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Optimising Fodder Maize Productivity across Soil Fertility Gradients: A Critical Review of Soil Test Crop Response Strategies for Sustainable Nutrient Management

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Fodder maize (*Zea mays* L.) is a high-biomass, nutrient-responsive forage whose economic value depends on both harvested mass and nutritive quality. Fertiliser recommendations based on regional averages can therefore be inefficient when fields differ markedly in native nitrogen, phosphorus and potassium supply, organic matter, pH, texture, previous management and residual fertility. This critical narrative review evaluates soil test crop response (STCR) and related targeted-yield strategies as a basis for improving fodder maize nutrient management across soil fertility gradients. Literature published principally from January 2010 to 26 June 2026 was considered, with older foundational methodological sources retained where necessary. The evidence shows that STCR offers a defensible framework because fertiliser rates are adjusted to a yield target and to measured soil nutrient supply rather than applied as a uniform dose. Maize studies across Alfisols, Vertisols, Inceptisols and related soils generally demonstrate improved target attainment, nutrient-use efficiency or economic performance when calibrated STCR or STCR-integrated plant nutrient supply approaches are compared with blanket recommendations. Nevertheless, transfer to fodder maize remains less secure than the broader maize literature suggests. Direct fodder studies confirm strong interactions among nitrogen rate, plant density, zinc supply, water regime, cultivar and harvest endpoint, while recent fodder-specific STCR work shows that deliberate fertility gradients can be established in lateritic soils. Yet contemporary multi-location validation of fodder-specific target equations, dry-matter removal, feed-quality safeguards, residual nutrient credits and environmental outcomes is still limited. The most defensible pathway is therefore an STCR-plus strategy: locally calibrated pre-season soil-test prescriptions, explicit organic nutrient credits, and in-season nitrogen adjustment using crop sensing, with potassium and micronutrient balance evaluated against whole-plant removal. Future research should prioritise multi-soil calibration and external validation using green-fodder yield, dry-matter yield, nutritive quality, nutrient recovery, profitability and soil nutrient balance as joint outcomes. STCR can support sustainable fodder maize intensification, but its reliability depends on calibration domain, measurement quality and repeated validation rather than on universal transfer of published equations.

Keywords: Fodder maize; soil test crop response; targeted yield; integrated plant nutrient supply; site-specific nutrient management; nitrogen-use efficiency; soil fertility gradient; precision nutrient management.

1. Introduction

Fodder maize (*Zea mays* L.) occupies a distinctive agronomic position because the harvested product is the vegetative crop itself rather than grain alone. Rapid canopy development, high biomass accumulation and broad adaptation make maize attractive for green fodder and conserved feed, but these same characteristics create a substantial and time-concentrated demand for mineral nutrients. The agronomic objective is consequently not simply to maximise plant growth. Nutrient management must support a harvestable biomass target, maintain an acceptable feed-quality profile, avoid economically wasteful fertiliser surpluses, and preserve soil nutrient stocks in systems where most above-ground biomass may leave the field. Reviews of fodder maize nutrition have consistently identified nitrogen (N), phosphorus (P), potassium (K) and zinc (Zn) as influential, while direct field studies show that response depends on cultivar, crop density, water supply and the form and timing of nutrient application (Bhaumik et al., 2025; Kumar et al., 2017a, 2017b; Mohan et al., 2015). These interactions make a single regional fertiliser dose an inherently weak representation of crop need when soil fertility varies within and among farms.

The physiological basis for this variability is well established in maize. Nutrient accumulation is dynamic rather than proportional throughout the season, and modern maize hybrids can continue taking up substantial quantities of N, P and K after early vegetative growth. Uptake, partitioning and remobilisation also differ among nutrients, which means that the soil-fertiliser system must provide an adequate supply at stages that are not identical for all elements (Bender et al., 2013). Nitrogen efficiency is likewise the product of several component processes, including soil supply, crop uptake and the conversion of acquired N into biomass or yield; improvements in one component do not guarantee improvement in the others (Ciampitti & Vyn, 2012). For fodder production, the challenge is further complicated because harvest may occur before physiological maturity. Consequently, grain-based nutrient requirement coefficients and assumptions about post-anthesis remobilisation cannot automatically be treated as equivalent to whole-plant fodder requirements.

Soil fertility gradients are the practical expression of this heterogeneity. Fields can differ in organic carbon, pH, clay mineralogy, available nutrient pools, previous fertilisation, manure history, residue removal and crop sequence. Even within the same soil order, these factors alter the fraction of total crop uptake that can be supplied by soil and the fraction that must be supplied by fertiliser or organic inputs. Site-specific nutrient management (SSNM) studies in maize have repeatedly shown large spatial differences in indigenous nutrient supply and in crop response to individual nutrients. For example, maize response in an Inceptisol of eastern India was strongly ordered by nutrient limitation, with N generally exerting the largest yield effect, but the magnitude of response depended on the existing nutrient supply and treatment combination rather than on a fixed nutrient hierarchy (Ray et al., 2018). Multi-location precision nutrient management studies likewise indicate that a recommendation effective at one site can lose efficiency when transferred without adjustment to another soil-climate-management context (Singh et al., 2020). Recent field evidence from smallholder maize systems further supports the value of tailoring nutrient recommendations to local conditions, indicating that site-specific advice can improve nutrient-use efficiency and environmental performance when fertiliser management is adjusted to field context (Maertens et al., 2023).

The soil test crop response (STCR) approach was developed to address this problem more explicitly than blanket recommendations. Its central logic is to relate a defined yield target to crop nutrient requirement while crediting the contribution expected from soil-test nutrients and, where integrated plant nutrient supply (IPNS) is used, from organic sources. The approach is historically associated with the targeted-yield concept and the deliberate creation or use of fertility gradients so that crop response can be quantified over a sufficiently wide range of nutrient availability. Contemporary interpretation also stresses the need to reconcile nutrient deficiency with nutrient excess: the agronomic optimum lies between insufficient supply and environmentally or economically costly over-application (Velayutham, 2017). STCR therefore has an intuitive advantage for fodder maize because the crop is highly responsive and fields can differ substantially in their capacity to supply nutrients.

Evidence from grain maize and sweet corn supports the internal logic of targeted-yield calibration. On Alfisols, STCR equations developed under fertiliser-only and fertiliser-plus-farmyard-manure regimes have been validated against yield targets, with integrated treatments often improving nutrient-use efficiency and economic return relative to general recommendations (Coumaravel et al., 2013; Rangaiah et al., 2024). In Vertisols of northern Karnataka, an STCR-IPNS programme for maize achieved a high target yield while reducing N, P_2O_5 and K_2O requirements relative to an STCR fertiliser-only treatment, demonstrating that manure credits can be incorporated rather than simply added on top of mineral fertiliser (Reddy et al., 2025). In longer maize-based rotations, STCR target management has also been used for several years, providing evidence that nutrient prescriptions interact with residual soil fertility and micronutrient cycling rather than operating as isolated single-season decisions (Kurbah et al., 2024).

The specific evidence base for fodder maize is narrower but no longer absent. Recent work in southern lateritic soils of Kerala deliberately established low, medium and high fertility strips for fodder maize and documented progressive increases in available N, P and K, nutrient uptake and green-fodder yield across the gradient (Anitha et al., 2026). This is directly relevant because it demonstrates the feasibility of creating the response range needed for fodder-specific STCR calibration in an acidic, nutrient-constrained soil environment. Yet the study primarily establishes the fertility-gradient phase rather than providing broad, multi-location confirmation that a single set of fodder equations will reliably predict green or dry-matter yield across soils, cultivars, harvest dates and management systems. At the same time, direct fodder-maize experiments using conventional dose-response, integrated nutrient management and sensor-based N management show that biomass maxima, nutrient-use efficiency and feed-quality outcomes do not always occur at the same fertiliser rate (Gholami et al., 2024; Kumar et al., 2022, 2023; Shekara et al., 2025). The resulting evidence landscape requires synthesis across STCR methodology, fodder physiology and precision nutrient management rather than simple extrapolation from grain maize. Direct fodder-maize evidence also indicates that zinc management and the distribution of nitrogen between basal and topdressing applications can alter herbage productivity, quality and nutrient-use efficiency, reinforcing the need for locally calibrated nutrient strategies (Kumar et al., 2024; Li et al., 2025). Recent precision-nitrogen research in maize further demonstrates that combining crop modelling, canopy sensing and field information can refine in-season nitrogen recommendations, which is consistent with the need to complement pre-season soil-test prescriptions with responsive within-season adjustment (Wang et al., 2025).

Two earlier review traditions are informative but leave this intersection unresolved. Reviews of fodder nutrition have summarised the effects of N, P, K and Zn on yield and quality, but they largely organise evidence by nutrient rather than by soil-test calibration or target-yield prediction (Bhaumik et al., 2025; Mohan et al., 2015). Conversely, the STCR literature is strongest for grain, vegetable and other economic-yield endpoints and usually evaluates calibration within a particular soil series or agro-ecological domain. The missing analytical question is therefore not whether fertiliser increases fodder maize growth, nor whether STCR can work in maize generally. It is how the targeted-yield logic should be interpreted and modified when the harvested product is whole-plant fodder, soil fertility varies strongly, nutritive quality matters, and nutrient removal can be large. That question also has a sustainability dimension because repeated whole-plant harvest without accurate nutrient replacement can accelerate depletion, particularly of K, while excessive N can reduce profitability and increase loss risk.

