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Review article

Current agronomic evidence on nano-urea in the nitrogen transition of cropping systems. A mini-review

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ABSTRACT

Nitrogen fertilisation remains a major challenge in the transition towards more sustainable cropping systems. Despite decades of research, nitrogen use efficiency (NUE) is still low in many agricultural contexts, while reactive nitrogen losses continue to affect air quality, water quality and climate targets. Within this broader search for innovation, nano-urea has emerged as one of the most visible cases of nano-enabled agriculture, although its agronomic value remains debated. This mini-review examines the current evidence on nano-urea in conventional cropping systems and places it within a broader regulatory and strategic context. A PRISMA-informed literature search was conducted in the Scopus and Web of Science databases for the period 2015–2026, complemented by bibliometric mapping. After screening and de-duplication, 194 relevant records were retained. The literature is recent, strongly India-centred, and increasingly dominated by field-oriented studies. The agronomic evidence shows a consistent pattern: first-generation nano-urea does not replace soil-applied urea, but it can support moderate reductions in soil N input, generally around 20–25%, when combined with adequate basal fertilisation and correctly timed foliar sprays. Attempts to replace 50% or more of conventional urea usually led to yield penalties or weaker N uptake. Reported gains in NUE and emission-related indicators are modest and appear to depend more on lower N rates and improved management than on a distinctly nano effect. Overall, nano-urea is best regarded not as a breakthrough substitute for conventional urea, but as an early test case within the wider nitrogen transition in agriculture.

1. Introduction

Agricultural systems are a cornerstone of prosperous societies and must therefore be maintained and protected. The EAT-Lancet framework, developed by the non-profit organisation EAT (https://eatforum.org/) and updated in October 2025, identifies the Planetary Health Diet as a reference model for feeding nearly 10 billion people by 2050 in a healthy and sustainable way (Rockström et al., 2025). At the core of this perspective is the transformation of food systems so that they remain within planetary boundaries, including land use and greenhouse gas emissions, while improving public health. One of the central issues in this discussion is fertiliser-use efficiency.

Within this broader tension between agricultural sustainability and food security, nitrogen fertilisation remains one of the main bottlenecks. Global use of inorganic fertilisers continues to increase and in 2023 reached 195.1×10^6 Mg, including 112×10^6 Mg of nitrogen fertilisers (Food and Agriculture Organization FAO, 2025). Despite decades of research and agronomic progress, nitrogen use efficiency (NUE) remains low in many systems, and surplus N contributes to ammonia volatilisation, nitrous oxide emissions and nitrate leaching, with consequences for air and water quality alongside climate targets. Urso and Gilbertson (2018) also argued that fertiliser efficiency should not be assessed only at field level, because important inefficiencies arise earlier in the chain, during fertiliser synthesis and nutrient conversion before nitrogen even reaches the crop.

A key family of technologies developed to improve NUE is enhanced-efficiency fertilisers (EEF), which include stabilised fertilisers based on urease or nitrification inhibitors as well as slow- and controlled-release fertilisers (Melara et al., 2024). These products were developed to delay, protect or regulate nutrient release in soil (ISO 8517:2015; ISO 8157:2015; Govil et al., 2024). Because of their higher cost compared with conventional fertilisers, they are used mainly in horticulture and other high-value crops rather than in large-scale arable farming (Lammel, 2005). Taken together, low NUE values, growing fertiliser use and tightening environmental constraints indicate that improving fertilisation efficiency in field crops remains a major challenge and a

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priority for innovation.

The fertiliser issue has also acquired a more explicitly strategic dimension. Fertilisation is one of the foundations of global food security, yet the technical structure of fertiliser production depends heavily on global logistics networks and energy. This double vulnerability has become increasingly visible in recent years. The Russian-Ukrainian conflict showed how rapidly the fertiliser sector can be affected by price spikes and supply disruptions (Jia et al., 2024). New tensions in the Strait of Hormuz point to an even broader risk, because they combine global energy insecurity with the possible disruption of ammonia, urea and other strategic inputs. In this setting, fertilisation efficiency is no longer only an agro-environmental objective. It has become part of a wider question of agricultural resilience and, ultimately, food security (FAO, 2026).

Growing concern for the sustainability of agricultural systems was initially driven mainly by environmental awareness and by the evidence associated with climate change. The present scenario raises further questions, and many of them are likely to be answered only through innovation. Digital technologies, geolocation, sensor networks, real-time weather monitoring, precision techniques, nanotechnologies, new energy systems and innovative services all offer tools that can be progressively integrated into farming systems. With specific reference to fertilisation, further improvements in efficiency, both in industrial fertiliser production and in field application, require genuinely new approaches (Zhang et al., 2015). In Europe, sustainable intensification is therefore unlikely to depend simply on increasing the number of inputs and machines per hectare. A more plausible direction is to build management systems that are more intensive in information and knowledge. Using an effective slogan, what is needed is “more knowledge per hectare” (Buckwell et al., 2014). A similar view has been expressed by the Italian Association of Agricultural Scientific Societies (AISSA, 2022), which recently argued that sustainable intensification also means embedding more knowledge and technology into production processes, drawing on advances in science, technology and ICT.

