

Nitrogen Use Efficiency of Hybrid Maize Under Split Application of Urea and Neem-Coated Urea

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ABSTRACT

Hybrid maize responds strongly to nitrogen, yet a large share of the urea applied to it never reaches the crop, and the question of how to apply that nitrogen more efficiently is argued on agronomic, economic and environmental grounds at once. This narrative mini review asks what published work can and cannot say about the nitrogen use efficiency of hybrid maize when urea is split across the season and when it is coated with neem. It draws on literature covering the definitions of efficiency, the timing of crop demand, the fate of urea nitrogen in soil, enhanced-efficiency fertilisers and maize hybrid physiology, and it reports no new data. Split application is well supported as a way of matching supply to demand, particularly on soils and in seasons where losses are large. Neem coating has a plausible mechanism, a slowing of nitrification, but its benefit appears modest and inconsistent across soils and seasons. Efficiency metrics differ in meaning and are often compared as if they were interchangeable, and gains in yield per unit of nitrogen may sit beside unchanged or even larger losses to the environment. The review closes with the reporting that would make future trials comparable.

Keywords: Nitrogen use efficiency; Hybrid maize; Split application; Neem-coated urea; Enhanced-efficiency fertilisers; Narrative review

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Article Class: Mini Review

1. Introduction

Nitrogen is the nutrient that most often limits cereal yield, and maize is among the cereals that respond to it most readily. It is also the nutrient that farmers lose most easily. Reviews of fertiliser use in cereal systems have long reported that only part of the nitrogen applied is recovered in the crop, with the remainder left in the soil or lost to air and water [1, 2]. The part that escapes is not simply wasted money. Reactive nitrogen moves through the environment in a cascade, contributing to nitrate in water, ammonia and

nitrous oxide in air, and wider ecological change [3, 4].

Urea is the dominant nitrogen fertiliser in much of the world and the main one in South Asia. It is cheap per unit of nitrogen, easy to handle and highly soluble, which are also the reasons it can behave badly: it hydrolyses quickly, and what it releases is vulnerable to several loss routes at once [5, 6]. Two management ideas have therefore become standard in advice for hybrid maize. One is to split the dose so that most of the nitrogen arrives when the crop can use it. The other is to

modify the fertiliser itself, and in India the best known modification is the coating of urea with neem, which has been widely used for years and is now routine for much of the urea sold. The aim is to separate what has been shown from what is simply repeated.

Both ideas are sensible, and neither is a guaranteed gain. Reports on them use different efficiency measures, different hybrids, different soils and very different weather, and then the results are discussed as though they were interchangeable. The central question of this mini review is how far published work can support the claim that split application, neem-coated urea, or the two together raise the nitrogen use efficiency of hybrid maize, and what that gain does or does not mean for losses to the environment.

The article is a narrative review. It draws on published work on how efficiency is defined, how maize takes up nitrogen, what happens to urea in soil, how enhanced-efficiency fertilisers perform and how hybrids differ. It reports no new data, and where evidence on neem-coated urea in maize is thin, we say so.

2. Literature Review

2.1 What Nitrogen Use Efficiency Means

Nitrogen use efficiency is a family of measures, not one number. Some express grain produced per unit of nitrogen applied, some express the extra grain produced by fertiliser compared with an unfertilised plot, some describe the share of applied nitrogen found in the crop, and some describe how much grain is made per unit taken up [7, 8, 9]. Each answers a different question. The first can rise simply because less nitrogen was applied; the second needs a control plot; the third depends on how soil supply is estimated; and the fourth says nothing about what was lost on the way [2, 10]. Table 1 sets out the commonly used metrics and the main limitation of each.

Two studies can therefore both report improved efficiency and be describing different things. A treatment may improve recovery of fertiliser nitrogen and leave agronomic efficiency unchanged, or the reverse, and long-term analyses show that the relationship between yield and nitrogen input changes with the level of input [8, 11]. Any comparison of split or coated schemes must start by asking which measure was used and at what rate. This is why one scheme can look excellent in one report and unremarkable in the next.

Table 1. Common nitrogen use efficiency metrics and what each one hides.

Metric	What it expresses	Main limitation
Partial factor productivity	Grain per unit of nitrogen applied [8, 9]	Includes soil supply; rises as rate falls
Agronomic efficiency	Extra grain per unit applied, against an unfertilised plot [7, 8]	Needs a zero-nitrogen control
Apparent recovery	Share of applied nitrogen found in the crop [1, 2]	Difference method; ignores soil priming
Physiological efficiency	Extra grain per extra unit taken up [7, 10]	Says nothing about losses
Nitrogen balance	Applied minus removed in grain [4, 11]	Surplus is not the same as loss

Note: Definitions follow the standard agronomic usage in the cited literature; no values are given because they depend on the trial.