1.1 Scope, Research Gap and Objectives

This review focuses on nutrient management for fodder maize under variable soil fertility, with STCR and STCR-IPNS as the central analytical frameworks. Evidence from grain maize, sweet corn, long-term maize-based rotations and SSNM is used only where it informs calibration principles, nutrient supply, residual effects, precision adjustment or scaling. The review distinguishes direct fodder-maize evidence from transfer evidence and does not treat grain-yield equations as equivalent to fodder-yield equations. Its objectives are to evaluate the scientific basis and practical performance of STCR across fertility gradients; identify the crop and soil factors that limit transferability to fodder maize; integrate evidence on N, P, K, Zn, organic inputs and sensor-guided management; assess sustainability and adoption implications; and define a research agenda for robust fodder-specific calibration. The intended contribution is an evidence-calibrated framework in which soil testing provides the pre-season nutrient baseline, organic sources are credited explicitly, and in-season crop information is used to refine nutrients whose demand is highly dynamic. The emphasis is on field-scale nutrient management and agronomic sustainability rather than on animal feeding trials, silage fermentation technology or genetic improvement except where these directly affect nutrient-management interpretation.

2. Methods for Literature Selection

2.1 Review Design and Rationale

A critical narrative review design was selected because the evidence relevant to the question is methodologically heterogeneous. The literature includes fertility-gradient experiments, targeted-yield calibration studies, validation trials, multi-location precision-nutrient experiments, long-term soil-fertility studies, conventional factorial fodder-maize trials and recent sensor-guided N experiments. These studies differ in crop endpoint, soil test method, nutrient source, experimental duration, yield target and reported efficiency metric, precluding a defensible pooled effect estimate. Narrative synthesis is nevertheless not a licence for unsystematic selection. The review was structured according to principles of transparency, argument coherence, evidence appraisal and balanced interpretation emphasised in guidance for narrative reviews (Baethge et al., 2019; Ferrari, 2015; Green et al., 2006). The analytical objective was to explain where evidence converges, why findings differ, and which conclusions remain conditional on soil or management context.

2.2 Information Sources

Literature was identified through AGRIS, OpenAIRE, DOAJ, Semantic Scholar, PubMed and PubMed Central, Google Scholar, and the ICAR ePubs platform. The regional agricultural search was supplemented by the Indian STCR and agronomy literature available through institutional and scholarly journal records. Backward citation searching from relevant reviews and STCR articles, related-article searching, and targeted DOI and bibliographic verification were used to locate foundational or validation studies that were not retrieved consistently by a single index. Only sources for which bibliographic identity and relevance could be verified were retained. Publisher records, DOI landing records and recognised bibliographic databases were used for metadata verification but were not treated as separate literature databases.

2.3 Search Strategy and Search Period

The principal search period was January 2010 to 26 June 2026. Foundational publications outside that interval were retained only when they were methodologically necessary to explain narrative-review conduct or the conceptual basis of nutrient-use efficiency. Search concepts combined the crop, nutrient-management framework, soil-fertility domain and relevant outcomes. A representative search formulation was: ("fodder maize" OR "forage maize" OR "Zea mays") AND ("soil test crop response" OR STCR OR "targeted yield" OR "fertilizer prescription" OR "site-specific nutrient management") AND ("soil fertility" OR "fertility gradient" OR NPK OR "integrated nutrient management" OR FYM) AND (yield OR biomass OR quality OR "nutrient use efficiency" OR sustainability). Focused searches combined maize with N sensing, leaf colour chart, SPAD, zinc, potassium, long-term fertilisation, residual fertility, nutrient balance, farmyard manure, profit and farm typology. Searches were iteratively narrowed when a term retrieved grain-only studies that could not inform fodder-specific interpretation.

2.4 Eligibility Criteria

Peer-reviewed field studies and high-quality reviews were eligible when they addressed fodder maize nutrient response, STCR or targeted-yield calibration in maize, precision or site-specific nutrient management, integrated nutrient supply, long-term maize soil fertility, or closely related processes needed to interpret whole-plant nutrient removal. Studies were prioritised when they reported initial soil characteristics, nutrient treatments, crop yield or biomass, nutrient uptake, nutrient-use efficiency, quality, economics, validation against a target, or post-harvest soil properties. Grain-maize and sweet-corn studies were included as transfer evidence only when their design directly informed STCR calibration or soil-test interpretation. Laboratory-only studies, promotional material, unverified conference abstracts, patents and sources with incomplete or conflicting bibliographic identity were excluded. English-language sources predominated because only material that could be fully appraised and bibliographically verified was retained. No study was considered persuasive solely because it reported a statistically significant treatment difference.

2.5 Screening, Duplicate Handling and Study Selection

Titles and abstracts were first assessed for direct relevance to one of four evidence domains: fodder-maize nutrient response, STCR calibration and validation, SSNM or precision nutrient management, and long-term soil-fertility consequences. Full text or sufficiently detailed article records were then examined for study context, treatment structure and outcome relevance. Duplicates were identified using title, first author, publication year and DOI; where an online-first record and final issue record referred to the same study, the final bibliographic version was used. Studies were excluded when the reported crop endpoint could not be distinguished, when methodological information was too limited to support the intended claim, or when a DOI or article identity could not be reconciled. No screening count is reported because the selection process was designed for critical narrative synthesis rather than as a prospectively registered systematic review with auditable flow counts.

2.6 Critical Appraisal and Evidence Synthesis

Evidence was appraised using design features relevant to agronomy. Particular attention was paid to replication, duration, soil characterisation, breadth of the fertility gradient, treatment contrasts, crop cultivar and harvest stage, definition of the yield target, nutrient-source accounting, reported target deviation, external validation, and whether apparent nutrient contributions were interpreted within the calibration domain. For fodder studies, green-fodder yield was considered insufficient on its own when dry matter, nutrient uptake, feed-quality indicators or nutrient-use efficiency were available. For long-term studies, the direction of change in soil organic carbon, physical condition or available nutrient pools was considered more informative than a single-season yield response. The synthesis was thematic rather than study-by-study. Direct evidence was given greater weight for fodder-specific conclusions, whereas grain and sweet-corn evidence was treated as mechanistic or methodological support. Disagreement was interpreted in relation to soil order, indigenous nutrient supply, crop density, water availability, organic inputs, target level and duration rather than resolved by simple majority counting.

3. Scientific Basis and Evolution of STCR for Maize

3.1 Targeted-Yield Logic and Calibration Parameters

STCR differs from a blanket fertiliser recommendation because it begins with a quantitative relationship among target yield, crop nutrient requirement and the expected contributions of soil and applied inputs. The practical output is a field-specific fertiliser prescription: two fields assigned the same attainable yield target can receive different nutrient rates if their soil tests indicate different indigenous supply. This is important under fertility gradients because the soil is not treated as an inert medium. Rather, the soil test is used as an empirical predictor of the quantity of a nutrient that can contribute to crop uptake within a defined calibration system. Velayutham (2017) placed this logic within a broader concept of optimum plant nutrition, emphasising that the agronomic problem is simultaneously to correct deficiency and avoid excessive supply. The targeted-yield framework thus operationalises an economically and environmentally relevant middle ground between under-fertilisation and indiscriminate input escalation.

The central calibration parameters are commonly described as the nutrient requirement per unit of economic yield, the percentage contribution from soil, and the percentage contribution from fertiliser; IPNS versions add a contribution term for organic manure. These are empirical coefficients, not immutable physiological constants. Their values depend on the crop endpoint, soil test method, treatment range, nutrient interactions and the biological environment in which they were derived. The distinction is critical when transferring results to fodder maize. A coefficient estimated per tonne of fresh cob or per quintal of grain reflects the relation between total nutrient uptake and that economic yield. Whole-plant fodder has a different harvested fraction, water content and harvest date. Even when the same cultivar is used, the nutrient requirement per tonne of green forage cannot be assumed to equal the requirement per tonne of grain or cob. Rangaiah et al. (2024), for example, calibrated sweet corn against fresh cob yield and explicitly calculated nutrient requirements for that endpoint; the study demonstrates methodological flexibility, but not direct equivalence to fodder biomass.

An additional interpretive issue is that the estimated contribution from fertiliser can exceed 100% for some nutrients, particularly K, in certain STCR datasets. This does not mean that more than all of the applied fertiliser K was recovered in a simple mass-balance sense. The coefficient is derived from crop uptake relationships and can incorporate stimulated release from non-exchangeable pools, priming of indigenous nutrient supply, differences among plots and interactions with other inputs. In the sweet-corn Alfisol study, apparent K contribution from fertiliser was above 100% in the fertiliser-only calibration, illustrating why these coefficients should be interpreted as empirical response parameters within the model rather than as direct recovery efficiencies (Rangaiah et al., 2024). This caution is especially relevant for fodder maize because whole-plant harvest can remove large quantities of K; an optimistic apparent contribution coefficient should not be used to justify chronic K under-replacement.

