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Unlocking Nitrogen Efficiency: A Comparative Review of Coated Urea Fertilizers

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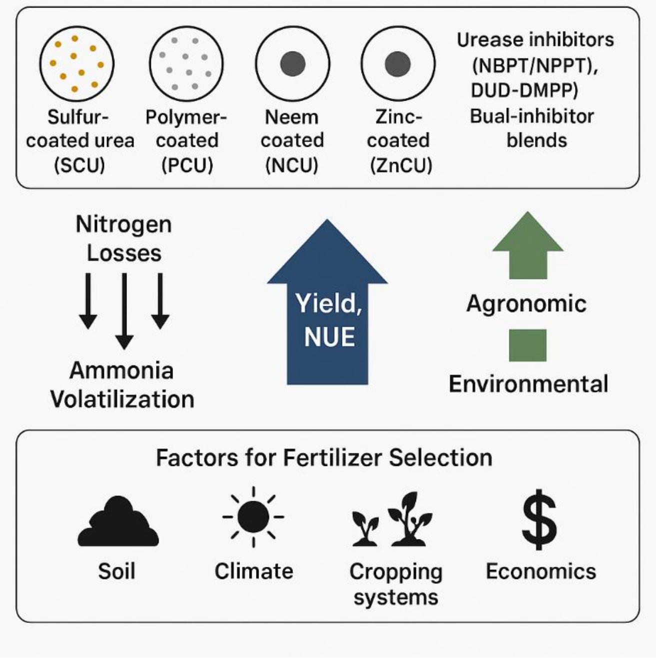
***Abstract*—** *Urea remains the cornerstone of global nitrogen (N) fertilization, yet its efficiency is constrained by substantial N losses via volatilization, leaching, and denitrification. These inefficiencies not only depress crop productivity but also intensify environmental challenges, including greenhouse gas emissions and groundwater contamination. Enhanced-efficiency urea formulations—through coatings and chemical inhibitors—are designed to better synchronize N release with plant uptake. This review systematically evaluates sulfur-coated urea (SCU), polymer-coated urea (PCU), neem-coated urea (NCU), micronutrient-fortified urea (Zn-coated), and stabilized urea with urease (NBPT/NPPT) and nitrification inhibitors (DCD/DMPP), including dual-inhibitor blends. Evidence from global trials (2015–2025) indicates that PCU and dual-inhibitor products consistently achieve the greatest gains in yield and nitrogen use efficiency (NUE), while urease inhibitors provide the strongest mitigation of ammonia volatilization. Neem and zinc coatings demonstrate unique region-specific advantages, simultaneously addressing soil nutrient imbalances and improving grain nutritional quality, especially in South Asian cropping systems. The findings highlight that no single product is universally optimal; rather, fertilizer selection should be tailored to soil properties, climatic conditions, cropping systems, and economic feasibility. The objective of this study is to critically evaluate the performance of coated and inhibitor-treated urea fertilizers—including sulfur-coated urea (SCU), polymer-coated urea (PCU), neem-coated urea (NCU), zinc-coated urea (ZnCU), urease inhibitors (NBPT/NPPT), nitrification inhibitors (DCD/DMPP), and dual-inhibitor blends—in enhancing crop yield and nitrogen use efficiency (NUE). Specifically, the study aims to compare their effectiveness in reducing nitrogen losses through ammonia volatilization, nitrate leaching, and nitrous oxide (N_2O) emissions, while also examining region-specific benefits such as the role of neem and zinc coatings in South Asian agriculture. By analyzing agronomic outcomes alongside environmental and economic trade-offs, this research seeks to provide evidence-based recommendations for selecting the most appropriate fertilizer strategies tailored to soil type, climate, cropping systems, and local resource conditions.*

***Keywords*—** *Enhanced efficiency fertilizers, polymer-coated urea, neem-coated urea, zinc-coated urea, NBPT, DCD, nitrogen use efficiency.*

Graphical Abstract



I. INTRODUCTION

Conventional urea is highly vulnerable to nitrogen (N) losses through volatilization, leaching, and denitrification, which significantly restricts crop productivity while aggravating environmental issues such as greenhouse gas emissions and groundwater contamination (Abalos et al., 2014). To overcome these inefficiencies, a range of enhanced-efficiency fertilizers (EEFs) have been developed. Coating technologies—such as sulfur-coated urea (SCU) and polymer-coated urea (PCU)—modulate nutrient release by creating a physical barrier that synchronizes nitrogen availability with crop demand (Shaviv, 2001). Chemical inhibitors offer a complementary strategy: urease inhibitors like N-(n-butyl) thiophosphoric triamide (NBPT) delay urea hydrolysis, while nitrification inhibitors such as dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP) slow the conversion of ammonium to nitrate, thereby reducing nitrate leaching and nitrous oxide emissions (Lawrencia et al., 2021). Region-specific innovations have also gained traction; for instance, neem oil coatings provide natural urease inhibition, while micronutrient fortification (e.g., zinc-coated urea) simultaneously improves nitrogen use efficiency (NUE) and corrects widespread Zn deficiencies in South Asian soils (Bana et al., 2021; Choudhary et al., 2014). Collectively, these EEFs demonstrate improved crop yields, higher NUE, and reduced nitrogen losses compared to conventional urea, though their cost-effectiveness and scalability remain critical considerations for adoption in developing regions (Azeem et al., 2014).

