protein formation, enzyme activation, and photosynthesis, which collectively promote vigorous vegetative growth and improved plant development (Nazir *et al.*, 2022) ^[13].

One of the most prominent effects of SRFs is the enhancement of plant height. The continuous supply of nitrogen promotes cell division and cell elongation, leading to increased vegetative growth and significantly taller plants than those treated with conventional urea fertilizers (Razaq *et al.*, 2017) ^[16]. Similarly, SRFs also lead to increased leaf expansion, resulting in larger leaf area and leaf area index (LAI). An expanded photosynthetic surface increases light interception and carbon assimilation, resulting in improved crop growth and biomass production (Iqbal *et al.*, 2020) ^[6].

Nitrogen is a key component of chlorophyll molecules, so SRFs that provide a constant supply of nitrogen allow for higher chlorophyll levels and delay leaf senescence. The prolonged retention of the green leaf area enhances photosynthetic efficiency during the later stages of crop growth, contributing to increased carbohydrate production and improved crop productivity (Nazir *et al.*, 2022) ^[13].

Furthermore, the gradual release of nutrients promotes extensive root growth and development, resulting in a more efficient root system capable of exploring larger soil volumes for water and nutrient acquisition. Improved root architecture enhances nutrient uptake efficiency, increases drought tolerance, and supports sustained plant growth under varying environmental conditions (Razaq *et al.*, 2017) ^[16].

Overall, the balanced and synchronized nutrient supply provided by slow-release fertilizers improves vegetative growth, physiological efficiency, and root development, thereby establishing a strong foundation for enhanced yield and sustainable maize production in the long term.

6. Impact of Slow-Release Fertilizers on Maize Yield and Yield Characteristics

Slow-release fertilizers (SRFs) have been widely reported to enhance maize yield and yield-contributing characteristics by ensuring a continuous and synchronized supply of nutrients during the critical reproductive stages of crop growth. Adequate nutrient availability during the flowering, silking, and grain-filling stages promotes efficient photosynthesis, improves assimilate production, and facilitates the effective translocation of photoassimilates from source tissues to developing kernels, thereby reducing nutrient stress and enhancing grain development (Iqbal *et al.*, 2020) ^[6].

The sustained release of nutrients through SRFs significantly improves important yield attributes, including cob length, cob girth, number of grains per cob, grain filling, 1000-grain weight (test weight), and kernel quality. Continuous nitrogen supply throughout reproduction enhances kernel development, weight, and grain quality over conventional fertilizer (Zhao *et al.*, 2021; Nazir *et al.*, 2022) ^[13, 26].

Numerous field studies have shown that the use of SRFs greatly enhances grain yield, biological yield, and harvest index by improving nutrient use efficiency and minimizing nutrient loss by leaching, volatilization, runoff, and denitrification (Li *et al.*, 2020; Li *et al.* 2022) ^[8, 9]. The long availability of nutrients leads to sustained biomass accumulation and prolonged photosynthetic activity, resulting in higher dry matter production and better assimilation of the assimilates towards grain.

The benefits of SRFs are particularly evident in sandy soils and regions receiving high rainfall, where conventional fertilizers are most susceptible to nutrient loss. Under such conditions, the gradual nutrient release from SRFs enhances fertilizer recovery efficiency, maintains adequate nutrient availability throughout the growing season, and ultimately leads to improved crop productivity and profitability (Shoji *et al.*, 2001) ^[18].

7. Environmental Advantages of Slow-Release Fertilizers

Slow-release fertilizers (SRFs) offer several environmental advantages over conventional fertilizers by enhancing nutrient-use efficiency and minimizing nutrient losses to the environment (Synder, 2017) ^[20]. Their gradual and controlled nutrient release closely matches crop nutrient demand, thereby reducing losses through leaching, surface runoff, volatilization, and denitrification. Consequently, SRFs improve fertilizer recovery efficiency while mitigating the adverse environmental impacts associated with the application of conventional fertilizers.

One of the major environmental benefits of SRFs is the reduction in nitrate leaching into groundwater. By maintaining a gradual supply of nitrogen in the root zone, these fertilizers reduce nitrate movement beyond the root profile, particularly in sandy soils and high-rainfall regions, where nutrient leaching is more pronounced (Zhang *et al.*, 2015) ^[25]. In addition, SRFs significantly reduce ammonia volatilization and nitrous oxide (N₂O) emissions by regulating the nitrogen transformation processes in the soil. As nitrous oxide is a potent greenhouse gas, its reduction contributes to climate change mitigation and supports environmentally sustainable agricultural production (Halvorson *et al.*, 2010; Xia *et al.*, 2017) ^[4, 24].

The use of SRFs also minimizes nutrient runoff into rivers, lakes, and other water bodies, thereby reducing the risk of eutrophication and protecting the aquatic ecosystems. Improved nutrient synchronization decreases nutrient wastage, limits environmental pollution, and reduces dependence on excessive fertilizer application (Snyder, 2017) ^[20]. Furthermore, the balanced and continuous nutrient supply provided by SRFs helps maintain soil fertility, preserve soil structure, and promote beneficial microbial activity by preventing nutrient imbalances and soil degradation associated with excessive fertilizer use (Zhang *et al.*, 2015) ^[25].

8. Economic Benefits of Slow-Release Fertilizers

Slow release fertilizers can be economically feasible as it improves fertilizer use efficiency, productivity and reduces production cost. Many field studies have shown that slow-release nitrogen fertilizers can increase maize grain yield by 5-15%, reduce nitrogen losses by 20-30%, and increase farm profitability by better nutrient utilization and enhanced fertilizer recovery efficiency (Li *et al.*, 2020; Zhao *et al.*, 2021) [9, 26].