3.2 Fertility-Gradient Experiments and the Inductive Approach

The inductive-cum-targeted-yield approach deliberately creates variability in soil fertility before the test crop is used to establish nutrient-response relationships. Low, medium and high fertility strips are commonly generated through graded fertiliser additions and, in some protocols, an exhaustive crop is grown to redistribute and stabilise the added nutrients biologically. The subsequent test crop then receives factorial combinations of N, P and K, sometimes with organic manure, across the established fertility strata. This design widens the range of initial soil test values and crop nutrient uptake so that the fitted relationships are not based on a narrow band of fertility. Coumaravel et al. (2013) applied this logic to hybrid maize on an Alfisol, while Reddy et al. (2025) used fodder maize as an exhaustive crop when establishing fertility strips before calibrating grain-maize STCR and STCR-IPNS equations on Vertisols. The use of fodder maize in the exhaustion phase itself is agronomically revealing: its rapid biomass production can create substantial nutrient withdrawal, but this role should not be confused with validation of a fodder-yield prescription.

Direct recent evidence shows that the gradient concept can be applied with fodder maize as the response crop. In southern laterite soils of Kerala, Anitha et al. (2026) established three fertility levels and reported progressive increases in available soil N, P and K from the low to high fertility strip. Green-fodder yield increased from approximately 32 to 40 t ha^{-1} across that gradient, accompanied by higher nutrient uptake and vegetative growth. The study is valuable because it confirms a sufficiently strong fertility signal in an acidic lateritic context where nutrient constraints can be pronounced. Its limitation is equally important: a gradient-establishment study is one component of the STCR sequence, not proof of externally valid fertiliser prescription equations. Robust recommendation development still requires treatment response across the gradient, estimation of crop- and soil-specific coefficients, and validation in independent fields and seasons.

The fertility-gradient strategy reduces one common calibration problem: when all plots begin with similar nutrient status, response coefficients may be unstable or relevant only to that narrow band. Yet deliberate gradients can introduce their own interpretive constraints. Added fertiliser may alter pH, ionic balance, microbial activity or the availability of nutrients other than the target nutrient. An exhaustive crop can also redistribute nutrients through roots and residues. For this reason, the subsequent response surface reflects a managed soil system rather than a single isolated nutrient pool. The advantage is empirical relevance; the cost is that coefficients remain conditional on the soil test method and experimental domain. Calibration should therefore be regarded as a local prediction exercise that requires validation rather than as a universal conversion of soil-test numbers into fertiliser rates.

3.3 STCR-IPNS and the Credit for Organic Nutrient Sources

STCR-IPNS extends the targeted-yield concept by recognising that manure and other organic nutrient sources contribute measurable quantities of plant-available nutrients. This is preferable to a common additive practice in which a full mineral fertiliser recommendation is applied and manure is added without credit. In northern Karnataka Vertisols, Reddy et al. (2025) found that an STCR-IPNS treatment designed for a high maize yield target reduced the mineral N, P_2O_5 and K_2O requirement relative to the corresponding fertiliser-only STCR prescription while maintaining a strong yield response. In an Alfisol, Rangaiah et al. (2024) similarly developed separate equations with and without farmyard manure (FYM). These studies support the principle that organic inputs should be integrated quantitatively into the prescription rather than treated as a qualitative soil-health supplement.

The complication is that organic-source coefficients are more variable than fertiliser salts because manure nutrient concentration, moisture, decomposition and timing of mineralisation differ among materials and seasons. The apparent contribution of FYM derived in one experiment therefore cannot be transferred safely to another farm without accounting for manure quality and local mineralisation conditions. Long-term studies show why this matters. Organic and balanced fertiliser inputs can improve soil organic carbon and physical properties in maize-wheat systems (Brar et al., 2015), but the agronomic value of that accumulated soil capital is not captured fully by a single-season nutrient-credit coefficient. Conversely, repeated manure application can increase residual nutrient availability, so using a fixed annual credit without periodic soil testing may eventually underestimate soil supply. STCR-IPNS is therefore best interpreted as a dynamic accounting framework, with soil-test updating and realistic organic-source analysis, rather than as a permanent substitution ratio.

Taken together, the evidence indicates that STCR has three scientifically defensible strengths: it acknowledges indigenous soil supply; it links 111ertilization to an explicit, attainable target; and it can incorporate organic nutrient sources within the same accounting logic. The weaknesses arise when coefficients are detached from their calibration domain, when apparent contribution terms are read as universal recovery efficiencies, or when the chosen yield endpoint does not match the harvested product. These distinctions are particularly consequential for fodder maize, where the harvest removes most above-ground biomass and where green mass alone can obscure dry-matter and nutrient-removal differences. Table 1 summarises the core STCR components and the adaptations required for fodder-maize use.

Table 1. Core STCR components and their implications for fodder-maize calibration

Component	How it functions	Evidence strength	Main limitation	Fodder-maize implication	Supporting references
Yield target	Defines the desired economic output used to calculate nutrient requirement.	Strong within validated maize domains.	An unrealistic target converts non-nutrient constraints into apparent fertiliser need.	Use attainable green-fodder and dry-matter targets at a defined harvest stage.	Velayutham (2017); Venkatesh et al. (2022)
Nutrient requirement	Relates total crop nutrient uptake to a unit of target yield.	Strong as an empirical calibration parameter.	Endpoint-specific; grain, cob and fodder coefficients are not interchangeable.	Derive coefficients from whole-plant fodder uptake and report dry matter.	Rangaiah et al. (2024); Reddy et al. (2025)
Soil contribution	Credits indigenous soil nutrient supply using calibrated soil-test values.	Strong conceptually; local calibration essential.	Sensitive to extractant, sampling, soil order and fertility range.	Standardise soil testing and restrict equations to their calibration domain.	Coumaravel et al. (2013); Ray et al. (2018)
Fertiliser contribution	Estimates crop response attributable to applied fertiliser within the calibration experiment.	Useful for prescription equations.	Apparent values can exceed 100% and should not be read as simple recovery efficiency.	Interpret as model coefficients and cross-check against nutrient balance.	Rangaiah et al. (2024)
Organic-source contribution	Credits nutrients supplied by FYM or other organic material in STCR-IPNS.	Supported by maize calibration and validation studies.	Varies with manure composition, mineralisation and application history.	Analyse manure quality and update soil tests after repeated applications.	Rangaiah et al. (2024); Reddy et al. (2025)
External validation	Tests whether target-specific prescriptions work in independent fields or seasons.	Essential for confidence in transfer.	Often limited to few sites and short periods.	Validate across soil gradients, cultivars, seasons and farmer-managed fields.	Reddy et al. (2025); Singh et al. (2020)

Note. FYM = farmyard manure; IPNS = integrated plant nutrient supply; N = nitrogen; P = phosphorus; K = potassium; STCR = soil test crop response

4. Soil Fertility Gradients as the Central Scaling Problem

4.1 Soil Properties and Indigenous Nutrient Supply

A soil test has value only to the extent that it predicts the nutrient-supplying capacity that matters to the crop. This relationship varies with soil texture, mineralogy, organic matter, pH, moisture regime and rooting environment. In maize, SSNM experiments demonstrate that indigenous N, P and K supplies differ enough to change both the size and ranking of treatment responses. Ray et al. (2018) showed that maize hybrids on an Inceptisol responded most strongly to N, followed by K and P, while yield convergence across a broad band of complete NPK rates indicated that proportional dose increases do not produce proportional yield gains. Such response curvature is precisely why a fixed percentage of a recommended dose cannot substitute for a calibrated soil-response model. A field with a high soil-test K value may require only a maintenance or minimum dose, whereas a K-depleted field exposed to repeated whole-plant harvest may need substantial replacement even when short-term N response is visually dominant.

Soil pH modifies this picture because it affects P sorption, micronutrient availability and biological mineralisation. Acid Alfisols can simultaneously exhibit low base status, strong P fixation and micronutrient imbalances, while calcareous or alkaline soils can reduce Zn availability despite apparently adequate total Zn. The Kerala fertility-gradient study is therefore more than a demonstration of increasing NPK levels: it illustrates the need to derive fodder recommendations in a soil environment where acidity and low native fertility are integral to the response (Anitha et al., 2026). Likewise, long-term STCR management in an acid Alfisol influenced micronutrient transfer and uptake over nine years, showing that targeted macronutrient fertilisation cannot be evaluated solely through NPK yield response when repeated management changes the broader soil nutrient environment (Kurbah et al., 2024).

Organic carbon is another key source of variation because it is both a reservoir of N and a driver of physical and biological soil function. Long-term maize-wheat experiments demonstrate that integrated organic and inorganic fertilisation can increase soil organic carbon and improve physical properties compared with nutrient-deficient or unbalanced treatments (Brar et al., 2015). These improvements can alter water retention, root exploration and mineralisation, thereby changing the effective crop response to a given soil-test nutrient value. An STCR equation derived on soils with a narrow organic-carbon range may therefore underperform when exported to fields with very different organic matter histories. Periodic recalibration or inclusion of robust covariates may be necessary where organic carbon exerts a strong independent effect on attainable biomass.

