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Derleme Makalesi / Review

Coated Urea Fertilizers: A Comprehensive Review on Slow-Release Nitrogen Fertilizers

Kemal Yalçın GÜLÜT [1*]
[1] Cukurova University, Department of Soil Science and Plant Nutrition, Faculty of Agriculture, Adana
*Corresponding author: kygulut@cu.edu.tr

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Abstract

This review explores the important findings of recent research on slow-release nitrogen fertilizers (SRNFs) as a response to concerns about unsustainable nitrogen use in agriculture. By analyzing recent scholarly literature, the paper investigates how SRNFs, which utilize coatings to deliver nutrients gradually, can improve nutrient utilization efficiency and minimize environmental impact compared to conventional fertilizers. The review examines various coating materials, including inorganic minerals, synthetic polymers, and biodegradable polymers, highlighting the advantages and limitations of each. Biodegradable polymers emerge as a promising and sustainable alternative due to their eco-friendly nature. The analysis reveals that SRNFs can enhance plant growth, optimize nutrient use efficiency, and reduce environmental pollution from fertilizers. However, challenges remain in precisely controlling nutrient release rates and aligning them with plant growth stages. This review underscores the potential of SRNFs as a sustainable solution for nitrogen management in agriculture, while acknowledging areas for further research.

Keywords: Slow-release nitrogen fertilizer, nutrient utilization efficiency, biodegradable polymers

1. Introduction

The increasing global population, which is expected to be 9.7 billion in 2050, necessitates increased food and fiber production, leading to a more intensive use of inputs like fertilizers, water, and pesticides to support this demand. Nitrogen stands as the most crucial element and primary input for ensuring crop health, fostering proper growth, development, and production. Often it is required in larger quantities than all other mineral elements combined, highlighting its essential role in various physiological processes within plants (Islam et al., 2019; Kharazmi and Tan, 2021; Lawrencia et al., 2021). In 1970, the global consumption of nitrogen in agriculture was 32 million tons, which increased to 100 million tons in 2010 and further reached 195 million tons in 2021. Nitrogen fertilizers account for approximately 56 % of global fertilizer consumption, followed by phosphate and potash fertilizers with 24 % and 20 % shares, respectively (Statista, 2024). However, excessive N application in agricultural lands led to reduced nitrogen use efficiency by plants, deterioration of surface and groundwater quality, and significant greenhouse gas emissions from agricultural soils (Vitousek et al., 2009).

Urea, an artificial fertilizer, boasts the widest global usage due to its unparalleled nitrogen content (46 %), surpassing all other solid nitrogenous fertilizers. Additionally, it exhibits the highest water solubility among them. Owing to its rich nitrogen composition, urea delivers a greater quantity of nitrogen to both plants and soil compared to alternative nitrogenous fertilizers (Beig et al., 2020). Significant losses of conventional urea fertilizer occur through leaching, decomposition, and ammonia volatilization, with estimates ranging from 20 % to 70 % ending up in soil, water, or the atmosphere. This not only pollutes the environment but also reduces fertilizer effectiveness and increases toxicity levels, harming plant growth and food safety (Naz and Sulaiman, 2016; Duan et al., 2023). Therefore, improving urea utilization is crucial to maximize crop yields while minimizing the adverse environmental impact (Gülüt and Şentürk, 2024). Recognizing the potential of slow-release fertilizers (SRFs) to address unsustainable nitrogen use, researchers are actively developing slow-release nitrogen fertilizer (SRNF) production technologies (Ni et al., 2011; Zhao et al., 2020; Jiang et al., 2024). Polymer-based controlled-release fertilizers offer a multifaceted green solution. By controlling the release rate of nitrogen, this technology optimizes nutrient uptake by plants, minimizing nitrogen loss through volatilization and leaching (Remya et al., 2021).

