



# Biodegradable Alternatives to Synthetic Polymer Coatings in the Production of Controlled-Release Fertilizers

Fluzin Sarah

Engagement Manager, Energy Expert, Doha, Qatar.

## Abstract

*The article examines the scientific and technological prospects of biodegradable coating materials as substitutes for synthetic polymer shells in controlled-release fertilizers. The study is grounded in the sustainability challenge facing nitrogen fertilizers, whose agronomic utility coexists with fossil-dependent production, greenhouse gas emissions, persistent soil residues, and microplastic formation from conventional coated products. The article aims to assess the relevance of biodegradable coatings for fertilizer design, to examine their capacity to maintain regulated nutrient delivery, and to evaluate their environmental significance within contemporary agricultural systems. The novelty of the article lies in its integrated interpretation of agronomic performance, material degradability, industrial compatibility, and environmental fate within a single analytical framework. The review indicates that biodegradable coatings based on polysaccharides, lignin-rich feedstocks, biodegradable polyesters, bio-based polyurethanes, and hybrid systems can preserve the core release-regulating function of controlled-release fertilizers while reducing the risk of persistent polymer accumulation in soil. The main conclusion is that biodegradable coatings constitute a promising pathway for reconciling nutrient-use efficiency with improved material stewardship, although field biodegradation, mechanical durability, and scale-up constraints remain decisive research priorities. This article will be useful for researchers in agronomy, materials science, environmental studies, and fertilizer engineering.*

**Keywords:** *Controlled-Release Fertilizers, Biodegradable Coatings, Nitrogen-Use Efficiency, Polymer Alternatives, Microplastic Pollution.*

## INTRODUCTION

The sustainability of the fertilizer sector has shifted from a narrow focus on yield maximization to a broader inquiry into climate exposure, resource security, soil quality, and product design. A recent research frames fertilizer innovation within responsible plant nutrition and identifies enhanced-efficiency fertilizers as part of a wider transition toward lower environmental burdens and higher nutrient-use efficiency across diverse agricultural systems (Maaz et al., 2025). Nitrogen fertilizers occupy a central place in this debate because their benefits for crop productivity are accompanied by high energy demand, substantial greenhouse gas emissions, and significant losses across the food system (Mingolla & Rosa, 2025). The reliance on ammonia synthesis for production of nitrogen fertilizer means that in many parts of the world, our nitrogen supply is linked to continued reliance on fossil feedstocks, with the instability of the energy market transmitting through to fertilizer supply, pricing and subsequent food insecurity. For 1.8 billion people, who Mingolla and Rosa estimate are reliant

on food systems using imported fertilizers or natural gas, nitrogen fertilizer production is linked to wider geopolitical and energy security issues (Mingolla & Rosa, 2025).

To address this dependence, further research has focused on fertilizer technologies that maximize the agronomic efficiency of a given amount of N applied to a field, for example, controlled release fertilizers that are designed to synchronize nutrient availability to plant uptake, reduce nutrient loss, and ease better use of fertilizers across heterogeneous field conditions (Lam et al., 2022). Recent reviews describe controlled-release systems as a key branch of enhanced-efficiency fertilizers and connect their development to crop sustainability, lower nutrient leakage, and new material platforms for precision nutrient delivery (Govil et al., 2024). The coating layer is the functional core of these products because release kinetics depend on barrier properties, permeability, elasticity, and resistance to rupture during storage, transport, and soil exposure (Levett et al., 2025). This technical logic explains the widespread use of synthetic polymer coatings in coated urea and related

**Citation:** Fluzin Sarah, "Biodegradable Alternatives to Synthetic Polymer Coatings in the Production of Controlled-Release Fertilizers", Universal Library of Business and Economics, 2026; 3(2): 19-25. DOI: <https://doi.org/10.70315/uloap.ulbec.2026.0302004>.

products, yet it also exposes a material contradiction within the sustainability narrative of controlled-release fertilizers (Levett et al., 2025).