4.2 Measurement Uncertainty and Interpretation of Soil Tests

Soil-test values are analytical indices rather than direct inventories of all plant-available nutrient. Their predictive meaning depends on extractant, sampling depth, timing, sample representativeness and the calibration population. The same numerical value generated by two different methods need not imply the same nutrient supply. Within-field sampling error can be especially problematic in manured fields or where fertiliser has been banded. For STCR, this measurement uncertainty enters the prescription directly because soil contribution is multiplied by an initial test value. The practical consequence is that improved mathematical precision cannot compensate for poor sampling. A prescription reported to the nearest kilogram per hectare may convey false accuracy if the composite soil sample fails to represent the management zone.

Potassium illustrates the danger of over-literal interpretation. Maize can access exchangeable and, under some conditions, non-exchangeable K pools, and fertilisation can shift the equilibrium among these pools. Long-term evidence from intensive systems shows that nutrient management alters the soil's K-supplying capacity and that omission or imbalance can deplete pools not captured fully by a single routine test (Das et al., 2021). In STCR calibrations, apparent fertiliser K contributions above 100% should therefore be understood as model behaviour reflecting soil release and treatment interactions rather than evidence that high K removal can be sustained with negligible replacement (Rangaiah et al., 2024). For fodder maize, where stems and leaves are removed with the harvested material, a soil-test strategy needs a mass-balance check in addition to response-based optimisation.

Nitrogen presents a different measurement problem. A pre-season soil N index can be informative, but actual N supply during rapid maize growth is strongly affected by mineralisation, rainfall, irrigation, temperature and loss processes. This temporal uncertainty helps explain why in-season crop sensing has become attractive as a complement to pre-season recommendations. The STCR base rate can incorporate soil fertility and target yield, while leaf colour or chlorophyll sensing can update the N decision according to realised crop status. Shekara et al. (2025) showed that SPAD- and leaf-colour-chart-guided schedules altered fodder yield and N-use efficiency relative to fixed N rates. The study does not validate an STCR-sensor hybrid, but it provides direct evidence that fodder maize N demand can be managed dynamically and that a single pre-season N quantity may not capture within-season variability.

4.3 Residual Fertility, Crop Sequence and Time

The fertility gradient experienced by fodder maize is partly inherited from previous crops. Residual fertiliser, manure, biological N inputs, residue management and prior nutrient removal can all change starting soil fertility. In a maize-lentil rotation, STCR-targeted nutrition improved maize performance, but the extent to which yield targets were realised differed between crops, demonstrating that a prescription calibrated for one crop does not automatically ensure target attainment in the next (Venkatesh et al., 2022). This has two implications for fodder systems. First, target equations should be crop-specific. Second, nutrient credits and soil-test updates should be timed to the actual crop sequence rather than carried forward mechanically from the previous season.

Long-term balanced fertilisation also affects the environmental efficiency of the system. Dhawan et al. (2022) reported lower N losses under long-term balanced fertilisation than under nutritionally distorted management in a maize-wheat system. Integrated nutrient management in spring maize has likewise been associated with improved nutrient-use efficiency and lower greenhouse-gas intensity, although such findings arise from grain-maize systems rather than fodder-specific STCR trials (Nisar et al., 2023). The transfer inference is therefore limited but important: sustained nutrient balance influences both productive and environmental outcomes, so evaluating a fodder-maize prescription only by one-season green yield risks selecting a strategy that shifts costs to subsequent crops or to the environment.

The evidence in this section supports a central scaling principle: fertility gradients are not merely the experimental device used to derive STCR equations; they are the real-world condition that makes field-specific recommendations necessary. Soil order, organic matter, pH, analytical method, residual fertility and management history all alter the mapping from soil test to crop response. A valid recommendation must therefore state or respect its calibration domain. Table 2 identifies the principal gradient factors, the bias each can introduce into a prescription, and the corresponding mitigation required for fodder-maize application.

Table 2. Soil-fertility gradient factors that can alter fodder-maize STCR prescriptions

Gradient factor	Why crop response changes	Risk to prescription	Calibration or mitigation	Supporting references
Soil pH and P sorption	Changes P availability and micronutrient solubility.	A soil P value may predict different uptake across contrasting pH/mineralogy.	Calibrate within soil groups; diagnose acidity and micronutrient constraints.	Anitha et al. (2026); Kurbah et al. (2024)
Organic carbon	Controls mineralisable N and affects physical and biological soil function.	Low or high organic-C fields can depart from equations derived on a narrow range.	Include representative organic-C range and repeat soil testing under long-term IPNS.	Brar et al. (2015)
Indigenous N supply	Varies with mineralisation, weather and prior crop management.	Pre-season N prediction can diverge from in-season supply.	Use a soil-test base with split N and crop-status refinement.	Shekara et al. (2025); Singh et al. (2020)
K reserves and mineralogy	Exchangeable and non-exchangeable pools contribute differently among soils.	Weak short-term K response can mask depletion under whole-plant removal.	Track K balance and post-harvest soil trends; avoid interpreting apparent contribution as recovery.	Das et al. (2021); Rangaiah et al. (2024)
Residual fertiliser and manure	Previous applications alter current nutrient supply and mineralisation.	Fixed annual credits may over- or under-estimate available nutrients.	Update soil tests and use measured organic-input composition.	Reddy et al. (2025); Venkatesh et al. (2022)
Water regime	Controls nutrient diffusion, mass flow, root uptake and attainable biomass.	A target calibrated under full irrigation can become unattainable under deficit water.	Set target within water-limited yield potential and validate N timing under irrigation regimes.	Gholami et al. (2024)
Farm management history	Tillage, residues, crop sequence and input access alter both soil supply and implementation.	Research-station performance may not reproduce on farms.	Use farmer-field validation and farm-typology analysis.	Goswami et al. (2026); Hazra et al. (2019)

Note. N = nitrogen; P = phosphorus; K = potassium; STCR = soil test crop response

5. Fodder Maize Nutrient Demand: Yield, Quality and Whole-Plant Removal

5.1 Nitrogen: Biomass Response versus Efficiency

Nitrogen is the nutrient most consistently associated with rapid canopy expansion, leaf area, chlorophyll formation, crude protein and biomass accumulation in fodder maize. This strong response can encourage high fixed N rates, yet the agronomic optimum depends on whether the objective is green yield, dry matter, protein yield, economic return or N-use efficiency. Amin (2011) demonstrated that fodder maize responded to both N source and supply, confirming that nutrient form can influence growth and quality rather than N rate acting alone. In the Indo-Gangetic Plains, increasing fertility levels improved fodder yield and nutrient yield, but the response was conditioned by seeding density and quality traits; yield response did not make all high-input combinations equally efficient (Kumar et al., 2017a). These findings are consistent with the broader maize literature in which N uptake and utilisation efficiencies are separable physiological processes (Ciampitti & Vyn, 2012).

Recent sensor-guided evidence sharpens the distinction between yield maximum and efficiency maximum. In a two-season fodder-maize experiment, Shekara et al. (2025) reported the highest green forage yield, dry matter and several quality yields under a 150 kg N ha^{-1} schedule in which a basal fraction was followed by a soil plant analysis development (SPAD) chlorophyll threshold. Yet agronomic N efficiency was highest at a lower total N level managed with a leaf colour threshold. The important inference is not that one of these treatments is universally optimal. Rather, the outcome demonstrates an objective-function problem: a treatment that maximises biomass may not maximise the additional biomass obtained per unit of N. An STCR system for fodder maize should therefore define whether the target is constrained by an efficiency threshold, an economic criterion or a quality requirement instead of using target yield as the only endpoint.

Water availability further modifies N response because N uptake depends on root access and mass flow. Gholami et al. (2024) found that irrigation regime interacted with N and Zn nutrition in fodder maize, affecting growth, physiology, nutrient acquisition and nutrient-use efficiency. This interaction limits the transfer of a prescription developed under full irrigation to water-limited conditions. A high target yield implicitly assumes that the non-nutritional production environment can support that target. STCR theory recognises target attainability, but operational recommendations often present formulae without an explicit water constraint. For fodder systems in which irrigation is variable, the target should be revised downward when water supply is insufficient rather than maintaining the target and increasing fertiliser to compensate for a non-nutrient limitation.

Nitrogen timing matters for the same reason. Pre-season soil tests describe a starting condition, while the crop integrates weather, mineralisation and losses during growth. A rational fodder-maize programme can therefore separate the N decision into a soil-test-informed basal component and responsive topdressing. This is compatible with STCR rather than a competing philosophy. The target-yield equation estimates seasonal need after soil contribution is credited; a sensor can then help determine whether and when the remaining N should be supplied. The evidence for such an integrated algorithm is not yet sufficiently validated to prescribe universal thresholds, but direct fodder sensing results and multi-location maize precision studies make the concept agronomically plausible (Shekara et al., 2025; Singh et al., 2020).

5.2 Phosphorus, Potassium and Zinc

Phosphorus is required for early root development, energy transfer and establishment, but crop response is strongly conditioned by soil P availability and fixation. In STCR calibration, this is reflected by a soil-contribution term that can reduce the fertiliser rate when soil-test P is high. The weakness of a blanket P dose is particularly evident in soils that have received repeated fertilisation or manure, where residual P can accumulate. Conversely, strongly weathered or acidic soils may immobilise P and require different calibration. Fodder-maize dose-response studies generally support adequate balanced P as part of the N response rather than as an independently dominant driver, and reviews of kharif fodder crops have repeatedly concluded that N-P-Zn interactions matter for both yield and quality (Mohan et al., 2015). The critical implication for STCR is that P cannot be assigned as a fixed companion to N; the soil test must determine whether P is limiting, sufficient or potentially accumulating.