2.2 When Hybrid Maize Needs Nitrogen

Maize takes up nitrogen over a long period, with uptake accelerating through the rapid vegetative phase, continuing around flowering and persisting during grain filling [12, 13]. Studies of hybrids released across several decades suggest that newer hybrids rely more on nitrogen taken up after flowering and tolerate crowding and stress better, so the pattern of demand has shifted as breeding has progressed [12, 14]. A single large dose at sowing therefore supplies the crop long before most of its demand arrives (Figure 1).

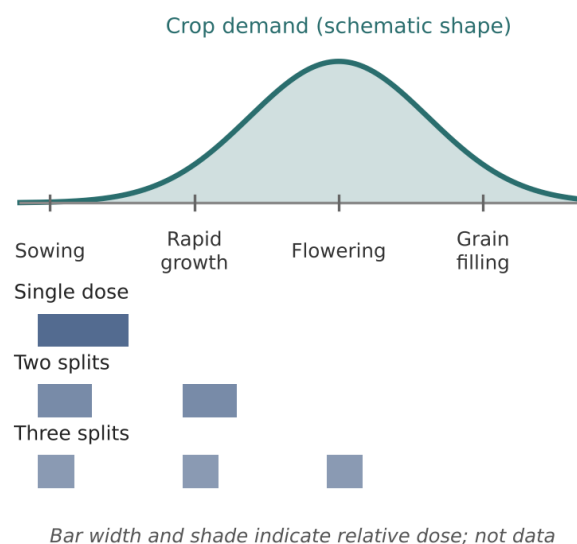


Figure 1. Crop demand and supply timing for maize under single and split nitrogen schemes (schematic, not data).

Field timing experiments make the point. Yield depends on both the amount and the timing of nitrogen, and early deficiency can be partly corrected by later application up to a point [15, 16]; on coarse-textured, irrigated soils, where

leaching risk is high, timing mattered more than on heavier soils [16]. In-season diagnostics such as chlorophyll meter readings can indicate whether a later dose is needed at all [17]. Splitting is thus an attempt to align supply with a moving target, not a ritual of two or three passes. Weather in the weeks after application often matters more than the product spread.

2.3 The Fate of Urea Nitrogen

Once urea is applied it is hydrolysed by soil urease to ammonium, a step that can proceed within days and that temporarily raises pH around the granule. Where urea is left on the surface, particularly on warm, moist soils with crop residue, a substantial part of the nitrogen can be lost to the air as ammonia [5, 18]. Ammonium that remains is oxidised by soil microbes to nitrate, which moves easily with water and can be lost by leaching or, where soil is waterlogged, by denitrification, which also releases nitrous oxide [6, 19].

Which route dominates depends on soil texture, rainfall, irrigation, temperature and placement. Management designed for tile-drained temperate soils has to deal with nitrate leaching [20], whereas on warm, residue-covered soils the larger worry may be ammonia. A product that targets one loss route cannot be expected to fix the others (Figure 2).

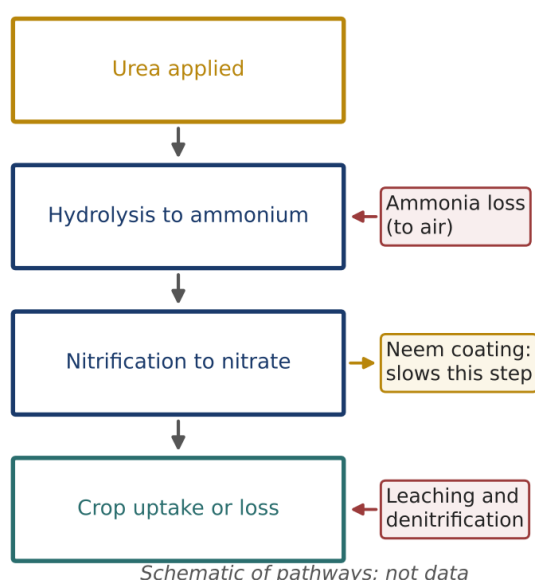


Figure 2. Fate of urea nitrogen in soil and the step at which neem coating is thought to act (schematic, not data).