Researchers and fertilizer manufacturers have become increasingly concerned about the unsustainable use of nitrogen, particularly its impact on natural resources. In an effort to address these issues, they have been developing environmentally friendly nitrogen fertilizers, including SRNFs. By reducing the solubility rate, SRFs provide nutrients to plants at a slower rate, thereby extending the period of availability. SRFs offer several advantages, including improved crop nutrition due to a consistent nutrient supply, reduced labor costs from fewer fertilizer applications, and minimized environmental impact due to reduced nutrient leaching. Improving nutrient utilization and limiting nutrient loss can lead to a decrease in fertilizer application rates by 20 to 30 percent, while maintaining the same yield (Gil-Ortiz et al., 2020).

Despite the numerous advantages of SRFs, they also have specific drawbacks that impede their widespread use. The SRFs, while designed to deliver nutrients gradually, exhibit limitations in precisely controlling the release rate, pattern, and duration. These limitations stem from external factors that significantly influence nutrient release. These factors include handling conditions, such as storage, transportation, and field application, as well as soil characteristics like moisture content and biological activity (Rajan et al., 2021). One significant limitation of SRFs is the testing difficulties. There is no consistent, standardized method to assess the rate at which nutrients are released from SRF products. Moreover, laboratory findings frequently do not accurately represent the performance of SRFs in practical scenarios, complicating the decision-making process for consumers (Trenkel, 2010). SRFs have a notable drawback in terms of environmental issues, which is the second most significant limitation. Certain SRFs, such as sulfur-coated urea, can result in a considerable increase in soil acidity. Moreover, SRFs that depend on synthetic polymer coatings may exhibit slow degradation, thereby posing potential risks of pollution. Enhancing nutrient utilization efficiency is a significant advantage of utilizing SRFs; however, the ongoing nutrient release from SRFs post-harvest results in a phenomenon known as tailing, leading to nutrient wastage. This may result in inefficiencies and pose potential environmental risks (Shaviv, 2010). The use of SRFs in agriculture is currently limited due to their higher production costs compared to conventional fertilizers. Therefore, while SRFs offer many advantages, their limitations must be carefully considered and managed to ensure their sustainable and effective use in agriculture and practices. This review explores the principles, types, benefits, and potential drawbacks of slow-release nitrogen fertilizers (SRNFs).

2. General characteristics of coated slow-release fertilizers

The concept of SRFs lies in their ability to gradually release nutrients over time, mimicking the natural nutrient cycling processes in the soil. This controlled release is achieved through various mechanisms, including, coating, impregnation and chemical modification. One technique for producing SRFs involves encapsulating granular fertilizers within a coating of material, with low water solubility or insolubility and is typically a polymeric membrane. This membrane acts as a controlled-release barrier, regulating the diffusion of nutrients from the fertilizer core (Zhao et al., 2020). Various techniques can be utilized to apply coatings of granular fertilizers, such as immersion, liquid spraying, precipitation from supercritical fluids, and powder deposition using an electrostatic method. The most commonly used methods for coating fertilizers are immersion and liquid spraying onto the substrate. In general, liquid spraying is done within a coating pan (rotary drum) or a fluid bed coater (Naz and Sulaiman, 2016). The coated fertilizers utilize a core-shell structure. This innovative approach shields the fertilizer core with a protective outer layer, minimizing immediate dissolution and ensuring sustained nutrient availability (Kassem et al., 2024).