Within this broader search for innovation, nanotechnology has been proposed since the early 2000s as an enabling set of tools for agriculture, often referred to as Nano-Enabled Agriculture (NEA). The concept gained wider visibility through a dedicated editorial and special issue in Nature Nanotechnology (Pulizzi, 2019). In plant nutrition and fertilisation, NEA is relevant mainly through nanostructured nutrient carriers, coatings and delivery systems designed to increase nutrient-use efficiency and reduce reactive N losses. Nanofertilisers can be broadly defined as fertiliser products that contain nutrients in the nano-size range and/or use nanostructured carriers to enhance nutrient delivery, control nutrient release and improve nutrient-use efficiency (Haydar et al., 2024). Within this broad field, nano-urea has attracted particular attention as a foliar N input proposed to complement conventional urea-based fertilisation strategies. At the same time, this domain remains marked by conceptual and experimental uncertainty. The term nano-urea is used in different ways to describe different formulations and delivery methods, which creates inconsistencies across studies and products. Experimental research conducted in greenhouses, pots and field settings has in some cases shown that nano-urea may improve crop performance and increase NUE compared with conventional urea, often at lower nitrogen application rates. The evidence, however, remains limited and strongly dependent on context, and nano-urea should not be viewed as a direct replacement for granular or prilled urea. More broadly, NEA is still immature and cannot yet provide definitive answers to the problem of fertilisation efficiency. Still, technological advances derived from nanotechnology have already transformed many production sectors (Roco and Bainbridge, 2013), and it is unlikely that agriculture will remain entirely outside that wider trend. Even within a field that is still taking shape, nano-urea has already emerged as a visible and controversial case, and for that reason it deserves closer examination. What matters here is to distinguish carefully between industrial promises, political expectations and verified agronomic evidence.

Against this background, the present paper is organised on two levels. The first develops a focused mini-review of the agronomic efficacy of nano-urea as a nitrogen fertiliser within conventional cropping systems. To delineate the current evidence base, a PRISMA-informed literature search was conducted in the Scopus and Web of Science databases (2015–2026), selected for their broad coverage and bibliometric compatibility. The search was restricted to peer-reviewed articles and reviews published in English, excluding non-agricultural applications. The second part examines the broader regulatory and strategic context surrounding nano-fertilisers, which is developing with different intensity across geographical regions. The aim is not only to review the emerging agronomic evidence on nano-urea, but also to position it within the wider technological and strategic transition currently affecting nitrogen fertilisation.

2. Bibliometric overview of the nano-urea literature

This article is not intended as a meta-analysis or as an exhaustive systematic review of all nano-enabled fertiliser research. Rather, it is a focused mini-review centred on nano-urea, based on a PRISMA-informed literature search and selection workflow and complemented by a broader scientific and contextual discussion. Because the topic is recent, relatively specialised, and still characterised by a limited and geographically concentrated evidence base, a structured search strategy was adopted to identify the subset of studies most relevant to agronomic interpretation and critical discussion.

The literature search was conducted using the Scopus and Web of Science databases, selected for their broad coverage and compatibility with bibliometric mapping. Records were retrieved and the final screening workflow was updated on 28 April 2026. The search strategy was based on nano-urea-related terms in titles, abstracts and keywords, including nano urea, nano-urea, nanourea, liquid nano urea, liquid nano-urea, urea nanoparticles, urea nanocomposite and urea nanocomposites. The search window covered the period 2015–2026, with restriction to English-language peer-reviewed articles and reviews. Following merging of the two databases, duplicate removal, and manual cleaning of clearly irrelevant or non-agricultural items, the final dataset retained 194 relevant records (A+B+C). This workflow was organised according to a PRISMA-informed logic of identification, de-duplication, screening, eligibility assessment and final inclusion, and is summarised in Fig. 1.

The purpose of this dataset was twofold. First, it provided the bibliographic basis for the descriptive analysis of publication trends, geographical distribution and study profiles. Second, it was used for bibliometric mapping in VOSviewer (version 1.6.20), in order to visualise the conceptual and temporal structure of the nano-urea literature. Keyword co-occurrence analysis was performed on the updated dataset after exclusion of rare terms below the minimum occurrence threshold.

The updated Scopus–Web of Science dataset shows continued growth, but not a radical expansion of the field. More importantly, the evidence base remains highly geographically unbalanced. India accounts for the overwhelming majority of records and for most of the field-oriented evidence, whereas contributions from Europe, the Middle East, Africa, the Americas and Oceania are far fewer and more fragmented. The current literature is therefore not only recent, but also spatially concentrated, which already suggests caution in generalising results across agroecological regions and production systems. Table 1 summarises the geographical structure of the dataset, including the distinction between greenhouse, field and other study types.

The temporal profile of the literature reinforces this interpretation. As shown in Fig. 2A, annual publication output remained very low until the end of the 2010s and then increased sharply after 2020, with a particularly strong rise in 2024–2026. At the same time, the composition of the literature also changed.

Fig. 2B shows that earlier publications were sparse and relatively mixed, including reviews, formulation-oriented studies and controlled-