2.4 Enhanced-Efficiency Fertilisers and Neem Coating

Enhanced-efficiency fertilisers are a broad group: slow- and controlled-release products, urease inhibitors and nitrification inhibitors. They aim to

bring nitrogen release closer to crop demand or to slow the transformation steps that precede loss [21, 22]. Controlled-release products rely on a physical barrier; inhibitors act chemically on particular microbial steps. A urease inhibitor, for example, holds back hydrolysis and has been shown to reduce ammonia loss in many circumstances [18].

Neem-coated urea belongs to the inhibitor and slow-release group, though it does not fit neatly in either. Neem products contain terpenoid compounds that are reported to slow nitrification, and the coating may also slow the dissolution of the granule [23]. In India, neem coating of subsidised urea became standard policy in 2015, partly to discourage diversion of the fertiliser to industry as well as for agronomic reasons. The mechanism is plausible. What is less clear is how large its effect is in the field, because the best-known evidence on nitrification inhibition comes from synthetic compounds, not from neem, and the neem literature in maize is comparatively small and uneven in how it reports soil, rate and weather.

Syntheses of inhibitor trials give a useful, if sobering, background. Meta-analyses have found that inhibitors tend, on average, to improve crop productivity and nitrogen use efficiency, but with a wide spread between studies [24]. In rice, enhanced-efficiency products raised yield and uptake on average by modest amounts that varied with product and conditions [25]. Pooled analyses of nitrous oxide find that such products reduce emissions on average but do not do so everywhere [26]. In other words, even for well-studied inhibitors, the answer is conditional. These cautions apply to any new fertiliser product, not only to neem.

2.5 Maize Hybrids and Genetic Variation in Efficiency

Efficiency is not a property of the fertiliser alone. It is shaped by the hybrid, which determines how much nitrogen is taken up, how it is remobilised to the grain, and how the crop responds to low supply. Work on the genetics of nitrogen use efficiency in maize has stressed that uptake and utilisation components behave differently and that their relative importance changes with nitrogen level [27, 28]. A long-term comparison of hybrids from different eras found that grain yield and nitrogen efficiency have improved together [29]. Trials rarely name the hybrid, plant density and maturity group together, though all three affect demand [13, 14].

3. Materials and Methods

3.1 Scope and Question

The review asks a single question in three parts. First, what does published work show about the effect of splitting urea on the nitrogen use efficiency of hybrid maize? Second, what does it show for neem-coated urea, alone or in combination with splitting? Third, how well can the answers be compared across studies, given differences in metrics and conditions, and how do gains in efficiency relate to environmental losses? None of these choices is difficult, but each one is easy to leave unstated.

3.2 Literature Assembly

The review draws on peer-reviewed work in four areas: definitions and measurement of nitrogen use efficiency; the timing and fate of nitrogen in maize systems; enhanced-efficiency fertilisers and their syntheses; and hybrid physiology and genetics. Sources were chosen for relevance, standing in the field and clarity of methods.

We did not run a formal systematic search and we do not claim one. This is a narrative synthesis, and the choice of sources reflects the authors' judgement. The practical consequence is that the review is a better guide to how evidence should be read than to the exact size of any one effect, and it avoids quoting numerical results from neem-coated urea trials that could not be verified against their primary reports for this article.

3.3 Appraisal Framework

To judge how far a report can be trusted, we asked four questions of each source. Which efficiency metric was used, and was a zero-nitrogen control available [8, 9]? Were the dose and the date of every split reported, and was the response to rate described by a suitable model [30]? Were the hybrid, density, soil and rainfall stated? And were losses measured, or was a gain in yield simply taken to imply a reduction in loss [19, 26]? Table 2 compares the schemes under review, and Table 3 lists the sources of inconsistency we looked for.

4. Results

4.1 What Splitting Contributes

The case for splitting is the best supported of the options considered here. It follows directly from the way maize takes up nitrogen: a smaller first dose reduces the amount sitting in the soil during early growth, when roots are small and rain can move nitrate beyond reach, and later doses are applied closer to the period of greatest demand [12, 15]. Studies of drainage and leaching show

that management of both rate and timing influences nitrate loss [20], and on sandy soils the value of timing is clearest [16].

Table 2. Single plain urea, split plain urea and neem-coated urea compared qualitatively.

Attribute	Plain urea, split	Neem-coated urea
Principle	Supply follows crop demand [15, 16]	Slower nitrification of released ammonium [21, 23]
Extra passes	Yes, labour and timing risk	No, if applied as one dose
Early losses	Reduced by a small first dose [20]	Reduced if coating is effective [22]
Ammonia loss	Not addressed [5, 18]	Not addressed by nitrification delay
Evidence base	Long, mostly field trials [32]	Smaller, uneven in reporting [24, 25]

Note: The comparison reflects mechanisms described in the cited literature; relative size of effects varies by soil and season and is not quantified here.