Coating is a popular method for developing SRFs due to its simplicity, efficiency, and most importantly, its ability to precisely control nutrient release rates through variations in coating thickness (Jiang et al., 2024). The quality of the final polymer coating on SRFs depends on a several factors. These factors can be broadly categorized into three groups: coating material properties (e.g., viscosity), fertilizer granule properties (e.g., shape, size), and the coating process itself (Kassem et al., 2024). The choice of coating material significantly impacts the release rate of nutrients in SRFs. This influence stems from the varying permeability characteristics of different materials. Polymers with a higher water absorption capacity, for instance, tend to release nutrients at a slower rate. This is because the water acts as a medium for nutrient diffusion from the core fertilizer through the coating (Azeem et al., 2020). Researchers have investigated a diverse range of coating materials to optimize the development of SRFs. The development of SRFs relies heavily on choosing the right coating materials. The controlled release of nutrients from polymer coatings is a complex process that is influenced by various factors. The properties of the polymer, such as its hydrophilicity and concentration, are crucial in determining the rate of nutrient release. Higher polymer concentrations typically result in thicker coatings, which can impede the diffusion of nutrients. Additionally, the coating process itself, including the viscosity of the solution and the use of modifying agents, can impact the porosity and movement of nutrients. The number of coating layers applied, and the application technique used also play a role in determining the structure of the final coating, particularly its thickness and porosity The thickness of the coating plays a critical role in nutrient release. Thinner coatings offer less resistance, allowing nutrients to readily reach the surrounding environment. Conversely, thicker coatings act as a barrier, slowing down the release rate and extending the overall release time (Tomaszewska, 2002; Channab et al., 2023). In addition to the thickness of the coating, the concentration of polymer in the coating directly impacts how quickly nutrients leave the fertilizer granules. Higher polymer concentrations create thicker, denser coating layers. These thicker layers act as a barrier, hindering the diffusion of water and nutrients out of the granules, consequently slowing down the release rate (Channab et al., 2023). Furthermore, formulation and hydrophobicity of polymers, types of soils which coated fertilizers applied, the viscosity of the polymers, temperature and moisture of soils are other important factor affecting the solubility rate of SRFs (Salimi et al., 2023).

Controlled release of nutrients from fertilizers coated with polymers has been modelled by Shaviv et al. (2003) to specifically investigate the diffusion process responsible for nutrient release from individual slow-release fertilizer granules. The following section summarizes the key findings of their investigation. The SRFs demonstrate a nutrient release profile characterized by three distinct phases: an initial lag period, followed by constant release, and finally a decay period. Initially, water vapor permeates through the cracks in the coating, gradually penetrating the fertilizer core. While some fertilizer may dissolve during this phase, significant release is not observed. In the case of hydrogels, they absorb water and swell, indicating the time required to saturate internal voids with a critical water volume or achieve equilibrium between water inflow and solute outflow. As water infiltration continues, more fertilizer dissolves within the core, resulting in increased internal osmotic pressure and a saturated solution volume. This facilitates a controlled release of nutrients through either the coating cracks or the expanded hydrogel network. As long as the core solution remains saturated, the diffusion rate into the surrounding soil remains steady. However, excessive pressure buildup may lead to coating rupture and a sudden release of nutrients. In the final phase, most of the fertilizer has dissolved and been released, causing a decrease in the concentration gradient and driving force for diffusion, resulting in a gradual reduction in the release rate (Shaviv et al., 2003).

3. Types of coated slow-release nitrogen fertilizers

A diverse range of natural and synthetic polymers are employed as coating materials in fertilizer production. The coating materials used in the development of slow-release nitrogen fertilizers (SRNFs) generally can be broadly categorized into three functional groups based on their composition: 1) inorganic mineral compounds, 2.) petroleum-based synthetic polymers, and 3.) natural biodegradable polymers (Duan et al., 2023). It's important to consider that natural polymers degrade over time, which can influence the rate at which nutrients are released. In contrast, synthetic polymers are more stable and offer a more consistent release of nutrients. Ultimately, the best polymer choice depends on the specific application and the desired nutrient release profile (Ma and Wen, 2020).