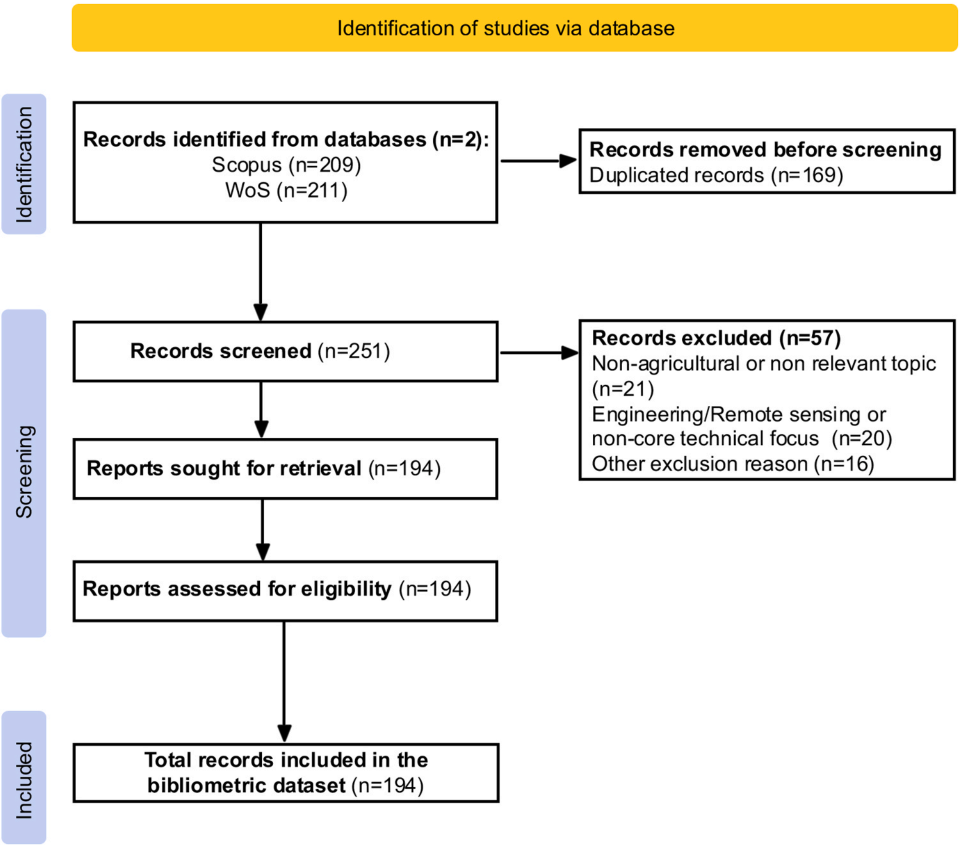

Fig. 1. PRISMA-informed flow diagram of the literature search and record selection process used to construct the updated nano-urea dataset.

Table 1
Geographic distribution and typology of studies on nano-urea. A = agronomic studies; A-G greenhouse/pot studies; A-F = field studies; B/C = reviews, formulation-oriented and other records.

Macro Region	Total	A	A-G	A-F	B/C
India	139	112	13	99	27
Rest of Asia	15	8	2	6	7
Europe	14	9	4	4	5
Africa	8	5	1	4	3
Middle East	8	4	3	1	4
North America	5	3	3	0	2
South America	4	3	2	1	1
Oceania	1	1	1	0	0

environment experiments, whereas the most recent phase is characterised by the growing predominance of field-oriented studies. This pattern suggests a partial maturation of the field, with research moving from materials development and preliminary proof-of-concept work towards more explicit agronomic evaluation under crop-management conditions. However, because this recent expansion is still dominated by Indian studies and recurrent research networks, the apparent coherence of the emerging evidence should not yet be interpreted as broad multi-regional validation.

The keyword co-occurrence structure of the updated literature is shown in Fig. 3. The map highlights a clear dual thematic organisation. One cluster is centred on nanofertiliser materials and formulation-related concepts, including nanoparticle, nanofertiliser, hydroxyapatite, release fertiliser and related terminology. This side of the literature is primarily concerned with the design and functional properties of nano-enabled fertiliser systems. A second cluster is organised around agronomic management variables, particularly spray-based nano-urea application, nitrogen management and dose-related optimisation. This reflects the part of the literature in which nano-urea is evaluated more directly as a crop-management tool. The position of sustainable agriculture between these clusters suggests that it acts as a bridging concept linking technological innovation with agronomic use. Overall, the map indicates that the field still lies between proof-of-concept materials research and agronomic validation.

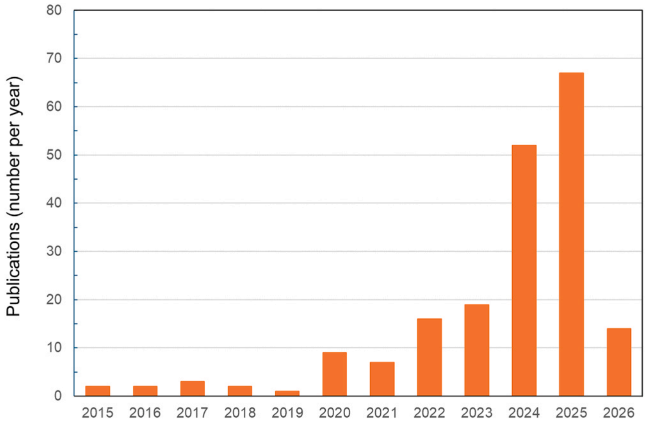

Fig. 2A. Annual number of publications in the updated nano-urea dataset (2015–2026). The figure shows the recent expansion of the field, with a marked increase after 2020 and a particularly strong rise in 2024–2026.