Potassium deserves greater attention in fodder maize than it often receives in grain-oriented recommendation discussions. The crop takes up substantial K, and whole-plant harvest exports K contained in leaves and stems that would otherwise partly return to the soil as residues. Direct fodder experiments have shown that balanced K combined with other nutrients can improve productivity and quality, while long-term system studies demonstrate that repeated nutrient imbalance changes the soil's K-supplying capacity (Das et al., 2021). The STCR response framework is useful because it recognises indigenous K supply, but a response-based prescription should be checked against longer-term replacement needs. A field can show a weak immediate yield response to K while still experiencing net K depletion. Thus, the absence of short-term response is not equivalent to evidence that K maintenance is unnecessary.

Zinc illustrates the importance of micronutrients that are not always included in classical NPK STCR equations. In two kharif seasons, Kumar et al. (2017b) reported higher green and dry fodder yields and improved Zn uptake with soil or combined soil-foliar Zn management compared with no Zn. The magnitude and optimal delivery method were context-specific, and the experiment was conducted in a defined north-western Indian environment. Still, the study demonstrates that an NPK-calibrated prescription can remain agronomically incomplete where Zn deficiency constrains the crop. A sustainable decision system should therefore use separate diagnostic rules for micronutrients based on soil or plant analysis rather than assuming that target-yield NPK equations automatically correct all fertility limitations. This is especially important in high-biomass forage because micronutrient concentration also influences the nutritional value of the harvested feed.

5.3 Cultivar, Density and Harvest Endpoint

Cultivar and plant density alter the relationship between nutrient supply and the measured fodder endpoint. Kumar et al. (2017a) found that seeding density affected fibre characteristics and interacted with fertility management, while Kumar et al. (2022) reported cultivar-dependent differences in dry-fodder production under contrasting nutrient strategies based partly on the recommended dose of fertiliser (RDF). These findings caution against treating a nutrient requirement coefficient as purely a soil property. The coefficient expresses crop uptake per unit of harvested yield, and both numerator and denominator can shift with canopy architecture, maturity and genotype. Calibration developed for an older tall fodder cultivar may therefore misestimate the requirement of a newer hybrid with different dry-matter partitioning or harvest maturity.

Harvest stage is equally important because green-fodder yield can rise through both dry-matter accumulation and changes in plant water content. Two plots with the same green mass can differ in dry-matter yield and nutrient concentration. For that reason, a fodder-specific STCR programme should preferably calibrate nutrient requirement against both green-fodder and dry-matter yield, with a defined harvest stage. Feed-quality outcomes should be used as safeguards rather than assumed to improve linearly with biomass. Higher N may increase crude protein yield, but the overall feeding value also depends on fibre fractions, digestibility and the balance of other nutrients. The direct fodder literature shows that these traits respond differently to fertility and cultivar (Kumar et al., 2017a, 2022). A yield target without a harvest-stage definition is therefore an incomplete agronomic target.

Integrated nutrient management experiments add another layer of evidence. Kumar et al. (2023) found productivity and profitability benefits from combinations of organic and inorganic nutrient sources in fodder maize, while Bhagat et al. (2026) showed that an efficient integrated nutrient-management combination in a potato-fodder maize-maize rotation could sustain high productivity with fewer inputs than the most intensive alternatives. These studies do not provide STCR coefficients, but they support two components of an STCR-IPNS interpretation: nutrient sources can be substituted partially when their contribution is recognised, and the most input-intensive treatment is not necessarily the most efficient. The implication is to quantify credits and compare marginal returns rather than to classify organic inputs as intrinsically superior or mineral fertiliser as intrinsically unsustainable.

The direct fodder evidence therefore supports a multidimensional definition of productivity. Green mass remains economically important, but dry matter, crude-protein yield, fibre composition, nutrient uptake, N-use efficiency and production cost determine whether additional fertiliser is useful. This is a stronger criterion than choosing the treatment with the largest biomass mean. Table 3 synthesises representative fodder-maize nutrient studies and indicates how each informs, but also constrains, transfer to an STCR framework.

Table 3. Representative direct evidence on nutrient management in fodder maize

Study context	Nutrient strategy	Main outcome	Critical limitation	Implication for STCR	Supporting references
Fodder maize; N-source experiment	Contrasting N sources and rates.	Growth, yield and quality responded to N management.	Single environmental context and not soil-test calibrated.	N source and availability can modify a fixed target-yield N requirement.	Amin (2011)
Indo-Gangetic Plains; two seasons	Seeding density crossed with graded fertility levels.	Higher fertility improved fodder and nutrient yield; density affected quality traits.	Uses percentages of recommended dose rather than soil-test target equations.	Calibration should control stand density and quality endpoint.	Kumar et al. (2017a)
North-western India; two seasons	Soil and foliar Zn strategies.	Zn management increased fodder yield, quality and Zn uptake relative to no Zn.	Micronutrient response is soil-specific and outside classical NPK STCR equations.	Add diagnostic Zn rules where deficiency risk exists.	Kumar et al. (2017b)
Karnal; two seasons and three cultivars	RDF, integrated organic-inorganic and bio-input strategies.	Cultivar and nutrient strategy jointly influenced dry-fodder productivity and quality.	Does not isolate soil-test contribution coefficients.	Fodder coefficients may require cultivar or maturity-domain validation.	Kumar et al. (2022)
Fodder maize; integrated sources	Panchagavya with organic and inorganic nutrient combinations.	Integrated strategies improved productivity and profitability in the tested setting.	Input packages complicate attribution of individual nutrient effects.	Quantify organic credits rather than adding packages to a full mineral dose.	Kumar et al. (2023)
Fodder maize under contrasting irrigation	N and Zn rates under irrigation regimes.	Water regime modified growth, physiology and nutrient-use efficiency responses.	Target-yield transfer across water environments is uncertain.	Constrain target by attainable yield under actual water supply.	Gholami et al. (2024)
Two winter seasons	Fixed and SPAD/LCC-guided N schedules.	Highest biomass and highest agronomic N efficiency occurred under different N strategies.	No direct STCR baseline comparison.	Use sensing to refine N timing after a soil-test-based seasonal plan.	Shekara et al. (2025)
Potato-fodder maize-maize rotation	Multiple integrated nutrient-management combinations.	An efficient combination sustained productivity comparable with more intensive inputs.	Rotation-level package rather than STCR calibration.	Evaluate marginal input value and residual credits across the rotation.	Bhagat et al. (2026)
Southern Kerala lateritic soil	Low, medium and high fertility strips for fodder maize.	Available NPK, nutrient uptake and green-fodder yield increased across the established gradient.	Primarily gradient-establishment evidence; broad equation validation remains pending.	Provides direct fodder foundation for local STCR calibration.	Anitha et al. (2026)

Note. LCC = leaf colour chart; N = nitrogen; NPK = nitrogen, phosphorus and potassium; RDF = recommended dose of fertiliser; SPAD = soil plant analysis development chlorophyll meter; STCR = soil test crop response; Zn = zinc

6. Evidence for STCR and Integrated Target-Yield Management in Maize Systems

6.1 Target Attainment across Soil Orders

The strongest support for STCR comes from studies in which equations are not merely derived but tested against independent target-yield treatments. In an Alfisol, Coumaravel et al. (2013) developed soil-test-based equations for hybrid maize under an integrated plant nutrition framework, demonstrating the conventional STCR sequence from soil-test relationships to target-specific prescription. In a Vertisol, Reddy et al. (2025) validated fertiliser-only and FYM-integrated STCR approaches and observed a particularly strong response under the integrated high-target treatment. Sweet-corn work on Alfisols provides a further example: Rangaiah et al. (2024) reported that validated target treatments produced fresh-cob yields within an acceptable deviation range while improving nutrient-use efficiency and economic returns compared with general recommendation and fertility-rating approaches. Collectively, these studies support the proposition that soil-test calibration can improve the probability of approaching a chosen yield target within the domain where equations were developed.

The qualifier 'within the domain' is essential. Soil order alone does not define transferability. Alfisols differ in acidity, organic carbon, clay content and P sorption; Vertisols differ in exchange capacity, shrink-swell behaviour and K reserves; Inceptisols encompass a wide range of parent materials and management histories. Target equations also depend on the soil-test methods used in calibration. A formula developed from alkaline permanganate N, Olsen P and ammonium-acetate K cannot be transferred numerically to values generated by unrelated extractants without re-calibration. For fodder maize, target units add further complexity. A 40 t ha^{-1} green-fodder target is biologically and analytically different from a 4 t ha^{-1} grain target, even if both are obtained from the same species. The common STCR architecture transfers; the coefficients do not.