The contradiction arises from the persistence of conventional coating polymers in soil and from the growing evidence that polymer-coated controlled-release fertilizers can generate microplastic residues during nutrient release and physical abrasion. Bhattacharjee et al. showed that cracks, pores, wet-dry cycles, and soil abrasion can increase microplastic generation from commercial polymer-coated fertilizers, with greater release in soil columns than in water (Bhattacharjee et al., 2025). Despite this, Levett et al. note that commercial products to date still rely on non-degradable coatings, with novel coating materials needing to be developed that match existing coatings for mineralization and barrier properties (Levett et al., 2025). This has driven a new line of research into bio-based and biodegradable coating systems that include polysaccharides, lignin-rich materials, natural resins and biodegradable polyesters (Singh, 2025). The present article examines the potential of biodegradable alternatives to synthetic polymer coatings for the production of controlled-release fertilizers, with attention to their relevance for fertilizer sustainability, their capacity to address plastic pollution associated with coated urea, and their prospects for reconciling agronomic performance with a lower environmental footprint.

Based on the literature review, the study proceeds from two hypotheses regarding the agronomic and environmental roles of biodegradable coatings in controlled-release fertilizers:

**H1:** Biodegradable coatings can preserve the core agronomic functions of controlled-release fertilizers because they are able to regulate nutrient release in line with plant demand and support higher nitrogen-use efficiency.

**H2:** Biodegradable coatings can improve the environmental profile of controlled-release fertilizers because their use reduces the risk of persistent polymer residues and microplastic accumulation in soil.

### MATERIALS AND METHODOLOGY

The materials for this study consisted of recent academic sources on fertilizer sustainability, nitrogen production, controlled-release fertilizers, and biodegradable coating materials. The source base included review articles, meta-analyses, life-cycle assessment studies, and mechanistic research that together defined the agronomic and environmental context of coated fertilizers (Lam et al., 2022; Govil et al., 2024; Maaz et al., 2025). Additional attention was given to studies on the fossil dependence of ammonia and urea production, the nitrogen fertilizer emissions burden, and the material limits of conventional polymer coatings in soil (Mingolla & Rosa, 2025; Mesquita et al., 2025; Katiyar & Gedam, 2025; Bhattacharjee et al., 2025).

The methodology combined a focused literature review,

comparative analysis, and qualitative synthesis. The review identified the main evidence on nutrient-release control, nitrogen-use efficiency, yield effects, and coating performance in controlled-release fertilizers (Govil et al., 2024; Hassan et al., 2024; Qiao et al., 2025). A comparative analysis was conducted to assess synthetic and biodegradable coatings using recurring criteria from the selected studies, including release control, mechanical strength, soil degradability, and industrial feasibility (Kassem et al., 2024; Levett et al., 2025; Singh, 2025).

### RESULTS AND DISCUSSION

Nitrogen fertilizer production remains anchored to ammonia synthesis, and ammonia still relies on natural gas as both feedstock and energy source across much of the global industry (Mingolla & Rosa, 2025). The same dependence extends to urea because its synthesis is downstream of ammonia and inherits the fossil-based structure of the Haber-Bosch platform and the Bosch-Meiser route used in industrial practice (Mesquita et al., 2025).

Natural gas price movements are transmitted into nitrogen fertilizer costs with unusual force. A 2024 pricing study reports that 1 metric ton of anhydrous ammonia requires about 30–35 MMBtu of natural gas, which accounts for 72% to 85% of ammonia production costs (Wongpiyabovorn & Hart, 2024). This cost exposure helps explain why nitrogen fertilizer markets react sharply to energy shocks and why the economic resilience of fertilizer supply remains tied to fossil fuel volatility (Tonelli et al., 2024).

The carbon footprint of nitrogen fertilizers is formed across both production and use phases. Mingolla and Rosa show that synthetic nitrogen fertilizer systems generate 450–500 Mt CO<sub>2</sub>e from production and 670–900 Mt CO<sub>2</sub>e from field use each year, for a total climate burden of 1.1–1.3 Gt CO<sub>2</sub>e annually (Mingolla & Rosa, 2025). Plant-level life-cycle work on urea production also confirms that the manufacturing stage alone carries a large climate burden, with reported footprints of 1.543E+03 and 1.882E+03 kg CO<sub>2</sub> equivalent per ton of urea in two Indian production cases using different technologies (Katiyar & Gedam, 2025).