3.1. Slow-Release Fertilizers Coated with Inorganic Minerals

Inorganic coating materials include minerals such as sulphur (Babadi et al., 2021; Asghar et al., 2022; El-Hassanin et al., 2024), gypsum (Babadi et al., 2021; El-Hassanin et al., 2024), hydroxyapatite (Bhavani et al., 2020), phosphogypsum (Vashishtha et al., 2010), zeolite (Dubey and Mailapalli, 2019; El-Hassanin et al., 2024) and bentonite (Babadi et al., 2021; Umar et al., 2022; Neto et al., 2023). Despite its initial appeal as a low-cost, secondary nutrient source, sulfur has limitations as a urea coating material. Sulfur-coated urea suffers from two key drawbacks: poor attrition resistance due to its inherently brittle nature, and susceptibility to disruption by soil microorganisms, leading to an irregular release pattern (Beig et al., 2020). A recent study by El-Hassanin et al. (2024) focused on creating sustainable slow-release nitrogen fertilizers. They employed various coating materials derived from agro-industrial waste products, including sugarcane and beet filter cakes (mud), alongside conventional materials like sulfur, gypsum, and zeolite. The study revealed significant variations in released nitrogen levels, influenced by three key factors: soil type, nitrogen source, and the coating material employed. Phosphogypsum, a byproduct extensively produced by the phosphorus fertilizer industry, primarily comprises calcium sulfate dihydrate. This versatile material has been used in construction materials, agriculture, and even the extraction of rare earth elements (Akfas et al., 2024). In a previous investigation, the potential of phosphogypsum to improve nitrogen fertilizer efficiency was explored by Vashishtha et al. (2010). The researchers examined a coating method utilizing phosphogypsum, neem oil, and polymeric suspensions applied to urea. Their results indicated that the phosphogypsum slurry formed a fine coating on the urea particles, effectively reducing nitrogen loss through denitrification. This approach facilitated a more controlled and sustained release of nitrogen, better aligning with the nutrient demands of crops over time. A field study conducted by Shivay et al. (2016) in India investigated the effects of coating urea with elemental sulfur, gypsum, or phosphogypsum on rice yield and nitrogen use efficiency. The results revealed significant yield improvements for all coated urea variants compared to the control. The grain yield of rice increased by 12.08 % with elemental sulfur, 6.78 % with gypsum, and 6.14 % with phosphogypsum. The sulfur-coated urea displayed the most substantial yield increase, nearly double that of gypsum or phosphogypsum coatings. Total nitrogen uptake by the rice plants also had a positive response to the coatings of urea fertilizer. Gypsum and phosphogypsum coatings increased nitrogen uptake by approximately 10 %, while sulfur-coated urea achieved a remarkable 20 % increase compared to the control.

The inherent hydrophilicity of most biopolymers presents a significant challenge in their application for controlled-release formulations. This characteristic facilitates rapid water uptake and nutrient release, often exceeding the desired timeframe. To address this limitation and broaden their applicability, researchers have explored various strategies to enhance the hydrophobic character of biopolymers. These strategies aim to create a more robust barrier for controlled nutrient release, aligning better with the specific needs of the formulation (Fertahi et al., 2021). Various minerals, including hydroxyapatite, bentonite, zeolite, and attapulgite, have been investigated for their potential to serve as soil conditioners as well as coating material of readily soluble fertilizers. These minerals could improve both the physical and chemical characteristics of soil, in addition to possessing ion-exchange properties that are beneficial for promoting plant growth (Manjaiah et al., 2019). In the context of SRNF (slow-release nitrogen fertilizer) production, clay minerals are often employed in conjunction with biodegradable materials like lignin and chitosan rather than solely as coating agents. This strategy aims to enhance the resistance of biodegradable materials to rapid degradation. The primary reasons for favoring clay minerals in these blends include their accessibility, affordability, and non-toxicity (Eddarai et al., 2022). Neto et al. (2023) developed two variants of urea controlled-release fertilizers utilizing carnauba wax, commercial granulated urea, and natural and sodium bentonite, respectively. The first variant employed the mechanochemical approach, which entailed mixing different proportions of commercial granulated urea, natural bentonite, and sodium bentonite to form fertilizer bars. Conversely, the second variant utilized the dip-coating technique to apply coatings with varying compositions of natural bentonite, sodium bentonite, and carnauba wax onto urea bars. The fertilizers generated via the dip-coating method exhibited even lower cumulative urea release than those produced through the mechanochemical method. Carnauba wax and bentonite (both natural and sodium-modified) exhibit potential as materials for crafting innovative urea controlled-release fertilizers. Zeolite emerged as the most effective coating material, promoting steady and adequate nitrogen supply across all tested nitrogen fertilizers throughout the incubation period. Conversely, beet mud treatments exhibited the lowest initial release, but a gradual increase in nitrogen release over time. These findings suggest that beet and sugarcane mud hold promise as environmentally friendly and cost-effective coating materials for slow-release fertilizers. Importantly, all coated fertilizers demonstrated sustained nitrogen release throughout the incubation period, highlighting their potential for practical agricultural applications.