The benefit is conditional on weather. In a dry spring on a heavy soil, little may be lost from a single early dose, and a split scheme costs extra labour without a corresponding return; in a wet spring on a light soil the opposite can be true. The effect of splitting is therefore better described as a reduction in risk than as a fixed gain in efficiency. Small differences of this kind add up over a season and across many fields.

4.2 What Neem Coating Contributes

For neem-coated urea the mechanism is clear but the effect is harder to pin down. If neem compounds slow nitrification, ammonium persists longer in the soil, and exposure to leaching and denitrification should fall when the soil is wet [23, 31]. That is the proposed route to better efficiency. It should operate most strongly where nitrate loss is the main problem and least where ammonia volatilisation or other routes dominate.

Here lies a complication that is easy to overlook. Work on nitrification inhibition as a whole indicates that holding nitrogen as ammonium can reduce nitrate leaching and nitrous oxide while leaving ammonia loss unchanged or even larger, because ammonium remains available for volatilisation for longer [31]. Neem coating does not address urea hydrolysis in the way a urease inhibitor does [18], so a surface-applied, neem-coated dose can still lose nitrogen as ammonia in conditions that favour it.

Evidence from inhibitor-treated and plain fertiliser underlines the variability. In a study on tile-drained corn the benefit of a nitrification inhibitor depended on when nitrogen was applied

[32], and syntheses across crops describe an average improvement with wide spread between studies [24, 25]. We found no basis in the sources we could verify for assigning neem coating a fixed percentage gain, and we have not invented one. A fair reading is that the benefit is likely to be small to modest on average, occasionally absent, and most visible on wet, light or free-draining soils. Seen this way, a null result in a single season is not proof that nothing is going on.

4.3 Do the Two Combine?

The two measures act on different parts of the problem, and it is tempting to assume that their effects add. Splitting reduces the amount of nitrogen exposed at any one time, whereas coating slows the transformation of what is exposed. In a wet season on a light soil the two could plausibly reinforce each other; in a dry season there is little loss for either to prevent, and neither gains much (Figure 3). When one measure already removes most of the exposure, the extra benefit of the second may be small [21, 22].

	Early leaching	Ammonia loss	Supply-demand match
Single plain	greater	unchanged	poor
Split plain	lower	unchanged	better
Single neem	lower?	unchanged	poor
Split neem	lower	unchanged	better

Expected direction under wet, light-soil conditions; not data

Figure 3. Qualitative expectation matrix for four management options (schematic of expected direction, not data).

Direct factorial comparisons of split application with and without a neem coating, in the same hybrid and soil, are rare in the material we could assess with confidence, so we treat the combined effect as an open question and not as a demonstrated synergy.

4.4 Why Studies Disagree

Much of the apparent disagreement in the literature is generated by the way studies are done and reported (Table 3). Changing the metric changes the ranking; changing the control changes the denominator; and efficiency is known to fall as the rate rises, so a comparison at unequal rates is not a comparison of schemes [9, 10, 30].

Experience from intensive Chinese systems shows that nitrogen rates can sometimes be lowered substantially with little yield penalty, which means that high rates in a reference treatment can make any alternative look efficient [33, 34]. Programmes that combined better advice with wide farmer engagement have raised yield while lowering inputs, a reminder that rate and advice often matter more than product [35].

Hybrid choice adds another layer, since uptake traits and stress responses differ between hybrids and eras of release [14, 29], and rainfall adds a third: a season with heavy rain soon after the first dose is a different experiment from a dry one [6]. Few reports give enough information to separate these effects, so the pooled impression of variable and often modest benefits is probably more reliable than any single headline result. The point is not that a trial is poor, only that its result travels less far than its abstract suggestions.

Table 3. Why reported efficiencies are hard to compare, and a fix for each.

Source of difference	Effect on comparison	Reporting remedy
Metric chosen	Same trial ranks differently under different metrics [9, 10]	State metric and formula
Control plot	Soil supply changes the denominator [8]	Report zero-nitrogen yield
Rate and split pattern	Efficiency falls as rate rises [30, 33]	Give dose and date of each split
Hybrid and density	Uptake traits differ by hybrid [13, 14]	Name hybrid and plant density
Soil and weather	Rain drives leaching and loss [6, 20]	Report rainfall and soil type
Loss measurement	Yield gain mistaken for lower loss [19, 26]	Measure losses directly

Note: The sources of inconsistency are those recurrent in the cited reviews and meta-analyses; they are not attributed to any single study.