This production profile has reinforced interest in fertilizer technologies that increase the agronomic return per unit of nitrogen applied to the soil. Reviews published in 2024 and 2025 describe controlled-release fertilizers as a major branch of enhanced-efficiency fertilizers because they reduce nutrient leakage, smooth nutrient delivery over time, and improve synchronization between nitrogen release and plant demand (Govil et al., 2024). The agronomic rationale is rooted in the poor retention of conventional urea in many soils, where nitrogen is lost through ammonia volatilization, nitrate leaching, and conversion to reactive nitrogen compounds (Hassan et al., 2024).

Controlled-release systems address this mismatch by

inserting a diffusion barrier around the fertilizer granule. That barrier slows water ingress and nutrient efflux, thereby compressing early loss peaks and extending nutrient availability during crop uptake (Kassem et al., 2024). Polymer-coated urea occupies a central place in this group because its coating thickness, porosity, elasticity, and permeability can be tuned to shape release kinetics with greater precision than bulk urea formulations.

The agronomic gains associated with controlled-release fertilizers are now supported by meta-analytic evidence across crops and production environments. A 2025 global meta-analysis on maize reports that controlled-release urea increased yield by 6.46% and nitrogen use efficiency by 33.23%, while reducing ammonia volatilization by 54.08% and nitrous oxide emissions by 3.61% relative to conventional

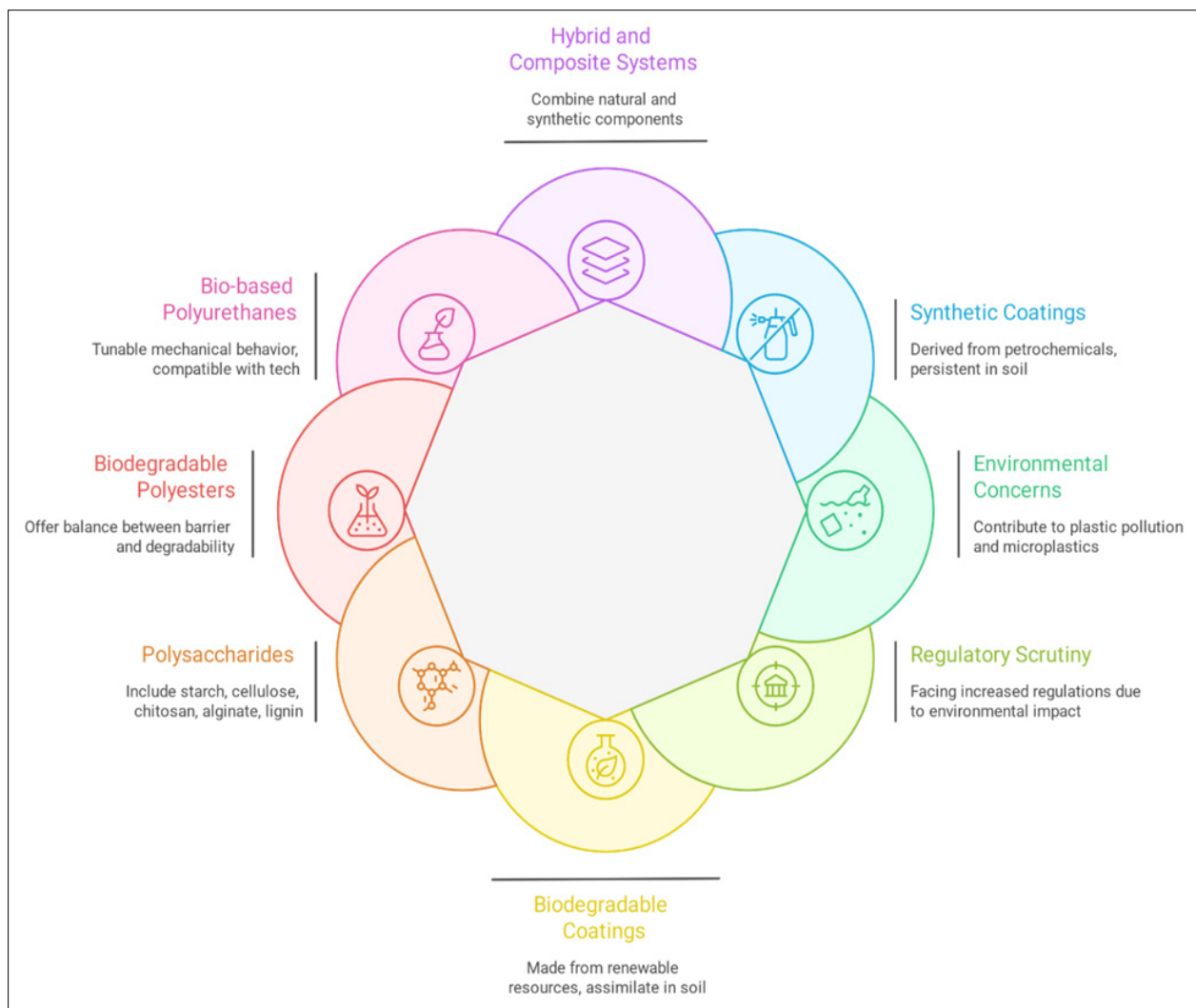
urea (Qiao et al., 2025). A 2024 field-oriented meta-analysis found that coated urea increased nitrogen use efficiency by 58.72% and reduced N<sub>2</sub>O emissions by 48.67% under field conditions, which indicates that the benefit of slower nutrient release extends beyond laboratory tests into farm-scale nitrogen management (Hassan et al., 2024). The same study links these effects to reduced nitrogen losses in gaseous form and to a release pattern that better matches crop demand during the growing season (Hassan et al., 2024). Broader reviews reach the same conclusion and note that controlled-release fertilizers can lower application frequency because a single coated product can sustain nutrient delivery over a longer interval than standard urea, reducing labor demand and narrowing the timing risk associated with repeated fertilization events (Govil et al., 2024).