3.2. Slow-Release Fertilizers Coated with Synthetic Polymers

Synthetic polymers are categorized into two main groups: Olefin and Resin. Polyethylene, polyvinyl chloride, polypropylene, polyvinyl alcohol, and polystyrene are some common olefin polymers used in fertilizer coatings. Pulse aldehyde resin, polyurethane, alkyd resin, urea formaldehyde resin, polyamide, and polysulfone are examples of resin group polymers. They provide superior mechanical strength and chemical resistance, protecting fertilizer granules from physical damage and harsh environments (Yuan et al., 2022; Kassem et al., 2024). The main disadvantages of using petroleum-based synthetic polymers such as polyethylene, polystyrene polyolefin (Chen et al., 2008; Tian et al., 2019), polypropylene, polyvinyl chloride (Ma et al., 2014), resin (Ge et al., 2024) and polysulfones and polystyrene as coating materials in SRFs production are their inability to biodegrade and the cost. Since these coating materials, which cannot biologically decompose, can remain in the soil after releasing the nutrients for many years, they pose a risk of pollution, thus limiting their usage (Lawrencia et al., 2021). The use of non-biodegradable synthetic materials in fertilizer coatings could lead to a concerning accumulation rate of approximately 50 kg/ha/yr of undesirable residues in the soil (Trenkel et al., 2010). Chen et al. (2008) investigated the efficiency of polyolefin-coated fertilizers as slow-release nitrogen sources for cotton. Compared to urea, polyolefin-coated fertilizer, applied pre-sowing, offered advantages: it maintained higher soil ammonium levels for longer, minimizing nitrate accumulation and potential losses. In another study, Xu et al. (2013) compared non-coated urea with polyolefin-coated urea, at 75 and 150 kg N/ha doses, in terms of ammonia volatilization losses, floodwater ammonium (NH_4^+) levels, and nitrogen accumulation in rice tissue. Non-coated urea application led to a rapid rise in floodwater NH_4^+ and pH within 7-10 days, followed by a sharp decline, indicating substantial nitrogen loss (16-30% of total applied nitrogen) due to ammonia volatilization. Conversely, polyolefin-coated urea exhibited slower nitrogen release, thereby better matching the nitrogen demand of rice crops throughout the season. This resulted in increased nitrogen accumulation in aboveground rice biomass. Application of polyolefin-coated urea at a rate of 75 kg N/ha provided optimal nitrogen levels for both early and late rice crops while minimizing ammonia volatilization losses.