The rotation evidence reinforces the need for crop-specific validation. Venkatesh et al. (2022) evaluated STCR-targeted nutrition in a maize-lentil rotation on an alkaline Fluvisol. Maize target performance was comparatively successful, while lentil targets were missed more substantially. This contrast demonstrates that the existence of a calibrated nutrient-management framework does not remove biological differences in crop response or constraints external to NPK supply. For fodder maize, a similar risk arises when target yield is set close to the climatic or cultivar ceiling. If water, temperature, stand density or disease constrains biomass, the equation may prescribe nutrients for a yield that is not attainable. The resulting failure is not necessarily evidence against soil testing, but it is evidence that target selection must be agronomically realistic.

6.2 Comparison with SSNM and Precision Nutrient Management

SSNM and decision-support approaches provide a useful comparator because they share the aim of matching nutrient supply to field-specific crop need but use different sources of information. Precision nutrient trials in maize have shown gains in productivity, profitability and nutrient-use efficiency when fertiliser is adjusted using field- or site-specific rules rather than fixed farmer practice. Kumar et al. (2015) reported benefits from precision nutrient management combined with conservation-agriculture practices, while Pooniya et al. (2015) found that a decision-support tool for maize-wheat systems could provide a viable alternative to conventional recommendation schedules. Field evaluations under conservation agriculture and other precision programmes similarly reported productivity or profitability advantages from more targeted nutrient decisions (Hasanain et al., 2021; Shyam et al., 2021). Multi-location testing across agro-ecologies further showed that precision management can improve maize performance but with responses that vary by site (Singh et al., 2020).

STCR and SSNM should therefore not be framed as mutually exclusive systems. STCR is particularly strong when soil tests can be calibrated reliably to a yield target and when a local response database exists. SSNM tools can incorporate broader information about omission-plot yield, expected response, crop sequence or field history. In-season sensing adds a temporal dimension that static soil tests cannot provide, especially for N. The most defensible fodder-maize strategy is consequently layered: use STCR/IPNS to establish the baseline NPK requirement for a defined soil and target, then use crop status and seasonal conditions to refine the timing or residual amount of N. This integration preserves the empirical soil-credit strength of STCR while recognising that N mineralisation and loss continue after sampling.

Evidence from eastern Indian smallholders also warns that agronomic algorithms are embedded in farm systems. Goswami et al. (2026) evaluated a nutrient decision-support approach across 112 farms and multiple farm typologies and found that performance was not uniform across resource and management contexts. The exact results are specific to grain maize, but the scaling lesson is directly relevant: a recommendation that requires timely split fertilisation, calibrated soil sampling or sensing may be difficult to implement where labour, irrigation, credit or input access is constrained. An STCR programme that performs well on research plots can therefore fail at scale for operational reasons unrelated to the equation itself. Validation should include farmer-managed conditions and record implementation fidelity rather than judging the algorithm only under researcher-controlled application.

6.3 Fertiliser Savings, Economics and Nutrient-Use Efficiency

The claim that STCR 'saves fertiliser' requires careful qualification. A soil-test prescription can reduce fertiliser where indigenous supply or organic credits are high, but it can also recommend more fertiliser than a blanket dose in a depleted soil or at a higher target. The sustainability advantage is not low input per se; it is better alignment between input, soil supply and attainable output. Reddy et al. (2025) provide a clear example of savings within an IPNS comparison, where incorporating FYM credits reduced mineral N, P_2O_5 and K_2O relative to fertiliser-only STCR at the same target. Rangaiah et al. (2024) similarly found favourable nutrient-use and economic outcomes for selected target treatments. These results support quantitative crediting of non-fertiliser sources, but they should not be generalised as evidence that every STCR prescription uses less fertiliser than every conventional practice.

Economic optimisation also differs from biological target attainment. A high target may be achievable but unprofitable if the marginal fertiliser cost exceeds the value of additional fodder. Conversely, a moderate target can have a higher value-cost ratio and lower risk. This matters in fodder systems because the value of green biomass can vary seasonally and spatially, and on-farm use may not have a transparent market price. The ideal prescription should therefore be offered across an attainable target range rather than as one maximum target. Farmers can then select a target using expected fodder value, input price, irrigation reliability and risk tolerance. This decision layer is conceptually compatible with STCR but is often underdeveloped in experimental studies that report only one or two target levels.

Nutrient-use efficiency metrics can also produce apparently conflicting rankings because each answers a different question. Agronomic efficiency expresses additional yield per unit applied nutrient; recovery efficiency expresses additional nutrient uptake relative to application; partial factor productivity divides total yield by nutrient input; and apparent STCR contribution coefficients are model terms rather than standard efficiency metrics. Shekara et al. (2025) demonstrated within fodder maize that the treatment with the highest yield was not the treatment with the highest agronomic N efficiency. For critical interpretation, studies should not claim a treatment is 'most efficient' without specifying the metric. Fodder-specific STCR validation should report at least yield, nutrient uptake, agronomic efficiency and an economic measure, and ideally distinguish N, P and K rather than aggregating them into a single input score.

6.4 Long-Term Soil and Environmental Effects

Short-term target attainment is necessary but not sufficient for sustainable nutrient management. Long-term experiments show that the nutrient balance of maize-based systems affects soil organic carbon, physical condition and nutrient-supplying capacity. Brar et al. (2015) observed beneficial changes in soil organic carbon and physical properties under long-term integrated nutrient use in a maize-wheat rotation. Hazra et al. (2019) found that diversification with legumes and integrated nutrient management increased soil aggregation and carbon sequestration. These effects arise over years and cannot be inferred from a one-season STCR validation. They nevertheless matter because a soil whose physical condition and organic matter improve may supply nutrients differently from the soil on which the original coefficients were derived.

Balanced nutrient management also influences nutrient losses. Dhawan et al. (2022) reported that long-term balanced fertilisation reduced N losses in a maize-wheat system relative to imbalanced management, while Nisar et al. (2023) linked integrated nutrient management in spring maize with improved yield, nutrient-use efficiency and lower greenhouse-gas intensity. These studies do not establish the environmental performance of fodder-maize STCR itself. Their appropriate role is to define the outcomes that future fodder STCR trials should measure. If targeted-yield management is promoted as sustainable, validation should include residual mineral N, nutrient balance, soil organic carbon trends or greenhouse-gas intensity where feasible rather than equating a high value-cost ratio with environmental sustainability.

Potassium balance deserves explicit long-term attention. Das et al. (2021) showed that long-term nutrient management changed soil K-supplying capacity under intensive cultivation. In a grain system, a portion of above-ground K may return through residues; in fodder maize, whole-plant removal can sharply reduce that return. Thus, a response-based K rate that is adequate for the current crop can still produce a negative balance if crop removal consistently exceeds inputs and replenishment from soil minerals is finite. STCR equations should be accompanied by periodic soil-test trends and, where feasible, nutrient-removal accounting. This is a safeguard against interpreting low short-term yield response as permission to mine soil K.

The representative evidence in Table 4 shows a consistent pattern. STCR and related site-specific approaches perform best when the soil-test method, crop endpoint and target are well matched to the calibration domain; integrated organic nutrient credits can reduce mineral 117ertilizer demand; and validation strengthens confidence substantially. The major weakness is external validity. Many experiments are conducted at one or a few sites, for one or two seasons, with grain or cob rather than fodder as the economic endpoint. The evidence justifies adaptation of the framework to fodder maize, but not uncritical transfer of published coefficients.

Table 4. Representative STCR and site-specific maize evidence relevant to fodder-maize adaptation

Soil/system	Approach	Main finding	Critical inference	Transfer limit	Supporting references
Alfisol; hybrid maize	STCR-IPNS calibration.	Soil-test-based target equations were developed under integrated plant nutrition.	Demonstrates the standard targeted-yield calibration architecture.	Grain endpoint and local soil calibration.	Coumaravel et al. (2013)
Inceptisol; maize hybrids	SSNM and graded NPK.	N was the dominant limitation, but response magnitude depended on indigenous nutrient supply and treatment.	Field response is nonlinear and cannot be represented by a fixed percentage of RDF alone.	Not a fodder or STCR validation study.	Ray et al. (2018)
Alkaline Fluvisol; maize-lentil rotation	STCR target-yield management.	Target attainment differed between crops in the rotation.	Crop-specific calibration remains necessary even within one system.	Rotation and grain endpoints differ from fodder harvest.	Venkatesh et al. (2022)
Alfisol; sweet corn	STCR fertiliser-only and STCR+FYM with independent validation.	Selected target treatments approached fresh-cob targets and improved nutrient-use/economic indicators.	Fresh economic endpoints can be calibrated, supporting methodological adaptation to fodder.	Fresh cob nutrient requirement cannot be transferred to whole-plant fodder.	Rangaiah et al. (2024)

Soil/system	Approach	Main finding	Critical inference	Transfer limit	Supporting references
Acid Alfisol; maize-wheat over nine years	Continuous STCR targeted-yield equations with FYM/fertiliser.	Long-term management altered micronutrient transfer and uptake.	Targeted macronutrient management changes the wider soil nutrient environment over time.	Cropping-system evidence rather than direct fodder calibration.	Kurbah et al. (2024)
Vertisol; northern Karnataka	STCR and STCR-IPNS maize validation.	FYM-integrated high-target treatment reduced mineral N, P_2O_5 and K_2O relative to fertiliser-only STCR.	Organic nutrient credits can be incorporated quantitatively.	Test crop was grain maize; fodder maize served as the exhaustive crop.	Reddy et al. (2025)
Multiple maize agro-ecologies	Precision nutrient management.	Productivity and profitability benefits varied across sites.	External validation is essential for scaling field-specific nutrient strategies.	Different decision framework and grain endpoint.	Singh et al. (2020)
Eastern Indian smallholders	Nutrient decision support across farm typologies.	Performance differed among farm types and resource contexts.	Implementation heterogeneity can be as important as agronomic calibration.	Not direct STCR or fodder evidence.	Goswami et al. (2026)