**Table 1.** Summary of controlled-release nitrogen fertilizers

Aspect	Key point	Evidence	Source
Fossil dependence	Ammonia and urea production remain structurally dependent on natural gas	30–35 MMBtu/t NH <sub>3</sub> ; gas = 72–85% of ammonia production cost	Mingolla & Rosa, 2025; Mesquita et al., 2025; Wongpiyabovorn & Hart, 2024
Emissions burden	Nitrogen fertilizers generate major emissions in both production and field use	1.1–1.3 Gt CO <sub>2</sub> e/year total; urea production: 1.543E+03–1.882E+03 kg CO <sub>2</sub> e/t	Mingolla & Rosa, 2025; Katiyar & Gedam, 2025
Why CRFs matter	Controlled-release fertilizers improve the timing of N supply and reduce nutrient losses	Lower volatilization, leaching, and reactive N losses	Govil et al., 2024; Hassan et al., 2024; Kassem et al., 2024
Agronomic effects	Controlled-release/coated urea improves yield and nitrogen use efficiency while cutting emissions	Yield +6.46%; NUE +33.23% to +58.72%; NH <sub>3</sub> –54.08%; N <sub>2</sub> O –3.61% to –48.67%	Qiao et al., 2025; Hassan et al., 2024

Synthetic polymer coatings used in controlled-release fertilizers are commonly derived from persistent petrochemical materials, whose field stability can pose an environmental liability after nutrient release has ended. Fragments of these coatings can persist in soil for long periods, contributing to the accumulation of non-degradable residues and altering the material profile of the agricultural environment. This persistence has linked coated fertilizers to wider concerns about plastic pollution and to the formation of microplastic particles through cracking, abrasion, weathering, and mechanical stress during handling and soil exposure. The agronomic value of controlled nutrient delivery is thus shadowed by a waste pathway embedded in the product itself, which has placed synthetic coatings under growing regulatory scrutiny and raised doubts about their long-term compatibility with sustainable soil management.