3.3. Slow-Release Fertilizers Coated with Natural Biodegradable Polymers

The European Union enforces strict regulations on SRFs. As of mid-2021, the EU banned the use of microplastics in urea fertilizer coatings. This regulation aims to conserve soil health and water resources from potential contamination by non-biodegradable microplastics. Looking forward, only biodegradable materials will be authorized for use in fertilizer coatings starting in 2026 (Anonymous, 2024). The SRFs coated using natural biodegradable polymers include natural rubber, offering flexibility and water resistance; Arabic gum, a water-soluble binder that enhances nutrient dispersion; and gelatin, a biodegradable material promoting controlled nutrient release. Seaweed-derived sodium alginate improves water retention and nutrient availability, while cellulose from plant cell walls provides strength and biodegradability with controlled release. Lignin (Wang et al., 2021), another plant cell wall component, offers similar benefits. Lignin's natural affinity for water (hydrophilicity) necessitates acetylation for use in fertilizer coatings. This approach not only utilizes a renewable resource, reducing environmental impact, but also offers a cost-effective alternative to synthetic polymers (Seddighi et al., 2023). Chen et al. (2023) successfully developed an advanced fertilizer coating called hydrophobic lignin-based polyurethane coated urea (HLPCU) by incorporating carbon black and polysiloxane. These additives were used to modify liquefied lignin-based polyurethane and significantly enhance its water-repelling properties. Compared to conventionally treated urea (TU), HLPCU treatment led to impressive improvements in cabbage plant growth. Plants treated with HLPCU exhibited increases of 29.68 % in height, 21.64 % in stem thickness, 15.34 % in SPAD value (a measure of chlorophyll content), 32.19 % in above-ground dry weight, and a remarkable 49.36 % increase in subterranean dry weight.

Starch, a common polysaccharide, acts as a binder and extender, enhancing nutrient dispersion and controlled release (Yuan et al., 2023). Starch, a naturally occurring, renewable biopolymer, holds significant promise for agricultural applications due to its biodegradability, abundance, and environmentally friendly nature (Naz and Sulaiman, 2017). In urea coatings, starch can play a multifaceted role. It can act as a modifier, binder, or sealant for chitosan, effectively plugging up pores on the surface of the urea granule (Savitri et al., 2019). Specifically, starch-based hydrogels offer a compelling solution for improving soil moisture retention. Their hydrophilic nature, unique network structure, and ability to form strong hydrogen bonds with water molecules allow them to act as water reservoirs within the soil (Fertahi et al., 2021). Researchers like Uzoh et al. (2019) explored the methods for creating SRNFs using biodegradable and renewable resources. They encapsulated urea fertilizer granules with bio-composites derived from castor seed oil or rubber seed oil, combined with cassava starch. These bio-composites were further modified using sorbitol, maleic anhydride, and phthalic anhydride. The study evaluated how these modifying agents influenced the release rate of nitrogen from the SRNF. They demonstrated that the synthesized SRNF effectively slows down nitrogen release, potentially improving fertilizer efficiency.

Humic acid, derived from soil organic matter, improves soil structure and nutrient retention. Natural resins (Uzoh et al., 2019; Ge et al., 2023), like rosin from pine trees, provide water resistance and controlled release. Chitosan (Ma et al., 2023), a derivative of crustacean shells, boasts biodegradability, antimicrobial properties, and aids nutrient uptake. Rosin, a natural pine tree resin, provides water resistance and controlled release. Vegetable oils act as lubricants and extenders, while beeswax and tar offer water resistance and controlled release. In a recent study by Jiang et al. (2024), researchers explored the use of biodegradable materials to create a novel SRNF. This eco-friendly SRNF utilizes acrylate epoxidized soybean oil, a biobased component, to encapsulate urea granules. This encapsulation technique effectively delayed the release of nitrogen. The positive impact of SRNF on corn growth was demonstrated through a controlled experiment. Compared to plants fertilized with conventional urea, corn treated with SRNF exhibited significant enhancements in root and plant length by up to 114 % and 52 %, respectively, during the initial 20 days of growth. Ghumman et al. (2022) developed a new type of SRF that enriched urea with sulfur. This innovative fertilizer used Poly(S-RSO), a sustainable, water-repellent, and naturally degradable copolymer derived from sulfur and rubber seed oil. A dip coating technique was used in its production. To evaluate the slow-release properties, researchers conducted two sets of tests. In the first, they submerged coated fertilizers with varying thicknesses (165, 254, and 264 micrometers) in distilled water. After 2, 19, and 43 days of incubation, respectively, these fertilizers released only 65 % of their total nitrogen, demonstrating the effectiveness of the coating in an ideal, water-saturated environment. The second test involved placing the thickest coated fertilizer (264 micrometers) in soil. Here, only 17 % of the nitrogen was released after 20 days, complying with the European standard (EN 13266, 2001) for slow-release fertilizers.