This interpretation is further strengthened by the overlay visualisation shown in Fig. 4. The temporal distribution of terms indicates that earlier literature was more strongly associated with synthesis-, nanomaterials- and release-oriented concepts, whereas the most recent terms are increasingly linked to agronomic use and nitrogen management. In particular, terms related to spray application, nitrogen management,

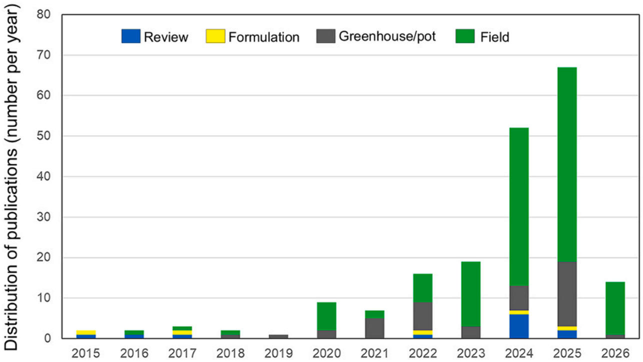

Fig. 2B. Annual distribution of publications in the updated nano-urea dataset (2015–2026), grouped by study profile. The figure highlights the methodological evolution of the literature from an initially sparse and mixed evidence base towards a clear predominance of field-oriented studies in the most recent years.

nitrogen application and practice-oriented agronomic optimisation appear among the most recent elements of the network. The temporal overlay therefore confirms that the field is not only growing numerically, but is also undergoing a thematic shift from formulation-centred research towards explicit agronomic evaluation.

Beyond publication growth, the updated dataset reveals a genuine methodological evolution of the evidence base. Early work was dominated by reviews, formulation studies and controlled-environment experiments, reflecting a phase in which the emphasis was placed on material design, release behaviour and preliminary plant responses. By contrast, the literature published from 2020 onwards increasingly focuses on crop performance under field conditions, nutrient management strategies and partial substitution scenarios involving soil-applied urea plus foliar nano-urea. This transition is important because it marks the passage from a literature mainly concerned with whether nano-urea might work in principle to one more explicitly concerned with how, and under which nitrogen-management conditions, it performs in real cropping systems. Even so, the field remains both geographically and methodologically uneven, and the present evidence base is still too concentrated to support broad generalisation.

The distribution of journals is highly fragmented, with 194 records published across 107 different journals. Notably, 79 of these journals contributed only one paper each from 2015 to 2026 (Table. S1). The interpretative message is that the field is disciplinarily segmented between agronomic and field-oriented journals, on the one hand, and outlets more closely associated with nanomaterials, formulation studies, or broader environmental framing, on the other. This disciplinary split is consistent with the dual structure observed in the keyword maps. Furthermore, the publication output is not randomly distributed; it is concentrated in a small core of agronomic journals that primarily focus on field-oriented studies in the Indian context. This trend indicates that research on nano-urea is growing, but nano-enabled agriculture has not yet achieved a stable editorial placement between nanoscience,

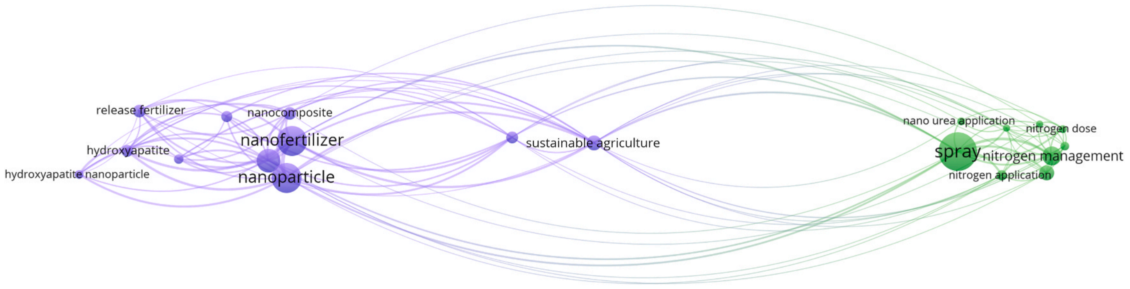

Fig. 3. Keyword co-occurrence map of the updated nano-urea literature. The map highlights a dual structure, with one cluster centred on nanofertilizer materials and formulation-related concepts and a second cluster focused on agronomic management variables, particularly spray-based nano-urea application, nitrogen management and dose optimisation. Sustainable agriculture acts as a bridging theme between these domains.

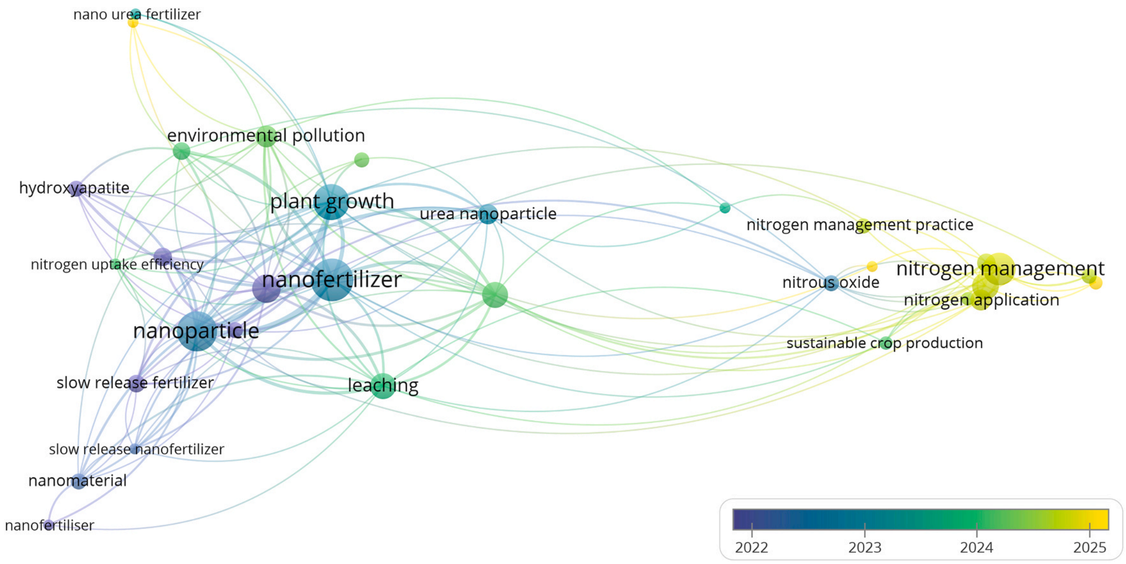

Fig. 4. Overlay visualisation of term co-occurrence in the updated nano-urea literature. Node colours indicate the average publication year of the selected terms, showing a temporal shift from earlier materials- and release-oriented terminology towards more recent agronomic and nitrogen-management concepts.