In response, the literature has shifted toward biodegradable coating systems built from renewable or degradable polymers that can combine nutrient retention with eventual assimilation in natural environments. Polysaccharides and other natural biopolymers such as starch, cellulose, chitosan, alginate or lignin, owing to their biogenic origin, structural and functional diversity and possibility of chemical modification, are one of the most important film-forming biopolymers. Another important group of film-forming biopolymers are biodegradable polyesters that offer a better balance of barrier properties and biodegradability. Bio-based biodegradable polyurethanes have also been evaluated for their tunable mechanical properties and compatibility with coating deposition methods applied to fertilizer production. Hybrid and composite systems involve the use of natural and synthetic biodegradable polymers to allow the permeability of the coating, the strength of the matrix material, and the release and environmental behavior to be controlled. Evolution of fertilizer coatings is illustrated in Figure 1.



**Fig. 1.** Evolution of Fertilizer Coatings

The performance of a biodegradable coating in controlled-release fertilizers is defined first by its ability to regulate nutrient release with enough precision to match plant demand over time. The coating must form a barrier that limits rapid water penetration and slows the diffusion of dissolved nutrients from the fertilizer core. This barrier cannot be treated as a static membrane because its function depends on thickness, porosity, surface continuity, swelling behavior, and resistance to cracking under changing moisture and temperature conditions.

Mechanical strength is inseparable from release control, as rupture, abrasion, and shell fragmentation can disrupt the intended release profile and convert a controlled system into a fast-dissolving one. A useful coating must also retain structural integrity during storage and transport, where granules are exposed to pressure, vibration, friction, and fluctuating humidity. Premature degradation during warehousing or distribution would compromise product quality before field application and weaken confidence in the material platform.

Industrial relevance is another layer of selection, whereby the coating must be compatible with the existing fertilizer production equipment (including coating technology, drying regimes and throughput rate), as a laboratory-scale coating may not translate easily to an industrial scale. Finally, the coating should be biodegradable in the soil environment at the end of its release function. This means understanding the effects of microbial activity, soil structure, soil moisture, temperature, and time of residue persistence in soil.

This requirement places field biodegradation at the center of evaluation because degradation observed under controlled test conditions does not guarantee the same outcome in agricultural soils. Cost and scalability determine the final adoption threshold. Raw material availability, processability, coating efficiency, and the ability to supply large production volumes determine whether a biodegradable alternative can progress from a promising formulation to a commercial product. The most valuable systems are those that join controlled nutrient delivery, physical resilience, industrial fit, environmental decay, and economic feasibility within a single coating architecture.

**Table 2.** Key performance criteria for biodegradable coatings in controlled-release fertilizers

Criterion	Requirement	Why it matters
Release control	The coating must regulate water ingress and nutrient diffusion through thickness, porosity, surface continuity, swelling behavior, and crack resistance	Ensures nutrient release matches plant demand over time
Mechanical integrity	The coating must resist rupture, abrasion, and fragmentation during handling, storage, and transport	Prevents failure of the controlled-release function before or during application
Industrial compatibility	The material must work with existing fertilizer production lines, coating equipment, drying conditions, and throughput requirements	Determines whether the coating is feasible beyond laboratory scale
Field biodegradation	The coating must degrade in real soil conditions after completing its release function	Ensures residues do not persist unnecessarily in agricultural soils
Economic scalability	The system must rely on available raw materials, efficient processing, and scalable production volumes at an acceptable cost	Determines commercial viability and adoption potential

Biodegradable coatings matter because the question reaches far beyond a narrow exchange of one coating material for another. The issue concerns the design logic of controlled-release fertilizers and their place within a changing agricultural input system. A fertilizer granule is no longer judged only by its nutrient content or its release profile. Its material afterlife in soil has become part of its agronomic and environmental meaning. This shift changes the frame of innovation from product performance alone to product integrity across the whole life cycle.

This broader frame exposes a double sustainability challenge in the fertilizer sector. Nitrogen fertilizers remain linked to fossil-based feedstocks through ammonia and urea production, which ties the sector to energy volatility, carbon emissions, and geopolitical dependence. At the same time, enhanced-efficiency products such as coated urea can introduce a second layer of environmental burden when their polymer shells persist in soil after nutrient release. The fertilizer industry faces two interlocked material problems. One problem begins at the point of synthesis. The other unfolds after field application. Any serious assessment of fertilizer sustainability must include both production emissions and the ecological fate of the product in use.