Note. FYM = farmyard manure; IPNS = integrated plant nutrient supply; N = nitrogen; P = phosphorus; K = potassium; RDF = recommended dose of fertiliser; SSNM = site-specific nutrient management; STCR = soil test crop response

7. Adapting STCR Specifically to Fodder Maize

7.1 Why Grain-Maize Equations Cannot Be Transferred Directly

The most important adaptation is to redefine the economic yield term. In grain maize, nutrient requirement is related to grain yield and total crop uptake; in sweet corn, fresh cob yield can be the target; in fodder maize, the harvested product is whole-plant green or dry biomass. This difference changes both nutrient removal and the denominator used to calculate nutrient requirement. A grain equation may understate the K replacement needed after whole-plant harvest because K retained in stover is removed rather than recycled. It may also misrepresent N requirement if harvest occurs before the redistribution of N from vegetative tissues to grain. The equation structure can be retained, but the nutrient requirement and contribution coefficients must be re-estimated against a defined fodder harvest stage.

The recent Kerala study provides a practical starting point because it demonstrates a fodder-maize response across deliberately generated NPK fertility levels in lateritic soil (Anitha et al., 2026). To move from gradient establishment to a robust prescription, subsequent experiments should superimpose factorial NPK treatments across those gradients, quantify total N, P and K uptake, derive nutrient requirement per tonne of green and dry fodder, and test resulting equations in independent fields. Green-yield target deviation should be reported together with dry-matter deviation. A treatment that hits a green-mass target because plant water content is unusually high is not agronomically equivalent to one that achieves the intended dry-matter production.

Older or regionally established fodder prescriptions can still have local value, but their numerical use should be conditional on cultivar, soil-test method and validation history. The broad literature on fodder nutrient response has changed through new cultivars, sensor tools and integrated nutrient practices (Bhaumik et al., 2025; Shekara et al., 2025). Consequently, legacy equations should be treated as hypotheses for revalidation rather than permanent constants. Where an existing equation consistently predicts target yield within a predefined tolerance under current varieties and management, revalidation can be more efficient than complete redevelopment. Where it fails systematically, recalibration should identify whether the problem lies in nutrient requirement, soil contribution, fertiliser contribution or target attainability.

7.2 Dual Targets: Green Fodder and Dry Matter with Quality Safeguards

A fodder recommendation is improved by separating quantity from composition. Green-fodder yield is operationally useful because it corresponds to harvested fresh biomass, but dry-matter yield is a more stable indicator of accumulated plant material and nutrient removal. The two should therefore be reported together in calibration and validation. Direct studies routinely show that nutrient treatments can alter both biomass and concentration-based quality traits (Kumar et al., 2017a, 2017b, 2022). A dual-target system could calibrate the equation primarily to dry matter while translating results to an expected green-fodder range at a defined harvest stage, or alternatively calibrate green yield but use dry-matter content as an obligatory validation variable. Either approach is stronger than treating green mass alone as the response variable.

Quality should function as a constraint rather than as an uncontrolled co-benefit. Nitrogen can raise crude-protein concentration and protein yield, and Zn fertilisation can improve mineral concentration and uptake, but the response of fibre fractions and other quality attributes is not necessarily parallel to green biomass (Kumar et al., 2017a, 2017b; Shekara et al., 2025). Thus, a high target should not be promoted if achieving it requires a nutrient regime that produces poor economic efficiency or an undesirable quality profile.

Future validation should define an acceptable feed-quality window appropriate to the cultivar and harvest purpose. The role of STCR is then to achieve biomass within that window, not to optimise each quality trait independently through a single NPK equation.

7.3 A Pre-Season STCR Base plus In-Season Nitrogen Adjustment

Nitrogen is the clearest candidate for dynamic adjustment because its soil supply and loss risk change rapidly within the season. A practical STCR-plus design would use a representative pre-sowing soil sample to establish the target-yield NPK prescription, apply P and a context-appropriate proportion of K before or early in the season, and divide N into a basal quantity plus one or more responsive topdressings. The total planned N would still be bounded by the STCR target, but a sensor could delay, reduce or confirm later N depending on realised crop status. Fodder-maize evidence from SPAD and leaf colour chart management demonstrates that threshold-triggered N can generate strong yield and efficiency responses (Shekara et al., 2025). The next research step is to test whether sensor refinement reduces target error or N input relative to STCR alone across contrasting soil N supplies.

Such a hybrid avoids a false choice between soil testing and plant sensing. Soil tests are strongest at characterising the starting nutrient environment and long-lived nutrient pools such as P and K. Plant sensors are strongest at integrating actual seasonal conditions experienced by the canopy. They are weaker as stand-alone tools for diagnosing P, K or micronutrient limitation because leaf colour and chlorophyll are not specific to N and can be affected by water stress, disease or other deficiencies. The combined system therefore requires diagnostic safeguards: if canopy sensing indicates low N status but soil moisture is inadequate or Zn deficiency is evident, additional N may not solve the limiting factor. This is where agronomic interpretation remains necessary despite digital decision support.

7.4 Nutrient Balance, Residual Credits and Micronutrient Diagnostics

The whole-plant harvest makes nutrient balance a central design requirement. For each validation treatment, nutrient removal in harvested dry matter should be compared with mineral and organic inputs and with changes in post-harvest soil tests. This need is strongest for K but also relevant to N and P. The goal is not to force zero annual balance, because soils can legitimately supply nutrients from reserves and management can operate over rotations. Rather, the balance should identify whether repeated target-yield prescriptions are systematically mining or accumulating a nutrient. Long-term maize evidence demonstrates that both K-supplying capacity and soil carbon respond to nutrient-management history (Brar et al., 2015; Das et al., 2021). A sustainable fodder equation should therefore be periodically recalibrated against changing soil status instead of assuming constant contribution coefficients indefinitely.

Organic inputs should be credited using measured or credible nutrient composition rather than assigned a universal substitution value. Their immediate N contribution depends on mineralisation, while their P and K contributions may persist beyond the application season. Repeated FYM use can also alter soil organic carbon and physical properties, changing future crop response (Brar et al., 2015). STCR-IPNS studies show that explicit manure credits can reduce mineral fertiliser needs at a given target (Rangaiah et al., 2024; Reddy et al., 2025), but the credit should be updated when the material source, rate or history changes. This turns IPNS from an input recipe into an accounting system.

Micronutrients require a parallel diagnostic layer. The positive fodder response to Zn fertilisation observed by Kumar et al. (2017b) indicates that an NPK-only equation can underperform when Zn deficiency limits growth or quality. Long-term targeted fertilisation can also alter micronutrient transfer and uptake (Kurbah et al., 2024). Accordingly, fodder STCR validation should measure at least soil Zn where deficiency risk is known and should not attribute unexplained target shortfall automatically to imperfect NPK coefficients. Where secondary or micronutrient deficiencies are common, local decision rules can be linked to the STCR platform without forcing every element into the same target-yield equation.

The resulting STCR-plus model is deliberately modular. Its established component is soil-test and target-yield calibration of NPK, with optional organic credits. Its evidence-supported extension is responsive N management using crop status. Its longer-term safeguard is nutrient-balance and soil-test trend monitoring, especially for K under whole-plant removal. Its context-specific module is micronutrient correction based on diagnostic evidence. This architecture is more defensible than a universal formula because it separates what can be predicted before sowing from what must be updated during crop growth and what must be checked across years.

8. Sustainability, Resource-Use Efficiency and Adoption

8.1 Soil Fertility and Environmental Performance

Sustainability claims should be tied to measurable outcomes. A nutrient-management system can be considered more sustainable if it maintains or improves productivity while reducing avoidable nutrient surplus, preserving soil fertility and limiting off-site losses. STCR contributes to this objective by crediting soil supply and avoiding automatic application of the same fertiliser dose to all fields. Yet a single high-yield season does not demonstrate sustainability. Long-term maize systems show that balanced organic and mineral inputs can improve soil carbon and aggregation (Brar et al., 2015; Hazra et al., 2019) and that balanced fertilisation can reduce N losses relative to deficient or distorted regimes (Dhawan et al., 2022). These outcomes establish a benchmark against which fodder STCR should be assessed over multiple seasons.

Environmental performance is especially sensitive to the choice of yield target. When the target exceeds the attainable yield under current water, cultivar or climate conditions, nutrient rates calculated for that target create surplus without corresponding biomass capture. Conversely, targets set too low can suppress profitable production and may encourage farmers to abandon the recommendation. The rational approach is an attainable target range linked to historical field performance and current resource constraints. This also creates an opportunity to express efficiency on a product basis, such as nutrient input or greenhouse-gas intensity per tonne of dry fodder, while retaining absolute loss indicators. Nisar et al. (2023) demonstrated the utility of combining productivity and greenhouse-gas-intensity assessment in maize; analogous metrics are needed for fodder-specific targeted-yield systems.