environmental research and mainstream agronomy.

This observation can also be reasonably extended to other applications of nanotechnology in agriculture, such as pathogen control, soil fertility, plant stress, and genetic engineering (Jiang et al., 2021). Such fragmentation is typical of a young and hybrid field: while it has moved beyond merely proving concepts in nanoscience, it has not yet fully aligned with the traditional experimental standards preferred by established agronomic journals.

Finally, a small number of recent publications suggest that the horizon of nano-enabled agriculture may be beginning to extend beyond fertiliser formulation and conventional agronomic testing. In this respect, one 2026 paper published in Drones (MDPI, Subject Area: Computer Science and Engineering) is noteworthy. Although excluded from the final agronomic dataset because of its engineering and remote-sensing focus, it remains relevant as a signal that research on nano-fertilisers is beginning to interact with adjacent technological domains, including digital monitoring and remote sensing. This does not alter the agronomic conclusions of the present review, but it does indicate that the broader innovation space surrounding nano-enabled agriculture may be widening.

3. What the current evidence on nano-urea actually shows

Table S2 summarises the key Q1–Q2 studies used in the agronomic synthesis and helps show how the nano-urea literature has changed over time. In an initial phase (2017–2022), most studies dealt with a simple question: whether nano-urea could replace conventional urea, and at what dose. A second phase (2023–2025) moved towards more agronomically structured strategies, combining foliar nano-urea with soil-applied urea, coated fertilisers and other nutrient-management approaches. The most recent literature points to a third phase, still emerging, in which the field begins to move beyond the basic replacement model. This includes work on tree crops, agroforestry systems, crop-specific management strategies and, in some cases, physiological or omics-oriented responses.

This broadening matters, but it does not change the main conclusion drawn from the earlier evidence. The literature remains strongly centred in India, and first-generation nano-urea still performs best as a complementary foliar N source that can support moderate reductions in soil-applied urea, rather than as a full substitute for conventional fertilisation. Reported gains in nitrogen use efficiency and emission-related indicators are generally modest. In most cases, they seem to reflect lower N rates and better management more than a distinctly “nano” mechanism.

3.1. *Multi-location cereal field trials: yield and N saving*

Multi-location cereal trials show a fairly consistent pattern: nano-urea does not replace soil-applied urea, but it can support moderate N savings. In irrigated wheat, Tripathi et al. (2025) reported across 21 sites that two foliar sprays of IFFCO liquid nano-urea combined with 75% of the recommended soil N dose maintained grain yield at levels comparable to the full-rate control, whereas the 50% RDN treatment produced a clear penalty. Kumar et al. (2024) found a similar response in salt-affected rice–wheat systems, where about one-third substitution of conventional urea with nano-N remained agronomically acceptable, but substitution levels of 50% or more progressively reduced yield and soil N status. In wheat–maize and pearl millet–mustard rotations, Upadhyay et al. (2023) again found that 75% RDN plus nano-urea maintained yield with a 25% N saving, while 50% or 0% RDN plus nano-urea was clearly insufficient. Under conservation tillage, Kumar et al. (2023) reached the same practical conclusion: full soil N remained the safer option, and increasing the number of nano-urea sprays did not compensate for strong reductions in basal N. In rice, both Sandeep et al. (2025) and Nagangoudar et al., (2025)) confirmed that moderate reductions in soil-applied N could be sustained when supported by foliar nano-urea, whereas stronger substitution or nano-urea-only regimes remained inferior to full-rate conventional fertilisation.

The more recent wheat studies do not overturn this picture, but they do make it more nuanced. Singh et al. (2026) showed that different commercial nano-urea formulations can produce somewhat different responses in wheat, although the best outcomes were still obtained when foliar nano-urea complemented, rather than replaced, a substantial basal N supply. Kaur et al. (2026) reached a similar conclusion: foliar nano-urea or foliar urea could help maintain performance under simplified split-N schedules, but the best overall treatment remained the fully supplied four-split soil-N programme. What changes here is not the agronomic message itself, but the level of the question. The field is no longer asking only whether nano-urea works or not; it is beginning to ask how different formulations and management schemes behave under practical agronomic conditions.

The same logic now appears in systems outside the classical cereal core. In peach, Chawla and Sharma (2026) found that foliar nano-urea was effective only above a minimum soil-N threshold and could support moderate reductions in soil-applied N, rather than replace it. In sugarcane, Nagargade et al. (2026) obtained the best results not with nano-urea alone, but with integrated nutrient-management packages combining reduced conventional N, nano-urea, micronutrients and biofertilisers. In a guava-based agroforestry system, Shukla et al. (2026) likewise found that the most effective strategy was 75% RDN plus foliar nano-urea. Across crop systems, the same practical point keeps returning: nano-urea may help refine an existing N programme, but it does not remove the need for an adequate soil-based nutrient supply.