SRFs offer slow nutrient release in response to crop nutrient demand, minimizing fertilizer waste and optimizing nutrient use efficiency. This reduces the amount of fertilizer required for optimum crop performance. The improved nutrient use efficiency also reduces the input losses and increases the fertilizer investment particularly in intensive maize production systems like Bihar and other major maize growing areas (Shyam *et al.*, 2021) [19].

Initial cost of slow-release fertilizers, especially polymer coated and nano-fertilizers is generally higher than urea. However, the long term economic benefits usually justify the extra cost. Improved nutrient supply for longer periods means less split-fertilizer applications are required, saving on labour and costs. Besides, better crop growth, grain yield and grain quality lead to more returns from farm income (Trenkel, 2010; Shyam *et al.*, 2021) [19, 21].

9. Limitations of Slow-Release Fertilizers

Although they have many agronomic and environmental benefits, the widespread use of slow-release fertilizers (SRFs) is limited by economic, technical and practical reasons. One of the biggest obstacles is their high initial cost. The manufacture of SRFs involves high-tech coating technologies, specialized polymers, and complex processes which make them more costly than urea and other conventional nitrogen fertilizers such as urea (Azeem *et al.*, 2014; Guo *et al.*, 2021) [1, 3]. Therefore, the higher purchase price may discourage adoption by small, resource-poor farmers in developing countries.

Another major constraint is the lack of knowledge on the use of SRFs in the most appropriate doses, timing and application methods for different crops and agroclimatic conditions. Inadequate extension services and limited access to technical information can limit their use, particularly in developing countries (Ministry of Agriculture & Farmers Welfare, 2024) [12].

The effectiveness of SRFs is also affected by environmental variables such as soil temperature, moisture, pH, and microbial activity. Depending on the specific conditions, nutrient release may not be synchronized with crop nutrient requirements leading to either insufficient or excessive nutrient availability at specific growth stages (Shaviv, 2005) [17].

Environmental concerns have been raised regarding the long-term use of polymer-coated fertilizers. Non-biodegradable polymer coatings can accumulate in the soil over time, potentially contributing to soil contamination and microplastic pollution. Therefore, the development of biodegradable coating materials has become an important area of research for improving the environmental sustainability of SRFs (Kalita *et al.*, 2024) [7].

In addition, long-term information on the effects of SRFs on soil fertility, nutrient cycling, soil microbial diversity and ecosystem functioning under different agricultural conditions is still limited. Their successful utilization also

necessitates integration with balanced fertilization, soil testing, and other best nutrient management practices to maximize agronomic benefits and environmental sustainability (Upadhyay *et al.*, 2023) [22].

10. Future Prospects of Slow-Release Fertilizers in Maize Production

Slow-release fertilizers will be a critical factor in developing sustainable, climate-resilient and resource-efficient maize production systems. As global agriculture confronts climate change, soil degradation, rising fertilizer costs, and environmental degradation, there will be a high demand for advanced nutrient management technologies. (Guo *et al.*, 2021) [3].

Recent progresses in fertilizer technology have been towards next generation slow-release fertilizers utilizing nanotechnology, biodegradable bio-based polymers and intelligent coating materials that can control nutrient release based on soil conditions and root exudates. These innovative formulations will enhance nutrient-use efficiency and reduce environmental losses with increased crop productivity (Duhan *et al.*, 2017; Wang *et al.*, 2023) [2, 23].

The integration of SRFs with precision agriculture technologies, including drone-based fertilizer application, Global Positioning System (GPS)-guided nutrient management, remote sensing, Internet of Things (IoT)-enabled sensors, and variable-rate fertilizer application systems, offers significant opportunities for optimizing nutrient delivery according to spatial and temporal crop requirements. Such integrated approaches are expected to enhance fertilizer use efficiency, reduce production costs, and improve environmental sustainability in modern maize production systems (Duhan *et al.*, 2017; Shyam *et al.*, 2021) [2, 19].

Future research should focus on the development of inexpensive and biodegradable coatings, optimization of nutrient release under different soil and climatic conditions, and long-term evaluations of their impact on soil health, microbial diversity, nutrient cycling, and environmental quality. In addition, supportive government policies, financial incentives, extension services, farmer training programs and on-farm demonstrations are required to encourage the large scale adoption of slow release fertilizers by small holder farmers (ICAR-IIMR, 2024) [5].

11. Conclusion

Slow-release fertilizers represent a sustainable and efficient approach to nutrient management in contemporary maize cultivation. By aligning the release of nutrients with the crop's needs, these fertilizers enhance nitrogen utilization, foster improved plant development, boost yield and its components, and minimize nutrient losses when compared to traditional fertilizers. Their use also leads to healthier soil, reduced greenhouse gas emissions, and less environmental pollution, thereby promoting climate-smart and sustainable farming practices. Despite challenges such as higher initial costs, limited farmer awareness, and the necessity for more extensive long-term research, ongoing progress in coating technologies, nanotechnology, and biodegradable formulations is anticipated to enhance their efficiency and cost-effectiveness. The combination of slow-release fertilizers with precision agriculture and balanced nutrient management strategies will further augment their impact. Overall, slow-release fertilizers hold significant

promise for boosting maize productivity while ensuring efficient resource use, environmental conservation, and the enduring sustainability of maize-based agricultural systems.

12. Declaration of AI Use

The authors declare that Artificial Intelligence (AI) associated tools, including Grammarly and ChatGPT, were used extensively to enhance the linguistic quality, grammar, formatting, reference formatting, and overall readability of this review manuscript. These tools were employed solely for editorial assistance and were not used to generate scientific content. All AI-assisted outputs were carefully reviewed, verified, revised, and approved by the authors to ensure their accuracy and appropriateness. The authors assume full responsibility for the accuracy, originality, scientific integrity, and ethical compliance of the manuscript.

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