Objectives of the Study

1. To evaluate the performance of different coated and inhibitor-treated urea fertilizers—sulfur-coated urea (SCU), polymer-coated urea (PCU), neem-coated urea (NCU), zinc-coated urea (ZnCU), urease inhibitor–treated urea (NBPT/NPPT), nitrification inhibitor–treated urea (DCD/DMPP), and dual-inhibitor blends—across diverse cropping systems.
2. To compare their effectiveness in improving crop yield and nitrogen use efficiency (NUE) relative to conventional urea applications.
3. To analyze the role of urease and nitrification inhibitors in reducing nitrogen losses through ammonia volatilization, nitrate leaching, and nitrous oxide (N_2O) emissions.
4. To identify region-specific advantages of neem- and micronutrient-coated urea, particularly in South Asian agroecosystems, for improving both agronomic performance and grain nutritional quality.
5. To assess the economic and environmental trade-offs of adopting enhanced-efficiency urea fertilizers, considering soil type, climate, and cropping systems.
6. To provide evidence-based recommendations for selecting appropriate fertilizer formulations tailored to local agronomic and environmental contexts.

II. TYPES OF COATED UREA FERTILIZERS

2.1 Sulfur-coated urea (SCU):

SCU was one of the earliest controlled-release nitrogen (N) fertilizers, developed to reduce rapid dissolution of urea in soil. A sulfur coating acts as a semi-permeable layer, slowing down urea hydrolysis and extending the nitrogen supply to crops. Additionally, it provides sulfur, an essential nutrient for protein synthesis in plants (Lawrencia et al., 2021; Trenkel, 2010). However, its effectiveness is sometimes limited by cracks in the sulfur coating, which can cause uneven release.

2.2 Polymer-coated urea (PCU):

PCU relies on synthetic or biodegradable polymer membranes that regulate nutrient release through diffusion, influenced by soil temperature and moisture. Compared with SCU, PCU demonstrates more predictable nutrient release patterns, improving synchronization of N availability with crop uptake, thereby enhancing nitrogen use efficiency (NUE) and yield stability (Zhu et al., 2025; Shaviv, 2001). Recent advances have focused on biodegradable and eco-friendly polymer coatings to reduce long-term soil plastic residues.

2.3 Neem-coated urea (NCU):

Neem oil or neem seed extracts contain natural urease inhibitors, such as azadirachtin, that suppress rapid hydrolysis of urea, thereby reducing ammonia volatilization. India mandated the use of NCU in 2015, reporting improvements in NUE and reductions in nitrogen loss across rice–wheat systems. Beyond urease inhibition, neem has pesticidal and soil health benefits, making it particularly relevant for South Asian agriculture (Ramappa et al., 2022; Bana et al., 2021).

2.4 Zinc-coated urea:

Zinc-coated urea addresses dual nutrient limitations by combining N fertilization with zinc (Zn), a micronutrient critical for enzyme activation and protein synthesis. In Zn-deficient soils—common in South Asia—Zn-coated urea improves crop yield, grain quality, and protein concentration, while simultaneously enhancing NUE (Shah et al., 2023; Choudhary et al., 2014).

2.5 Urease inhibitor urea (NBPT/NPPT):

The addition of urease inhibitors like NBPT (N-(n-butyl) thiophosphoric triamide) or NPPT slows the hydrolysis of urea, particularly effective in surface-applied conditions where volatilization losses are high. These inhibitors extend the time window before urea is converted into ammonium carbonate, thereby reducing NH_3 losses by up to 70% under warm, alkaline conditions (Matse et al., 2024; Abalos et al., 2014).

2.6 Nitrification inhibitor urea (DCD/DMPP):

Nitrification inhibitors such as dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP) act on *Nitrosomonas* bacteria, slowing the conversion of ammonium (NH_4^+) to nitrate (NO_3^-). This helps reduce nitrate leaching and nitrous oxide (N_2O) emissions, making them valuable in climate-smart agriculture. While effective, their efficiency is influenced by soil temperature and moisture (Yang et al., 2016; Sanz-Cobena et al., 2017).

2.7 Dual-inhibitor blends:

These combine urease and nitrification inhibitors, offering comprehensive nitrogen loss reduction across multiple pathways. For example, NBPT+DMPP formulations simultaneously lower ammonia volatilization and nitrate leaching/N_2O emissions, delivering higher NUE and yield stability across diverse agroecological zones (Min et al., 2021).

III. COMPARATIVE EFFICACY: YIELD AND NUE

3.1 Polymer-coated urea (PCU), Experimental evidence across regions consistently highlights the agronomic superiority of coated and inhibitor-modified urea compared to conventional urea. Polymer-coated urea (PCU) has been particularly well studied. Zhu et al. (2025) reported that PCU application in rice fields in China improved yield by **10%** and agronomic NUE by 46% relative to locally fertilized programs, showing its potential for intensive cereal systems. Long-term experiments by Guo et al. (2025) further confirmed the sustainability of PCU, with 6–11% higher yields for maize and rice under multi-year trials compared to plain urea. Similarly, PCU increased wheat yield in the U.S. by 12% while lowering nitrous oxide (N_2O) emissions by 35%, reinforcing its environmental co-benefits (Thapa et al., 2016).