Even broader categories like polysaccharides and guar gum offer diverse properties depending on the specific type, influencing water solubility, viscosity, and gel formation. Finally, latex (rubber particles in water), paraffin (waxy petroleum derivative), and asphalt (hydrocarbon mixture) all contribute water resistance and controlled nutrient release (Yuan et al., 2022). In conjunction with their biodegradable nature, biopolymers offer numerous additional benefits for soil health. They increase the soil's ability to retain water, thereby ensuring adequate moisture supply for plants especially in arid-semi-arid regions of the world where precipitation is not sufficient for plant growth. Additionally, the biodegradable polymers contribute to alleviate oxidative stress in plants, enhancing particle aggregation to improve soil structure, and minimizing soil erosion. Biopolymers can also be directly utilized as soil amendments, enriching soil quality and promoting the proliferation of beneficial microorganisms. The collective advantages underscore biopolymers as a promising and sustainable choice for diverse coating applications (Zhou et al., 2020). A wide range of natural polymers, including cellulose, alginates, dextran, starch, carrageenans, agarose, and chitosan, have already found diverse applications in agriculture (Benabid and Zouai, 2016). The most popular organic polymer coating materials used in the development of SRFs are biodegradable hydrogels (Tanan et al., 2021). Superabsorbent hydrogels are three-dimensional, polymeric networks with a remarkable ability to absorb and hold large volumes of water. A recent advancement in hydrogel research involves their combination with fertilizers. This integration offers a promising approach for managing both nutrients and water delivery within a single material (Sarmah and Karak, 2020).

Among naturally occurring biopolymers, chitosan stands out for its abundance and unique properties. Derived from chitin, the main component of crustacean shells, chitosan is obtained through a deacetylation process. This process modifies chitin's structure by removing acetyl groups, exposing free amino functions. These amino groups, along with hydroxyl groups, endow chitosan with cationic properties, meaning it carries a positive charge. This particular characteristic makes chitosan a highly versatile material with applications in numerous fields (Rinaudo et al., 1999). A study conducted by Ma et al. (2023) investigated the potential of chitosan microspheres-based SRNFs to improve plant growth and nutrient use of Chinese cabbage. The researchers created SRNFs by encapsulating urea fertilizer within chitosan microspheres using a straightforward emulsification and cross-linking process. Plants treated with SRNFs showed significant improvements in various growth parameters compared to those treated with conventional urea or no fertilizer. They suggested that SRNFs are a promising option for sustainable and effective fertilization. Mohammadi et al. (2020) developed a slow-release urea fertilizer using clay-polymer nanocomposites to enhance fertilizer use efficiency and control nitrogen release rate. The researchers used sepiolite and chitosan to form nanocomposites with varying clay-to-polymer ratios. The findings revealed a significantly slower release rate of coated urea fertilizer compared to the conventional urea. Around 75 % of the nitrogen content from SRNF released over a 25-day period, compared to just 3 days for urea. Furthermore, the rate of release further decreased with increasing sepiolite content in the clay-polymer nanocomposite.

The utilization of biodegradable polymers such as lignin, chitosan, cellulose, carboxymethyl cellulose, and starch as coating materials presents significant opportunities for the widespread adoption of slow-release fertilizers (Channab et al., 2023). Yuan et al. (2023) extracted cellulose from agricultural residues to develop a new coating material for fertilizer, called ethyl cellulose. This new material was applied to urea to reduce nitrogen release rate. The initial release rate of coated urea was significantly lower compared to uncoated fertilizer. Plants grown with coated urea showed a 17.69 % increase in nitrogen uptake and a 61.29 % decrease in leached nitrogen.