3.2. *Nitrogen use efficiency and soil N dynamics*

Studies dealing more explicitly with nitrogen use efficiency and soil N dynamics sharpen the same picture. In wheat–rice and wheat–maize systems, Reddy et al. (2025) and Upadhyay et al. (2024) showed that moderate reductions in soil-applied nitrogen, when supported by nano-urea, could help maintain yields and slightly improve selected efficiency indicators. Those gains, however, were not strong enough to justify deeper cuts in basal N. The conservation-tillage wheat system examined by Kumar et al. (2023) pointed in the same direction: once soil N was reduced more sharply, crop performance declined despite repeated foliar sprays.

The most consistent result, then, is that 75% of recommended soil N plus nano-urea can sometimes sustain yields and improve selected efficiency metrics, whereas 50% or less usually leads to weaker performance. Where gains in NUE were reported, they were generally modest. Reddy et al. (2025) observed somewhat higher NUE under intermediate N-saving strategies, but with lower profitability than the full-rate control. Upadhyay et al. (2024) found that 75% N plus nano-urea, with or without nano-zinc, maintained yield and N uptake while preserving microbial biomass, but nano-urea alone was clearly insufficient.

Pot-based work by Sadhu et al. (2025) adds an important caution. In their study, foliar nano-urea at reduced soil N supported yield and nitrogen recovery, but more advanced nano-clay–polymer composites performed better in maintaining soil N fractions and enzyme activity. That distinction matters. Short-term agronomic success with foliar nano-urea should not automatically be read as evidence of broader improvements in soil fertility or in longer-term nitrogen dynamics.

3.3. *Emissions and eco-efficiency*

The available studies also suggest that nano-urea can contribute to lower gaseous N losses, but the effect is clearly conditional. Under T-FACE conditions, Apoorva et al. (2025) found that integrating nano-urea with reduced neem-coated urea lowered cumulative N_2O emissions and NH_3 volatilisation relative to full-rate coated urea, although at the cost of modest penalties in yield and grain N. In rice systems, Sandeep et al. (2025) and Nagangoudar et al., (2025) showed that changes in global warming potential, eco-efficiency and water-use indicators depended strongly on crop establishment method, irrigation regime and moderate N-rate reductions supported by nano-urea. Upadhyay et al. (2023) reported a similar trend at the system level, with lower GHG emissions where moderate reductions in soil N were combined with foliar nano-urea.

These results suggest that nano-urea may help reduce emissions when it allows some reduction in soil N input. Still, the apparent benefit seems to come mainly from lower rates and better management integration, not from an intrinsically different "nano" emission factor. That is why nano-urea needs to be judged against established low-emission options such as coated and inhibitor-based urea, and not in isolation.

3.4. System-level and soil biological responses

Studies that include soil biological indicators do not show clear short-term adverse effects of nano-urea on microbial biomass or related soil proxies. Upadhyay et al. (2024) reported stable microbial biomass under 75% N plus nano-urea treatments, whereas Nagargade et al. (2026) found improved soil biological health under integrated nutrient-management packages combining reduced conventional N, nano-urea and biofertilisers in sugarcane. At the same time, positive soil-building effects are not consistently demonstrated, and the responses reported so far are modest when compared with those observed for some more advanced nanocomposites or integrated formulations. Sadhu et al. (2025) is again instructive here: foliar nano-urea performed reasonably well in terms of yield and N recovery, but the nano-clay–polymer composite was more effective in sustaining soil N fractions and enzyme activity.

At this stage, the most sensible conclusion is a cautious one. The short-term record does not point to obvious soil-biological damage, but it does not yet provide strong evidence for broader soil improvement either. Longer-term field data are still scarce, and that remains one of the clearest gaps in the literature.

3.5. Composite nanofertilisers and minor crops

The earlier Q1–Q2 studies also make it clear that commercial foliar nano-urea should not be judged in isolation. A broader family of nano-enabled fertiliser concepts is already present in the literature. Abdelgawad et al. (2024), for example, reported that hydroxyapatite-based controlled-release nano-urea formulations could maintain bean yield at reduced N rates under some conditions, suggesting a stronger N-saving potential than that observed for first-generation foliar products. In greenhouse or pot systems, Reis et al. (2022), Ullah et al. (2022) and Singam et al. (2021) explored nanocomposites, stress-mitigation sprays and slow-release UHA systems that widen the technical meaning of nitrogen nanofertilisers beyond commercial liquid nano-urea. Rajendran et al. (2017), even earlier, reported that integrated nano-SRF approaches could improve yield, seed quality and soil fertility relative to conventional fertilisers, although these systems are only partly comparable with the present foliar nano-urea literature. Abisankar et al. (2024) adds another useful contrast, showing in chickpea that a nano-emulsion biofertiliser outperformed nano-urea in yield and nutrient uptake.

Taken together, these studies suggest that nano-N sprays are not necessarily the best nano-based option in all crop systems, and that the future of nano-enabled fertilisation may well depend more on composite, controlled-release or multifunctional formulations than on current commercial foliar nano-urea alone. For that reason, these studies are best read not as direct support for the strongest claims made around nano-urea, but as signals of where the field may be moving next.