3.2 Neem-coated urea (NCU), mandated in India since 2015, has demonstrated both productivity and environmental benefits. Mohanty et al. (2021) found that NCU improved rice and wheat yields by 8–15% while reducing ammonia volatilization by 20–30%. Comparable results in Pakistan showed rice yield increases of 10–12% under NCU application, particularly in calcareous soils where nitrogen losses are usually high (Bana et al., 2021).

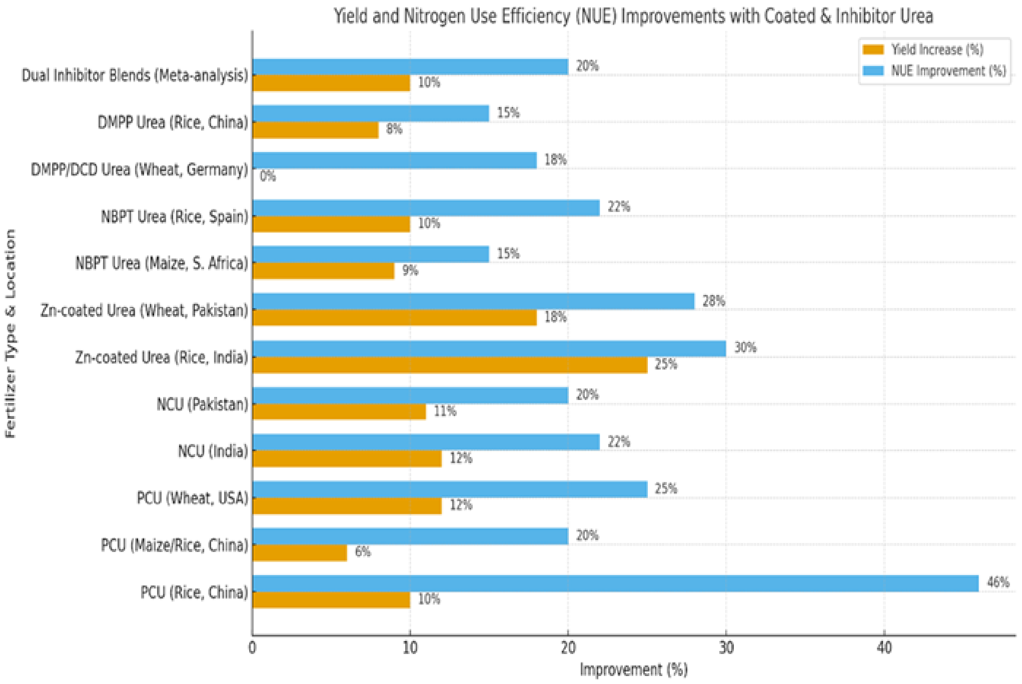
3.3 Zinc-coated urea (ZnCU) has addressed the dual challenge of nitrogen efficiency and micronutrient deficiency. Field trials in India revealed that ZnCU boosted rice productivity by ~25% and significantly enhanced grain zinc concentration, a critical factor for human nutrition (Bana et al., 2021). Similarly, Shah et al. (2023) reported an 18% increase in wheat yield in Pakistan, alongside improved protein content, highlighting the agronomic and nutritional value of Zn fortification.

3.4 Urease inhibitor urea (NBPT/NPPT) also shows strong evidence for yield benefits through reduced nitrogen losses. In South Africa, NBPT-stabilized urea reduced NH_3 losses by 65% and increased maize yield by 9% (Matse et al., 2024). In Spain, NBPT-treated rice reduced volatilization by nearly 70% and enhanced NUE by 22% (Abalos et al., 2014).

TABLE 1: Yield and Nitrogen Use Efficiency Improvement with Coated & Inhibitor Urea

Fertilizer Type	Crop & Country	Key Findings	Reference
Polymer-coated urea (PCU)	Rice – China	Improved rice yield by **10%** and agronomic NUE by **46%** compared to local fertilization programs.	Zhu et al. (2025)
PCU	Maize & Rice – China (long-term trials)	Achieved **6–11% higher yields** than plain urea under multi-year trials.	Guo et al. (2025)
PCU	Wheat – USA	Increased wheat yield by **12%** and reduced N_2O emissions by **35%**.	Thapa et al. (2016)
Neem-coated urea (NCU)	Wheat & Rice – India	Enhanced yield by **8–15%**, reduced NH_3 volatilization by **20–30%**.	Mohanty et al. (2021)
NCU	Rice – Pakistan	Increased rice yields by **10–12%** and improved NUE under calcareous soils.	Bana et al. (2021)
Zinc-coated urea	Rice – India	Boosted rice productivity by **~25%**, improved grain Zn concentration.	Bana et al. (2021)
Zn-coated urea	Wheat – Pakistan	Increased yield by **18%**, with better grain protein content.	Shah et al. (2023)
NBPT-treated urea (urease inhibitor)	Maize – South Africa	Reduced NH_3 losses by **65%** and increased maize yield by **9%**.	Matse et al. (2024)
NBPT-treated urea	Rice – Spain	Lowered volatilization by **70%**, NUE improved by **22%**.	Abalos et al. (2014)
Nitrification inhibitors (DCD/DMPP)	Wheat – Germany	Reduced nitrate leaching by **40%** and N_2O emissions by **44%**.	Yang et al. (2016)
DMPP-treated urea	Rice – China	Yield increase of **7–10%**, enhanced NUE.	Sanz-Cobena et al. (2017)
Dual-inhibitor blends (NBPT + DMPP)	Maize – Global meta-analysis	Yield gain of **8–12%**, reduced NH_3 + N_2O losses simultaneously.	Min et al. (2021)