In addition, agro-industrial residues are also renewable, abundant, and readily available materials, and are not only cost-effective but also represent a sustainable approach to nutrient recycling. Their abundance and affordability make them excellent nutrient carriers for formulating climate-smart and cost-effective SRFs (El-Hassanin et al., 2024; Zhang et al., 2023). El-Hassanin et al. (2024) investigated the development of eco-friendly SRNFs using waste materials from agro-industries. They used sugarcane and beet filter cakes, sulfur, gypsum, and zeolite as coating materials for two different nitrogen sources. Their findings revealed that the rate of nitrogen release was significantly influenced by soil type, the original nitrogen source, and the specific coating material employed. Zeolite demonstrated effectiveness as a coating material for all tested nitrogen fertilizers. Sugarcane-based coatings provided a consistent and sufficient supply of nitrogen throughout the incubation period. While beet mud treatments exhibited the lowest initial nitrogen release among all materials, nitrogen release gradually increased over time. The researchers suggested that both beet and sugarcane mud hold can be considered as sustainable and cost-effective coating materials for developing SRNFs.

4. Conclusions

Healthy plant growth relies on the consistent presence of essential nutrients in the soil. While conventional fertilizers have traditionally addressed this need, they often suffer from drawbacks like rapid nutrient loss, inefficient plant uptake, and environmental harm. These shortcomings have fueled the demand for novel and sustainable fertilizer technologies. Therefore, slow-release nitrogen fertilizers (SRNFs) have emerged as a promising strategy to address the limitations of conventional mineral fertilizers. Coated urea fertilizers, a type of SRNF, offer a promising solution to address the challenges associated with conventional urea application. These challenges include low nitrogen use efficiency, environmental pollution, and potential negative impacts on crop growth and food safety. A critical challenge in slow-release nitrogen fertilizer application involves synchronizing nitrogen release with the specific demands of plants throughout their growth stages. This approach, achieved through the use of coated fertilizers, promises to optimize nutrient use efficiency by delivering essential elements when they are most needed. Furthermore, it has the potential to significantly reduce environmental contamination associated with traditional fertilizer practices, promoting a more sustainable agricultural approach. One key approach to achieving controlled nutrient release in SRNFs involves the use of diffusion barriers around the fertilizer core. Both organic and inorganic materials can be employed for this purpose, allowing for tailored release profiles of essential nutrients such as nitrogen.

Despite their advantages, coated urea fertilizers also have limitations that need to be addressed for widespread adoption. The primary limitation is the higher production cost compared to conventional urea fertilizers. Additionally, achieving precise control over the nutrient release rate from coated fertilizers remains a challenge. The lack of standardized methods to assess nutrient release rates from SRNFs makes it difficult for farmers to make informed decisions about their use. Furthermore, a critical challenge associated with traditional SRNFs formulations lies in the use of petroleum-based, synthetic polymers as coating materials. These polymers are often non-biodegradable and non-renewable, raising concerns regarding their environmental sustainability. Additionally, the extraction and processing of these materials can pose environmental risks throughout their life cycle. As a result, the utilization of such polymers in fertilizer coatings is becoming increasingly unsustainable and hinders the widespread adoption of SRFs within the agricultural sector.

To address these limitations and promote the use of coated urea fertilizers, future research and development should focus on several key areas. First, developing cost-effective and scalable production methods for SRNFs is crucial. Second, exploring novel coating materials derived from biodegradable and sustainable sources can offer environmental and economic benefits. Third, improving techniques for precise control over nutrient release rates is essential for optimizing fertilizer application based on specific crop needs. Finally, establishing standardized testing methods for SRNF evaluation will allow farmers to make informed choices about these fertilizers.

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