4. Why nano-urea evidence is India-centred, and why this matters in Europe

The agronomic literature reviewed in 3 is recent, limited in scope, and heavily concentrated in India. This geographical imbalance is not accidental. It reflects the combination of policy support, industrial scale-up, regulatory permissiveness and large-scale field deployment that turned India into the main real-world setting for nano-urea. The European picture is very different: nano-fertilisers remain marginal, both on the market and in agronomic experimentation. For this reason, the apparent consistency of the available evidence should be interpreted with caution. Much of it comes from one national innovation system rather than from broad validation across regions and production contexts.

4.1. India: policy push, industrial scale-up and evidence concentration

Since the late 2000s, India has combined strong investment in nanoscience with a dedicated pathway for the evaluation of nano-based agri-inputs. An important step was the 2020 "Guidelines for the Evaluation of Nano-Based Agri-Input and Food Products", coordinated by the Department of Biotechnology, which provided a framework for addressing human, animal and environmental safety and helped open the way to commercialisation (Department of Biotechnology, 2020). Within this setting, nano-urea became the most visible case by far, and its promotion reached a scale not seen elsewhere.

The clearest example is IFFCO Nano Urea (Liquid), a 4% N formulation in which a substantial fraction of particles or clusters falls within the tens-of-nanometres range and is stabilised by surfactants and polymer matrices. What matters, however, is not only the product itself, but the broader programme around it: multi-location trials, farmer demonstrations, industrial production, and a political narrative linking nano-urea to lower import dependence, reduced subsidy pressure and technological modernisation in agriculture. India has therefore provided not only most of the papers reviewed here, but also the institutional environment in which nano-urea could move from laboratory promise to large-scale agronomic testing. This helps explain why the literature is so strongly concentrated in Indian wheat, rice, maize and related systems. The pattern reflects more than scientific interest alone; it reflects a coordinated innovation trajectory in which product development, extension activity and agronomic experimentation reinforced one another.

At the same time, the Indian case also reveals the limits of the dominant public narrative around nano-urea. One of the most widely repeated promotional claims, often condensed into the slogan that "one 500 mL bottle replaces one 45-kg bag of urea", is not supported by the agronomic evidence reviewed here. Across the studies discussed in 3, the most recurrent result is not one-to-one substitution, but the possibility of maintaining yield when soil-applied urea is reduced by roughly 20–25% and foliar sprays are well timed. Once soil N is cut more sharply, yield penalties become common. This is why independent analyses have called for greater caution and for clearer mechanistic evidence. Frank and Husted (2024) questioned the scientific basis for near-complete substitution claims, and Sikka et al. (2025) similarly failed to confirm the performance claimed for IFFCO Nano Urea.

These criticisms do not rule out a role for nano-urea in specific and well-defined management strategies. They do, however, make it necessary to separate technological visibility from agronomic validation. India remains the unavoidable reference point for understanding nano-urea today, but it is also the place where the gap between promise and field evidence is most visible.

4.2. European Union: regulatory caution and limited agronomic uptake

The European situation is almost the reverse. The EU updated its horizontal definition of "nanomaterial" in 2022, but agricultural uses of nanotechnology are still handled mainly through case-by-case adaptation of existing rules. Key sectoral regulations, including those on plant protection products and fertilising products, do not contain dedicated provisions for nano-pesticides or nano-fertilisers. In practice, nano-specific issues are usually addressed through dossier-based demonstrations of safety and efficacy, while important uncertainties remain over physicochemical characterisation, environmental behaviour and traceability. Governance is shaped largely by the work of ECHA, including the EU Observatory for Nanomaterials, and by EFSA guidance focused mainly on the food and feed chain. Recent analyses have argued for clearer operational definitions of nano-agrochemicals, mandatory disclosure of nanoforms on labels, tailored risk-assessment procedures and better traceability tools. Yet, despite these discussions, nano-fertiliser products are still essentially absent from EU markets. Europe is therefore not a zone of active deployment, but a zone of regulatory caution and limited agronomic uptake (Urbani et al., 2024). This helps explain why the evidence reviewed in this paper contains so little European field experience. The issue is not simple neglect. Nano-urea has not yet found a stable place in Europe at the intersection of regulation, market access and agronomic experimentation. The result is that the literature on nano-urea still reflects a strong asymmetry: active deployment and concentrated evidence in India, caution and near-absence of agronomic uptake in Europe.

4.3. The Italian perspective and its relevance for intensive cropping systems

This European asymmetry becomes especially relevant in Italy, where nitrogen fertilisation is no longer only an agronomic and environmental issue, but also an increasingly explicit regulatory one. Italy's prolonged non-compliance with the Ambient Air Quality Directive eventually led to the adoption of the National Air Quality Action Plan (Consiglio dei Ministri, 2025), which introduced corrective measures across major emitting sectors, including agriculture. Within this framework, agricultural nitrogen management became directly linked to ammonia abatement. One of the most consequential steps is the planned ban on urea use in the Po Valley from 1 January 2028. To support that transition, the Plan promotes nitrification inhibitors, low-emission slurry-spreading equipment, innovative treatment of digestates and livestock effluents, and variable-rate fertilisation. These are all relevant tools, but they are also largely familiar ones, and their adoption remains uneven.

This is the point at which the nano-urea discussion becomes more than academic. The evidence reviewed in this paper does not support first-generation nano-urea as a breakthrough solution or as a one-to-one replacement for conventional urea. Still, it does suggest that in some conditions foliar nano-urea can support limited reductions in soil-applied urea and may help lower gaseous N losses when used within broader management strategies. From an Italian perspective, that is enough to justify scientific attention, though certainly not promotional enthusiasm. Nano-urea is better treated as one candidate among several low-emission options that deserve careful comparison.