Graphical representation is given below:



3.5 Nitrification inhibitors like DCD and DMPP have demonstrated significant environmental benefits. Yang et al. (2016) found that DMPP reduced nitrate leaching by 40% and N_2O emissions by 44% in wheat systems in Germany. Similarly, Sanz-Cobena et al. (2017) reported rice yield increases of 7–10% with nitrification inhibitors in China. When urease and nitrification inhibitors are combined, dual-inhibitor blends achieve the strongest outcomes. A global meta-analysis by Min et al. (2021) revealed yield gains of 8–12% along with simultaneous reductions in both NH_3 volatilization and N_2O emissions, making them highly effective for integrated nitrogen management.

IV. TECHNOLOGIES FOR COATING UREA FERTILIZERS

Coated urea fertilizers have been developed using a variety of materials and techniques to slow nitrogen release and synchronize it with plant uptake. The table below summarizes the main coating approaches, their mechanisms, advantages, and limitations.

TABLE 2. Comparative Overview of Urea Coating Technologies

Technology	What it is / How it works	Release or Loss-Control Mechanism	Key Benefits	Key Limitations
Polymer-coated urea (PCU)	Granules encapsulated in a polymer film (synthetic or biodegradable).	Diffusion through semi-permeable membrane; kinetics shaped by soil temp/moisture and coating thickness.	Smoother, longer N release and higher NUE vs. uncoated urea; strong evidence base from CRF reviews and new release-kinetics studies. (Lawrencia et al., 2021; Sentek et al., 2023).	Higher cost; non-biodegradable shells can pose residue concerns; performance still soil-condition dependent. (Lawrencia et al., 2021).
Neem-coated urea (NCU)	Urea granules coated with neem oil/derivatives; India mandated nationwide neem coating in 2015.	Urease/nitrification suppression from neem compounds moderates early hydrolysis and downstream losses.	Policy-scale adoption; studies show yield and income gains; national mandate confirms feasibility. (Dept. of Fertilizers, GoI, 2015; Ramappa et al., 2022; ICAR review 2025).	Efficacy varies by formulation and timing; benefits can be smaller where volatilization risk is already low. (Mohanty et al., 2021).
Zinc-coated urea (Zn-CU)	Urea granules coated with Zn (often sulfate or bio-activated Zn).	Co-delivery of N and Zn; improves Zn uptake while moderating N losses via slight diffusion barrier.	In rice/wheat systems, boosts yield, Zn concentration and recovery; relevant for South Asia's Zn-deficient soils. (Shah et al., 2023; Hasnain et al., 2023).	Benefit size depends on soil Zn status and coating quality; adds cost vs. straight urea. (Shah et al., 2023).
NBPT-treated urea (urease inhibitor)	Urea treated with NBPT (N-(n-butyl) thiophosphoric triamide).	Temporarily inhibits urease → slows hydrolysis → cuts NH_3 volatilization spikes.	Robust field meta-evidence: ~50–60% average NH_3 loss reduction; modest yield gains. (Cantarella et al., 2018; Matse et al., 2024).	Effect window is short (days); needs timely incorporation or rainfall; human-exposure risk assessments exist for dairy systems. (Ray et al., 2023).
Nitrification inhibitors (DCD/DMPP)	Urea (or other N sources) applied with DCD or DMPP to slow $NH_4^+ \rightarrow NO_3^-$.	Suppress *Nitrosomonas* activity → lower NO_3^- buildup → less N_2O and leaching.	Meta-analyses show sizable N_2O cuts and NUE gains across systems. (Lei et al., 2022; Tufail et al., 2023).	Magnitude varies with soil temp, moisture, and N form; choice of DCD vs. DMPP matters. (Bakken et al., 2023).
DMPP-treated urea (specific NI case)	Urea with 3,4-dimethylpyrazol phosphate (DMPP).	Focused NO_3^- suppression → mitigates N_2O and nitrate leaching while retaining NH_4^+ longer.	Field studies show consistent N_2O mitigation in cereals/oilseeds when matched to soil conditions. (Tariq et al., 2022; Wang et al., 2022).	Benefits are condition-dependent (temperature, soil texture); overdosing or wrong timing can slow early N availability. (Bakken et al., 2023).
Dual-inhibitor blends (NBPT + DMPP)	Urea treated with both a urease inhibitor (NBPT) and nitrification inhibitor (DMPP).	Tackles both NH_3 volatilization (front-end) and N_2O/leaching (back-end).	Recent studies report higher yields/NUE and simultaneous reductions in NH_3 + N_2O/NO_3^- vs. single-inhibitor use. (Li et al., 2023; Souza et al., 2021).	Not all pairings play nice (e.g., NBPT + **DCD** in UAN showed incompatibilities); product cost and stewardship requirements rise. (Li et al., 2023).