4.5 Efficiency Versus Environmental Loss

A higher nitrogen use efficiency is not automatically a lower environmental burden. Efficiency expressed as grain per unit applied can improve while the absolute surplus left in the field stays large, particularly in high-yielding systems where a lot of nitrogen is applied [4, 11]. Conversely, an intervention can reduce loss without raising yield at all. A balance-based view and a yield-based view are both needed, and they sometimes point in different directions. Some regions apply too little nitrogen and others far too much, so a surplus in one place says nothing about a deficit in another [36].

Nitrous oxide illustrates the tension. Emissions rise nonlinearly with the nitrogen supplied, increasing faster at higher inputs [19], so moderating the rate often matters more than altering the product. Enhanced-efficiency fertilisers can lower emissions on average [26], but studies that report yield and efficiency alone cannot settle the environmental question, and those that measure losses seldom measure yield on the same plots with equal care.

5. Discussion

5.1 Interpretation and Practical Reading

The main finding of this review is conditional. Splitting is well supported as a way of matching supply to demand and tends to matter most on light soils, in wet seasons and with high-yielding hybrids that take up nitrogen late. Neem coating has a credible mechanism but a modest and inconsistent effect, strongest where nitrification and nitrate loss dominate. The two have not, as far as we can verify, been shown to combine in a way that is more than the sum of their parts. Nothing here argues against splitting or coating; it argues for measuring what each does.

For a grower the implications are practical. A smaller early dose followed by one or two later applications timed to crop stage is a sound default, and the later dose can be adjusted using in-season diagnostics where they are available [15, 17]. Neem-coated urea is a reasonable choice when it costs little extra, as it often does where it is the standard product, and when the soil and season make nitrate loss likely.

5.2 Limitations

This is a narrative review, with the limitations that implies. The choice of sources reflects judgement, there was no formal search or quality scoring, and we do not quote numerical results from individual neem-coated urea trials, because these could not be checked against primary reports for this article. A reader who needs an effect size should consult the original studies directly, applying the appraisal questions above, or wait for a formal systematic review.

The review also relies on evidence from other crops and from inhibitors other than neem, which are imperfect proxies; studies on rice and on synthetic nitrification inhibitors describe different crops and chemistry [25, 37]. We used them to frame expectations, not to stand in for maize results. Long-term effects of nitrogen fertiliser on soil biology are only touched on here [38]. Reviews of this kind are more useful when they say where

the evidence stops than when they smooth it over.

5.3 Implications for Trial Design

A trial that could settle the question would include a zero-nitrogen control and report at least two efficiency metrics with their formulas. It would compare single and split schemes with plain and neem-coated urea in a factorial arrangement, at the same total rate, with each split dose and its date recorded. It would name the hybrid, plant density and maturity group, describe soil and rainfall through the season, and run for more than one season.

On the environmental side it would measure at least one loss pathway directly, such as nitrate in drainage, ammonia loss after application or nitrous oxide flux, and report it beside yield on the same plots [20, 26].

5.4 Directions for Future Work

Three needs stand out. First, maize-specific, field-based comparisons of neem-coated and plain urea, with a split design and direct loss measurements, across contrasting soils and rainfall regimes. Second, a formal systematic review with a transparent search and appraisal, ideally with meta-analysis that treats variation between studies as a result to be explained [24, 25]. Third, work that links hybrid traits to fertiliser scheme, so that recommendations can differ for hybrids that take up nitrogen early and those that take it late [27, 28].

6. Conclusion

Splitting urea is a well-founded way to improve the match between supply and demand in hybrid maize, and its value is greatest where losses are likely. Neem-coated urea has a plausible mechanism and probably a modest benefit, but that benefit is inconsistent across soils and seasons, and it does not touch every loss route. Efficiency metrics differ in meaning, and comparing them across studies without care produces false agreement or false disagreement.

The most defensible position is also the most useful one. Use split application to follow crop demand, treat neem coating as a helpful but limited addition rather than a cure, and judge both by what is lost as well as by what is harvested. Properly designed trials that measure efficiency and loss together would let the next review say more than this one.

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9. Conflict of Interest

The authors declare no conflict of interest.

10. Author Contributions

R.O. conceived the review and wrote the sections on fertiliser management and trial design. L.E. wrote the sections on weather, soil processes and nitrogen loss. A.M. wrote the sections on maize physiology and hybrid variation. All authors revised the manuscript and approved the final version.

11. Ethics Statement

This is a review of published literature. No human or animal subjects were involved and no ethical approval was required.

12. Data Availability

No new data were generated. All sources are cited in the reference list.

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