Even if the EU already had a dedicated regulatory framework for nanofertilisers, the period leading to 2028 would still be too short for nano-urea and related products to become fully validated tools across all cropping systems. It is, however, long enough to define a credible research agenda. The real questions are agronomic and comparative: in which crops and management systems could nano-urea or other nano-enabled fertilisers be useful, at what N rates, and with what effects on yield, NUE and emissions compared with nitrification inhibitors, slow- or controlled-release fertilisers, digestate-based strategies and precision N management? Seen in this light, the Italian transition away from urea is not only a constraint. It is also a chance to test, under demanding field conditions, whether nano-enabled fertilisation can earn a place within the broader nitrogen transition of European agriculture.

5. What current nano-urea may offer, and why the evidence remains insufficient

5.1. Limited benefits under moderate N-saving strategies

The literature reviewed here suggests that nano-urea may provide some agronomic and environmental benefits, but only within a fairly narrow range of conditions. The most consistent result is that foliar nano-urea can support moderate reductions in soil-applied nitrogen, usually in the order of 20–25%, without yield penalty in some cereal-based systems when application timing is appropriate and the overall fertilisation programme remains adequate. Under those conditions, some studies also report modest gains in nitrogen use efficiency and lower gaseous losses.

These results do not point to a radically new fertilisation paradigm. Nor do they support nano-urea as a direct substitute for granular or prilled urea. Across the cereal studies discussed in this review, replacing half or more of soil-applied urea generally led to lower yields, weaker N uptake or poorer profitability. Where improvements in NUE or environmental indicators were observed, they were usually modest and often explained more convincingly by lower N inputs, better timing or better overall management than by any distinctly "nano" effect. For now, nano-urea looks less like a stand-alone product than like a possible adjustment within broader nitrogen-saving strategies. Its performance remains closely tied to crop type, soil-N threshold, formulation, spray timing and management context.

The narrowness of these benefits becomes clearer when the evidence base itself is considered. The available studies are still relatively few, strongly concentrated in India, and only weakly supported by independent multi-environment validation. Direct measurements of NH_3, N_2O, nitrate leaching, soil biological responses and longer-term soil processes remain scarce. Some advanced nanocomposites and controlled-release nano-formulations also appear to outperform commercial foliar nano-urea in maintaining soil N pools and broader soil-fertility indicators. On this basis, current nano-urea should be treated as an early and still incomplete option whose agronomic value depends heavily on context.

5.2. Nano-urea as a test case for future nano-enabled fertilisers

Precisely because its performance is limited, though not negligible, nano-urea still has scientific value. Its importance today lies less in what it has already solved than in what it helps to clarify. As a first-generation commercial nanofertiliser introduced at scale, nano-urea offers a concrete test case for asking which claims hold up under agronomic scrutiny, which mechanisms remain uncertain, and which directions seem more promising for future formulation work. In that sense, its relevance extends beyond the product itself. It sits in an intermediate space between conventional enhanced-efficiency fertilisers and a possible future generation of more advanced nano-enabled fertilisers.

Seen from this angle, the key question is not whether current IFFCO-type nano-urea has already solved nitrogen inefficiency. The more useful question is whether this first wave of products can help define the standards that future nano-enabled fertilisers will need to meet: measurable N savings, stable yield responses, transparent N balances, direct environmental endpoints and reproducible performance across crops and regions. In this sense, nano-urea is not the endpoint of innovation. It is an early test case within a broader shift toward more precise, lower-loss and more accountable nitrogen management.

6. Conclusions

The current scientific evidence does not support nano-urea as a direct substitute for conventional granular urea. At best, first-generation products can serve as a complementary foliar N source, allowing only moderate reductions in soil-applied urea under specific conditions. The strongest signal emerging from the literature is the possibility of maintaining yield in some systems when nano-urea is combined with adequate basal N supply and properly timed foliar sprays.

Important gaps remain in the knowledge base. Studies on nano-urea are heterogeneous in design, heavily concentrated in India, and still only weakly supported by independent multi-environment validation. Direct evidence on NH_3 emissions, N_2O emissions, nitrate leaching, soil biota, and longer-term effects on soil properties is still scarce. Many of the reported benefits appear to derive from lower N inputs and better management rather than from a distinctly "nano" effect. For this reason, nano-urea is better regarded, for now, as a product whose agronomic and environmental value still needs careful validation, rather than as a transformative solution.

In Europe, and especially in Italy, this is no longer a purely speculative issue. Regulatory pressure on high-emission nitrogen fertilisers is increasing, and the planned phase-out of urea in the Po Valley adds urgency to the search for credible low-loss alternatives. In this context, the point is not to promote nano-urea as a ready-made solution, but to evaluate it rigorously alongside other options within the broader nitrogen transition. These include nitrification inhibitors, slow- and controlled-release fertilisers, manure- and digestate-based strategies, and precision N management. At present, nano-urea is best viewed as an early and still limited test case in nano-enabled fertilisation, useful above all for clarifying the agronomic and evidentiary standards that future nano-enabled fertilisers will need to meet.

CRediT authorship contribution statement

Luca Marchiol: Writing – review & editing, Conceptualization. **Guido Fellet:** Writing – original draft, Methodology. **Laura Pilotto:** Writing – original draft, Data curation. **Paolo Ceccon:** Writing – review & editing.

Declaration of Generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT (OpenAI) exclusively to support language editing and improve textual clarity. All scientific content, interpretations and reference checks were performed independently and verified manually by the authors, who take full responsibility for the accuracy and integrity of the manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

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