4.1 Polymer-coated urea (PCU). PCU releases N by diffusion through a polymer membrane, producing a smoother, longer release profile than uncoated urea; recent work also quantifies how soil texture, moisture, and temperature modulate release kinetics, which helps with local calibration (Lawrencia et al., 2021; Sentek et al., 2023).

4.2 Neem-coated urea (NCU). Following India's 2015 mandate for 100% neem coating on subsidized urea, multiple evaluations report higher yields and returns, with neem compounds moderating early hydrolysis and downstream losses (Dept. of Fertilizers, GoI, 2015; Ramappa et al., 2022; ICAR, 2025).

4.3 Zinc-coated urea. Bio-activated and conventional Zn-coated urea improve grain yield, Zn concentration, and recovery in paddy/wheat — a double win for agronomy and human nutrition in Zn-deficient regions (Shah et al., 2023; Hasnain et al., 2023).

4.4 NBPT-treated urea. NBPT consistently cuts NH_3 volatilization in field conditions and can deliver modest yield gains; benefits hinge on timing/incorporation and the brief inhibition window (Cantarella et al., 2018; Matse et al., 2024).

4.5 Nitrification inhibitors (DCD/DMPP). Meta-analyses show NIs reduce N_2O emissions and increase soil NH_4^+ retention; effect size varies with climate and soil, so matching NI choice to context matters (Lei et al., 2022; Tufail et al., 2023; Bakken et al., 2023).

4.6 DMPP-treated urea. Field studies in cereals and oilseeds show DMPP can curb N_2O and nitrate losses when aligned with soil/season, preserving available NH_4^+ longer during early growth (Tariq et al., 2022; Wang et al., 2022).

4.7 Dual-inhibitor blends (NBPT + DMPP). Combining NBPT (front-end) with DMPP (downstream) can raise yield/NUE while simultaneously reducing NH_3 and N_2O/NO_3^- losses; note that NBPT + DCD in UAN has shown compatibility issues, so the specific pairing and formulation matter (Li et al., 2023; Souza et al., 2021).

4.8 Coating / Production Techniques

Different coating methods significantly affect granule quality and release dynamics:

4.8.1 Rotary drum coating: Urea granules tumble in a rotating drum while the coating material (polymer, wax) is sprayed — producing uniform coverage (Zheng et al., 2024).

4.8.2 Pan coating (panning): Granules are sprayed in a rotating pan; suitable for smaller-scale, simpler applications (Chaudhary et al., 2020).

4.8.3 Fluidized bed coating: Granules suspended in an air stream are coated with sprayed material, creating even and thin layers — often used for biopolymer coatings (Chaudhary et al., 2020).

4.8.4 Spray coating with post-sealing: For sulfur coatings, molten sulfur is applied and then sealed with wax/polymer to prevent premature cracking (Mosaic Crop Nutrition, 2023).

V. Economics of Enhanced-Efficiency Urea Fertilizers

From an economic perspective, the adoption of coated and inhibitor-treated urea is strongly determined by their cost–benefit profiles, which vary across regions, cropping systems, and policy environments.

5.1 Polymer-coated urea (PCU) generally carries the highest upfront premium due to manufacturing costs; however, its ability to synchronize nitrogen release with crop demand translates into yield gains, reduced weather-related nitrogen losses, and labor savings where frequent applications are impractical. Studies indicate that partial substitution of conventional urea with PCU (e.g., 50/50 blends) can maintain yield benefits while reducing total N use by 20%, improving both profitability and nitrogen use efficiency (Ma et al., 2024).

5.2 Urease-inhibited urea (e.g., NBPT/NPPT-treated) represents the lowest-cost enhancement relative to conventional urea. It significantly reduces ammonia volatilization at only a small incremental price per unit of nitrogen, making it attractive in surface-applied scenarios such as rice paddies, no-till fields, and alkaline soils (Khakbazan et al., 2013).

5.3 Nitrification inhibitors (e.g., DCD, DMPP) and dual-inhibitor blends show their greatest economic returns under wet and humid conditions, where nitrate leaching and N_2O emissions are dominant loss pathways. By stabilizing ammonium in the soil profile, they not only enhance yield stability but also reduce environmental costs, which may become increasingly important under carbon or nitrogen regulatory frameworks (Verburg et al., 2022).

5.4 Neem-coated urea (NCU), mandated across India's subsidized fertilizer system since 2015, has proven cost-effective at scale. Empirical studies report yield improvements, reduced nitrogen losses, and significant government savings in fertilizer subsidies—estimated at approximately USD 6 million annually (Ramappa et al., 2022). Furthermore, farmers require about 10% less NCU compared with conventional urea to achieve equivalent yields, making it both economically and environmentally sustainable (Government of India, 2025).

5.5 Zinc-coated urea (ZnCU) provides dual benefits: improved nitrogen use efficiency and higher grain zinc concentrations. Although the latter is not always reflected in yield-based economic analyses, its contribution to reducing micronutrient deficiencies offers broader societal and health-related returns, particularly in zinc-deficient regions of South Asia (Wahid et al., 2022).

Ultimately, the program-level economics of these technologies depend on local fertilizer price spreads, subsidy structures, and crop value chains. Hence, while all enhanced-efficiency urea products improve nitrogen recovery and sustainability, their adoption should be guided by site-specific trade-offs between upfront costs, nitrogen savings, yield responses, and co-benefits beyond the farm gate.