This perspective carries strategic weight for fertilizer producers, especially for firms seeking to create value beyond upstream operations. Biodegradable coatings create room for differentiation in a market where many nitrogen products remain difficult to distinguish by core chemistry. A coating with verified soil biodegradation can support a stronger environmental profile, reduce exposure to plastic-related criticism, and improve the credibility of premium fertilizer lines aimed at sustainability-sensitive segments. These advantages become more relevant under pressure to decarbonize and tighter regulatory oversight of persistent

materials in agriculture. Product design is used as a lever of strategy once carbon performance, soil stewardship, and regulatory compliance are reframed as a business decision.

Commercial development is uneven: some biodegradable polymers in early-stage laboratory studies have limited feedstock availability, processing stability, coating efficiency, and total production costs. Natural biopolymers have a more appealing story, and a wider variety of chemical modification possibilities. However, they are often sensitive to water and have a low mechanical strength; hybrid systems are more promising due to their combination of natural and synthetic materials with a better ability to tune permeability and mechanical properties. Biodegradable polyurethanes are also well-suited to coating applications, since the use of conventional coating development and production methods allows them to be commercialized in stages, for example, as hybrid coatings that span the gap between proof-of-concept and commercially relevant scales.

These conditions define a clear agenda for future research and industrial development. Field-based degradation studies are needed because soil is a heterogeneous, biologically active environment where coating behavior cannot be inferred solely from controlled tests. Standardized methods for evaluating biodegradability in soil are also required, since claims of environmental compatibility lose force without comparable criteria and shared benchmarks. Research on cost reduction, coating process integration, and supply reliability will shape the practical future of biodegradable materials as much as polymer chemistry itself. Fertilizer producers will need closer collaboration with materials science companies, resin developers, and biopolymer suppliers to develop formulations that meet agronomic, industrial, and environmental demands within a single product system.

## CONCLUSION

The evidence examined in this article positions biodegradable coatings as a pivotal frontier in the redesign of controlled-release fertilizers. Nitrogen fertilizers remain embedded in a fossil-dependent production system marked by high energy demand, substantial greenhouse gas emissions, and acute exposure to gas-market instability. In this setting, controlled-release fertilizers are significant because they improve nitrogen-use efficiency, reduce volatilization and leaching losses, and enhance the agronomic return per unit of applied nitrogen. Their promise, however, has been constrained by the persistence of conventional synthetic polymer coatings in soil and by the associated risk of microplastic generation during weathering, abrasion, and nutrient release.

Biodegradable alternatives address this contradiction at the material level. Polysaccharides, lignin-rich materials, biodegradable polyesters, bio-based polyurethanes, and hybrid coating systems expand the design space for fertilizer products whose environmental profile extends beyond release kinetics alone. The central scientific challenge lies in achieving a stable convergence of barrier performance, mechanical strength, industrial compatibility, field biodegradation, and economic scalability. A coating must regulate water ingress and nutrient diffusion throughout the intended crop cycle, withstand storage and transport stresses, integrate with existing manufacturing lines, and degrade under real soil conditions after its functional role has ended.

The evidence presented in this article confirms both hypotheses. The first hypothesis is supported by results showing that controlled-release fertilizer systems improve synchronization between nitrogen release and plant demand, increase nitrogen-use efficiency, reduce nitrogen losses, and contribute to yield growth compared with conventional urea. The second hypothesis is also supported because the reviewed studies identify persistent synthetic coatings as a source of residue accumulation and microplastic formation in soil, while biodegradable coatings are examined as a material solution that can reduce this environmental burden after the fertilizer has completed its release function. Taken together, these findings show that biodegradable coatings have the potential to preserve the agronomic value of controlled-release fertilizers and strengthen their environmental sustainability within a broader transformation of fertilizer design.