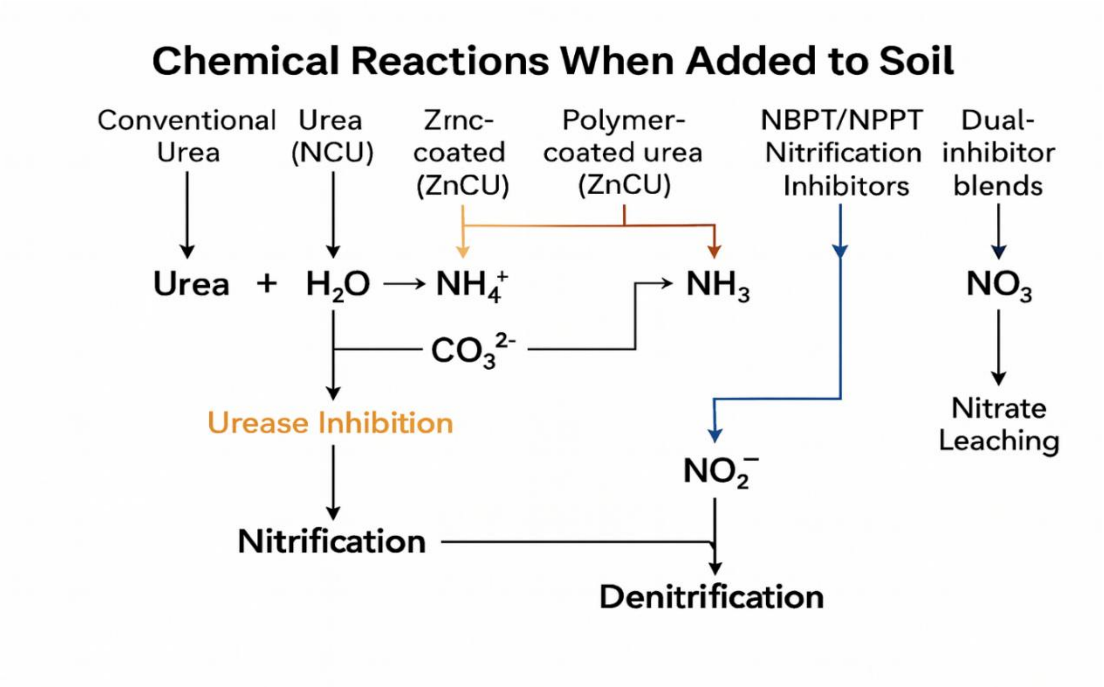
VI. Chemical Reaction when added to soil

Reactions took place in the soils are given in the following figure.

This figure shows the different chemical pathways that occur when urea-based fertilizers are added to soil, along with how coatings and inhibitors affect nitrogen (N) transformations. Conventional urea first hydrolyzes with water (H_2O) to form ammonium (NH_4^+) and carbonate (CO_3^{2-}). This ammonium can undergo further transformations into ammonia (NH_3), nitrite (NO_2^-), and nitrate (NO_3^-). However, significant nitrogen loss can happen in the form of volatilization (as NH_3 gas), leaching (as NO_3^-), or denitrification (producing gases like N_2O) (Cantarella, 2018; Gioacchini et al., 2002).

TABLE 3. Economic Comparison of Enhanced-Efficiency Urea Fertilizers

Fertilizer Type	Cost Premium vs. Conventional Urea	Best Use Case	Economic Advantage	Key References
Polymer-coated urea (PCU)	High (due to manufacturing cost)	High-value crops; labor-scarce systems; climates with high N loss risk	Synchronizes N release, reduces labor inputs, improves yield stability	Ma et al., 2024
Urease-inhibited urea (NBPT/NPPT)	Low (small increment per unit N)	Surface-applied urea (rice paddies, alkaline soils, no-till)	Cost-effective volatilization reduction, high return on small investment	Khakbazan et al., 2013
Nitrification inhibitors (DCD/DMPP) and dual blends	Moderate	Wet soils, humid climates, leaching-prone systems	Stabilizes ammonium, reduces nitrate leaching and N_2O emissions, yield stability under regulation	Verburg et al., 2022
Neem-coated urea (NCU)	Minimal (covered under subsidy in India)	Broad use in subsidized systems; South Asia	Yield increase, 10% less N needed, reduced diversion of subsidized urea, government savings	Ramappa et al., 2022; Government of India, 2025
Zinc-coated urea (ZnCU)	Moderate	South Asia; Zn-deficient soils	Enhances NUE and grain Zn concentration; contributes to human nutrition beyond yield gains	Wahid et al., 2022



Different coating technologies and inhibitors intervene at key steps to slow these losses and improve nitrogen use efficiency. Neem-coated urea (NCU) mainly targets urease activity, slowing the conversion of urea to ammonium (Mohd Zuki et al., 2020). Zinc-coated and polymer-coated urea regulate the release of NH_3 into soil, reducing volatilization (Qi et al., 2021; University of Kentucky Cooperative Extension Service, n.d.). Nitrification inhibitors such as NBPT/NPPT act on the ammonium-to-nitrite step, reducing conversion to nitrate and lowering leaching and denitrification risks (Nugrahaeningtyas, 2022). Finally, dual-inhibitor blends combine both urease and nitrification inhibition, directly minimizing nitrate formation and associated leaching losses (Li et al., 2020).

When quantitatively compared to conventional urea, enhanced efficiency fertilizers substantially reduce nitrogen losses. Urease inhibitors such as NBPT/NPPT typically cut NH_3 volatilization by 50–70%, with dual blends reaching ~75% (Pan et al., 2016; Abalos et al., 2014). Nitrification inhibitors (e.g., DCD, DMPP) reduce N_2O emissions by 45–60% and NO_3^- leaching by 30–50% (Gilsanz et al., 2016; Menéndez et al., 2012; Qiao et al., 2015). Polymer-coated urea decreases NH_3 volatilization by 70–80%, lowers NO_3^- leaching by 25–35%, and reduces N_2O emissions by 10–40% depending on soil and rainfall conditions (Halvorson & Del Grosso, 2013; Akiyama et al., 2010; Trenkel, 2010). Zinc-coated urea shows a 30–40% reduction in NH_3 loss when combined with biopolymer or matrix coatings (Pathak et al., 2016; Jilani et al., 2025). Neem-coated urea (NCU) has been widely recognized as an effective enhanced efficiency fertilizer for reducing nitrogen losses from conventional urea. Research shows that ammonia volatilization (NH_3) is typically 30–50% lower with NCU compared to standard urea applications (Mohanty et al., 2008; Gani, 2017). In addition, the nitrification-slowing properties of neem significantly reduce nitrate leaching (NO_3^-) by about 25–35% (Chinnamuthu & Boopathi, 2009). Field trials in South Asia further confirm that the combined effect of lowering volatilization, leaching, and nitrous oxide emissions leads to an overall nitrogen loss reduction of approximately 30–40% (Jilani et al., 2025). These reductions not only conserve nitrogen in the soil but also translate into improved nitrogen use efficiency especially in Pakistani conditions.

VII. SCOPE AND FUTURE DEMAND OF COATED UREA

Coated urea, a form of enhanced-efficiency fertilizer (EEF), has gained global attention due to its ability to reduce nitrogen (N) losses and improve crop yield sustainability. Inefficiencies in conventional urea use often lead to 10–30% N losses through volatilization, leaching, and denitrification (Abalos et al., 2014). By contrast, urease and nitrification inhibitors have been shown to cut ammonia volatilization by **~35%**, while polymer- and sulfur-coated products synchronize N release with plant uptake, thereby improving nitrogen use efficiency (NUE) (Abalos et al., 2014; Li et al., 2020).

7.1 Global Market Scope

The global coated urea market is projected to grow steadily. For example, the sulfur-coated urea (SCU) market is expected to expand from USD 1.20 billion in 2025 to USD 1.59 billion by 2030 at a 5.8% CAGR, with Asia–Pacific as the fastest-growing region (Mordor Intelligence, 2025). Similarly, polymer-coated urea (PCU) is forecast to reach USD 1.45 billion by 2032, growing at a 6.5% CAGR (Coherent Market Insights, 2025). Other estimates place the PCU market at USD 6.8 billion by 2032 (Verified Market Reports, 2025), highlighting the variability in projections but consistent upward growth. Combined polymer- and sulfur-coated urea (PCSCU) is anticipated to grow even faster, nearly doubling to USD 2.5 billion by 2033 (Verified Market Reports, 2025).

Global urea production capacity also supports this scope, with 199.7 Mt produced in 2024, the highest on record (International Fertilizer Association [IFA], 2025). The availability of abundant base urea ensures feedstock for coating technologies. Moreover, fertilizer price volatility, such as the swing from USD 801/t in March 2022 to USD 293/t in September 2024, further strengthens the economic case for coated products, since farmers are motivated to minimize losses during high-price periods (Food and Agriculture Organization [FAO], 2024).

7.2 Drivers of Future Demand

7.2.1. Environmental regulations. The EU Farm-to-Fork strategy aims to cut nutrient losses by 50% and reduce fertilizer use by 20% by 2030, directly incentivizing adoption of EEFs (Fertilizers Europe, 2025). Similarly, U.S. nutrient-reduction programs maintain pressure to curb leaching and surface-water contamination (United States Environmental Protection Agency, 2024).

7.2.2. Agronomic performance. Field studies in rice and wheat have shown that polymer-coated urea or stabilized products can save up to 20% N fertilizer while maintaining or even enhancing yields (Ma et al., 2024). Such products also delay leaf senescence and enhance antioxidant enzyme activity (Li et al., 2020).