## REFERENCES

1. Bhattacharjee, L., Gopakumar, A., Beheshtimaal, A., Jazaei, F., Ccancapa-Cartagena, A., & Salehi, M. (2025). Mechanisms of microplastic generation from polymer-coated controlled-release fertilizers (PC-CRFs). *Journal of Hazardous Materials*, 486, 137082. <https://doi.org/10.1016/j.jhazmat.2024.137082>
2. Govil, S., Duc, V., Escribà-Gelonch, M., & Hessel, V. (2024). Controlled-release fertiliser: Recent Developments and Perspectives. *Industrial Crops and Products*, 219, 119160. <https://doi.org/10.1016/j.indcrop.2024.119160>
3. Hassan, M. U., Guoqin, H., Arif, M. S., Mubarik, M. S., Tang, H., Xu, H., Yang, B., Zhou, Q., & Shakoor, A. (2024). Can urea-coated fertilizers be an effective means of reducing greenhouse gas emissions and improving crop productivity? *Journal of Environmental Management*, 367, 121927. <https://doi.org/10.1016/j.jenvman.2024.121927>
4. Kassem, I., Ablouh, E.-H., El Bouchtaoui, F.-Z., Jaouahar, M., & El Achaby, M. (2024). Polymer coated slow/ controlled release granular fertilizers: Fundamentals and research trends. *Progress in Materials Science*, 144, 101269. <https://doi.org/10.1016/j.pmatsci.2024.101269>
5. Katiyar, A., & Gedam, V. V. (2025). Life cycle assessment of urea production: Environmental impact comparison of two fertilizer technologies in Northern India. *Science of the Total Environment*, 971, 179034. <https://doi.org/10.1016/j.scitotenv.2025.179034>
6. Lam, S. K., Wille, U., Hu, H.-W., Caruso, F., Mumford, K., Liang, X., Pan, B., Malcolm, B., Roessner, U., Suter, H., Stevens, G., Walker, C., Tang, C., He, J.-Z., & Chen, D. (2022). Next-generation enhanced-efficiency fertilizers for sustained food security. *Nature Food*, 3(8), 575–580. <https://doi.org/10.1038/s43016-022-00542-7>
7. Levett, I., Pratt, S., Agarwal, A., Lant, P., & Laycock, B. (2025). A new tool to screen biodegradable polymers as technically and commercially viable fertiliser coatings. *Science of the Total Environment*, 976, 179371. <https://doi.org/10.1016/j.scitotenv.2025.179371>
8. Maaz, T. M., Dobermann, A., Lyons, S. E., & Thomson, A. M. (2025). Review of research and innovation on novel fertilizers for crop nutrition. *Sustainable Agriculture*, 3(1). <https://doi.org/10.1038/s44264-025-00066-0>
9. Mesquita, I. S., Melo, P. A., & Secchi, A. R. (2025). Novel pathways for urea synthesis decarbonization: An analytical review from Bosch–Meiser to electroreduction processes. *Applied Energy*, 400, 126527. <https://doi.org/10.1016/j.apenergy.2025.126527>
10. Mingolla, S., & Rosa, L. (2025). Low-carbon ammonia production is essential for resilient and sustainable agriculture. *Nature Food*, 6, 610–621. <https://doi.org/10.1038/s43016-025-01125-y>
11. Qiao, Y., Yue, G., Mo, X., Zhang, L., & Sun, S. (2025). Controlled-release urea derived from various coating materials on the impacts of maize production: A meta-analysis. *Industrial Crops and Products*, 225, 120485. <https://doi.org/10.1016/j.indcrop.2025.120485>

12. Singh, A. K. (2025). Bio-based materials for fabrication of controlled-release coated fertilizers to enhance soil fertility: A review. *Next Materials*, 8, 100701. <https://doi.org/10.1016/j.nxmate.2025.100701>
13. Tonelli, D., Rosa, L., Gabrielli, P., Parente, A., & Contino, F. (2024). Cost-competitive decentralized ammonia fertilizer production can increase food security. *Nature Food*, 5(6), 469–479. <https://doi.org/10.1038/s43016-024-00979-y>
14. Wongpiyabovorn, O., & Hart, C. (2024). Examining the factors of fertilizer pricing. *Journal of the Agricultural and Applied Economics Association*, 3(3), 572–583. <https://doi.org/10.1002/jaa2.133>