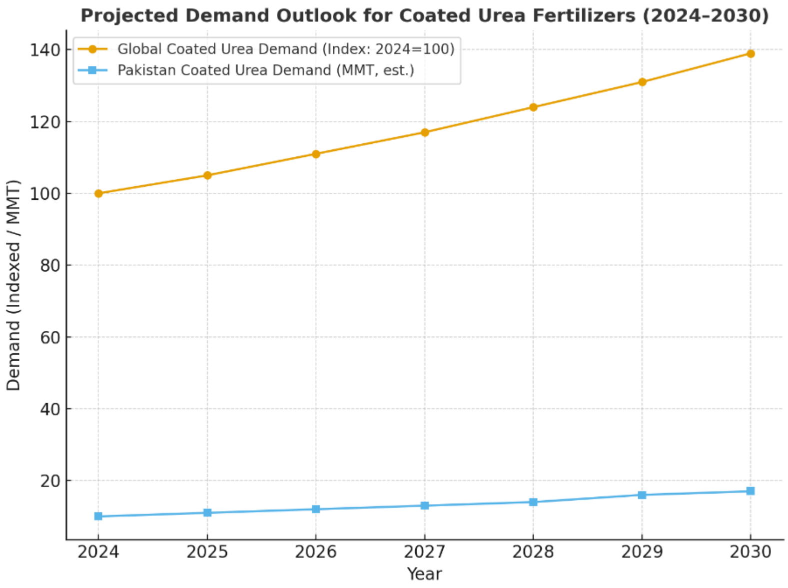
7.2.3. Farm economics. While coated urea carries a 10–40% price premium over conventional urea, reduced application frequency and improved nutrient-use efficiency often offset costs (University of Montana Extension, 2014).

7.3 Pakistan's Context and Global Scope

Pakistan is among the world's heaviest urea users, with fertilizer offtake reaching 9.5 million metric tons (MMT) in FY2024, while urea production grew 9% year-on-year (VIS Credit Rating Co., 2024). This large domestic market baseline presents significant potential for enhanced-efficiency fertilizers. Empirical evidence suggests that zinc-coated and inhibitor-treated urea (Neem Coated) can improve wheat and rice productivity under Pakistani agro-climatic conditions (Wahid et al., 2022). Lessons from global experiences further underscore this potential. For instance, India mandated 100% neem-coated urea in 2015, a policy that not only curtailed diversion of subsidized urea but also improved nitrogen use efficiency (Government of India, 2019; Ramappa et al., 2022). Similarly, in China, large-scale adoption of polymer-coated and inhibitor-treated fertilizers has been associated with measurable gains in crop yield and reduced nitrogen losses (Li et al., 2020). If Pakistan substituted even 5–10% of its conventional urea with coated or stabilized forms, it could open a sizeable domestic market while simultaneously aligning with global best practices in sustainability.

7.4 Future Demand Outlook

Globally, the coated urea market is projected to expand at a compound annual growth rate (CAGR) of 5–8% through 2030, with Asia–Pacific identified as the leading growth hub (Coherent Market Insights, 2025; GMInsights, 2024). Drivers of this trend include rising environmental regulations, farmer awareness of nitrogen use efficiency (NUE), and the demand for sustainable intensification of agriculture. In South Asia, India's neem-coating mandate has demonstrated how regulatory measures can accelerate adoption (Ramappa et al., 2022), while China's experience shows the value of linking subsidies to enhanced-efficiency fertilizers (Li et al., 2020). For Pakistan, introducing policy support similar to India's, coupled with on-ground demonstration plots for wheat and rice, could significantly expand adoption. By integrating regional lessons with domestic strategies, Pakistan has the potential to emerge as a regional leader in coated fertilizer deployment, contributing both to food security and environmental sustainability.



VIII. CONCLUSION

Coated and inhibitor-treated urea fertilizers represent complementary strategies to overcome the inefficiencies of conventional urea. Among them, polymer-coated urea (PCU) and dual-inhibitor blends consistently deliver the strongest agronomic and environmental benefits, while urease inhibitors such as NBPT provide the most cost-effective option for reducing ammonia volatilization. Neem and zinc-coated urea offer valuable region-specific sustainability advantages in South Asia, simultaneously improving crop yields and enhancing grain nutritional quality especially in Pakistan. Collectively, these results reinforce that no single product is universally optimal; rather, fertilizer adoption should be guided by soil type, climatic conditions, cropping system, and economic feasibility. By aligning agronomic performance with environmental stewardship and local needs, enhanced-efficiency urea fertilizers hold significant promise for advancing sustainable agricultural productivity.

IX. RECOMMENDATIONS

a. Promote Context-Specific Fertilizer Adoption

- Encourage farmers and policymakers to avoid "one-size-fits-all" solutions.
- Adoption decisions should be tailored to soil type, climate, cropping system, and economic feasibility.

b. Prioritize Polymer-Coated Urea (PCU) and Dual-Inhibitor Blends

- PCU and dual-inhibitor blends consistently provide the best balance of yield gains and environmental protection.
- Recommend these for high-value crops and regions with significant nitrogen loss problems.

c. Use Urease Inhibitors for Cost-Sensitive Farmers

- NBPT and similar inhibitors are effective, affordable, and easy to adopt.
- These can serve as the entry point for smallholder farmers transitioning to enhanced-efficiency fertilizers.

d. Leverage Neem- and Zinc-Coated Urea in South Asia

- Promote neem-coated urea to reduce diversion and improve nitrogen use efficiency.
- Promote zinc-coated urea for dual benefits: higher yields and better nutritional quality of grain, which addresses micronutrient deficiencies common in the region.

e. Align with Environmental and Sustainability Goals

- Position coated and inhibitor-treated urea as tools to advance sustainable intensification—boosting food security while reducing greenhouse gas emissions and water pollution.
- Link adoption strategies to SDG 2 (Zero Hunger) and SDG 13 (Climate Action).

f. Encourage Policy and Extension Support

- Recommend government subsidies, extension services, and awareness programs to accelerate adoption.
- India's successful 100% neem-coated policy offers a replicable model for Pakistan and other South Asian countries.

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