8.2 Economics, Farm Heterogeneity and Implementation

Economic performance depends on more than fertiliser savings. Soil sampling, laboratory analysis, manure handling, split application and sensor use all have transaction costs. These costs can be justified when they reduce unnecessary inputs or increase reliable fodder supply, but the net benefit will vary by farm scale and access to services. Integrated nutrient studies in fodder maize show that strategically combined organic and inorganic inputs can improve profitability, yet the best treatment is not necessarily the one with the greatest number of inputs (Bhagat et al., 2026; Kumar et al., 2023). STCR recommendations should therefore present expected fertiliser requirement and economic implications transparently rather than equating technological complexity with superior management.

Farm typology matters because the same agronomic recommendation can impose different constraints on a dairy farmer with assured irrigation and manure supply than on a resource-limited farm purchasing all fertiliser. Goswami et al. (2026) found heterogeneous performance of a maize nutrient decision-support approach across smallholder farm types in eastern India. This does not undermine field-specific nutrient management; it shows that scaling requires field-specific agronomy and farm-specific implementation. Advisory systems should capture at least irrigation reliability, manure availability, previous crop, expected fodder demand and target yield. A recommendation that is biologically precise but impossible to apply on time is operationally imprecise.

Digitisation can reduce some transaction costs if soil-test results, target choices and fertiliser calculations are integrated into a simple decision interface. Yet digital presentation should not conceal uncertainty. The system should retain the calibration domain, soil-test method, date of sampling, nutrient-source assumptions and range over which the equation was validated. Where the farmer's value falls outside that domain, the tool should flag the need for agronomic review rather than extrapolate silently. This is particularly important for newly reclaimed, severely depleted or heavily manured soils, in which linear extrapolation can produce implausible recommendations.

Adoption is therefore best understood as a quality-control problem as well as a communication problem. The minimum service chain includes representative sampling, reliable laboratory analysis, correct equation selection, realistic target setting, accurate fertiliser conversion, timely application and post-season learning. Error at any step can be misattributed to 'STCR failure'. A sustainable programme should audit these steps, collect target deviation from farmer fields, and recalibrate when systematic bias emerges. This feedback loop is analogous to external validation in predictive modelling and is essential if targeted-yield recommendations are to remain relevant as cultivars, input prices and soil fertility change.

9. Future Directions

The immediate research priority is fodder-specific calibration across contrasting soil orders and fertility ranges. The recent laterite-soil experiment demonstrates that a controlled gradient can be established for fodder maize, but the next phase should derive and validate equations across independent sites rather than relying on a single experimental station (Anitha et al., 2026). Multi-location programmes should include at least the major soil environments in which fodder maize is produced and should standardise soil-test methods, cultivar information, harvest stage and yield units. The objective is not to create one national coefficient, but to determine the scale at which coefficients remain stable and when separate soil- or zone-specific equations are required.

A second priority is to redefine the response endpoint. Calibration should report green-fodder yield, dry-matter yield, total NPK uptake and selected feed-quality indicators together. This would resolve a major weakness of fresh-mass targets and permit nutrient requirement to be expressed in relation to actual dry matter and nutrient removal. Direct fodder studies already demonstrate treatment effects on crude protein, fibre fractions, Zn concentration and nutrient yield (Kumar et al., 2017a, 2017b, 2022; Shekara et al., 2025). Future STCR trials should use these variables to test whether target attainment is achieved without sacrificing quality or efficiency. For high N targets, crop N status and residual soil mineral N should be monitored so that additional biomass can be distinguished from inefficient surplus.

A third priority is prospective testing of the STCR-plus concept. Randomised field experiments should compare at least a calibrated STCR/IPNS base prescription, the same prescription with sensor-guided N topdressing, a locally recommended dose and representative farmer practice. The key question is whether in-season sensing reduces N input, increases target reliability, or improves agronomic N efficiency under variable seasonal conditions. Shekara et al. (2025) provide direct fodder evidence that sensor thresholds can guide N successfully, while multi-location precision-maize studies show that site variability remains important (Singh et al., 2020). The hybrid approach should therefore be tested across soil N supply and irrigation regimes rather than at a single fertility level.

A fourth priority is long-term nutrient balance, with particular emphasis on K. Whole-plant harvest means that nutrient removal should be measured rather than inferred from grain coefficients. Trials should follow post-harvest soil-test trends, K fractions where feasible, soil organic carbon and nutrient balance over several crop cycles. Evidence that long-term management changes K-supplying capacity and soil structural properties justifies this timescale (Brar et al., 2015; Das et al., 2021; Hazra et al., 2019). Such studies would determine whether short-term target equations maintain fertility or progressively depend on soil mining.

A fifth priority is external validation under farmer-managed conditions. Algorithms should be tested across farm typologies, input-access constraints and manure histories, recording not only biological response but also implementation fidelity, labour requirement, profitability and the frequency with which recommendations fall outside the calibrated range. Evidence from maize decision-support systems indicates that agronomic benefit can vary across farm types (Goswami et al., 2026). Farmer-field validation would therefore distinguish equation error from service-delivery error and identify where simpler recommendations outperform information-intensive approaches because of lower transaction costs.

Finally, future work should treat recalibration as an expected part of the technology lifecycle. Cultivars change, soil fertility shifts, organic inputs accumulate and climate variability alters attainable yield. A robust programme should maintain machine-readable records linking soil-test values, nutrient applications, weather, harvest stage, green and dry yield, nutrient uptake and target deviation. Such datasets would permit periodic re-estimation of STCR coefficients and, where sample size supports it, evaluation of nonlinear or hierarchical models that retain agronomic interpretability. The priority is not algorithmic novelty for its own sake, but more reliable prediction across known sources of heterogeneity. Table 5 summarises the most important research priorities and the designs required to address them.

Table 5. Priority research agenda for fodder-maize STCR under soil fertility gradients

Priority	Unresolved problem	Preferred design	Essential outcomes	Expected value	Supporting references
Multi-soil fodder calibration	Contemporary fodder-specific equations are sparse and locally bounded.	Inductive-cum-targeted-yield trials across major soil orders with independent validation.	Green yield, dry matter, NPK uptake, target deviation and soil tests.	Defines calibration domains and transfer limits.	Anitha et al. (2026); Reddy et al. (2025)
Dual yield-quality endpoint	Fresh mass can obscure dry matter and feeding value.	Calibrate at a defined harvest stage with quality measurements.	Dry-matter yield, crude-protein yield, fibre traits and nutrient concentration.	Prevents biomass targets from displacing feed quality.	Kumar et al. (2017a, 2017b, 2022)
STCR plus crop sensing	Pre-season N supply is temporally uncertain.	Randomised comparison of STCR, STCR+SPAD/LCC, RDF and farmer practice.	N input, target deviation, agronomic/recovery efficiency and profit.	Tests whether in-season adjustment improves N efficiency and reliability.	Shekara et al. (2025); Singh et al. (2020)
K and whole-plant balance	Fodder harvest removes vegetative K that grain systems may recycle.	Multi-season nutrient balance with K fractions and post-harvest soil testing.	K removal, K balance, soil K pools and biomass stability.	Reduces risk of hidden soil K mining.	Das et al. (2021); Rangaiah et al. (2024)
Organic-source credit validation	FYM nutrient availability varies by material and history.	Measured manure composition with repeated STCR-IPNS validation.	Mineral fertiliser substitution, residual nutrients, soil carbon and profit.	Improves accuracy of IPNS and avoids double application.	Brar et al. (2015); Reddy et al. (2025)
Farmer-field external validation	Research-station equations may not survive operational constraints.	Clustered multi-farm trials stratified by farm typology and irrigation access.	Implementation fidelity, yield error, labour, profit and adoption.	Separates algorithm error from service-delivery error.	Goswami et al. (2026)
Environmental validation	Sustainability is often inferred from yield or fertiliser saving alone.	Multi-season comparative trials with environmental indicators.	Residual mineral N, nutrient surplus, soil carbon and emissions intensity where feasible.	Tests whether targeted yield reduces losses without lowering fodder supply.	Dhawan et al. (2022); Nisar et al. (2023)

Note. FYM = farmyard manure; LCC = leaf colour chart; N = nitrogen; NPK = nitrogen, phosphorus and potassium; RDF = recommended dose of fertiliser; SPAD = soil plant analysis development chlorophyll meter; STCR = soil test crop response

10. Conclusions

Soil fertility gradients are the central reason that fodder maize nutrient management should move beyond blanket fertiliser recommendations. The STCR framework is scientifically attractive because it links an attainable yield target to crop nutrient requirement while crediting indigenous soil supply and, in IPNS versions, organic nutrient sources. Evidence from maize across several soil environments shows that well-calibrated and validated STCR approaches can improve target attainment, nutrient-use efficiency, fertiliser allocation and economic performance. Direct fodder-maize evidence also confirms that substantial N, P, K and Zn responses occur, but that biomass, quality and efficiency do not share a single universal optimum.

The strongest conclusion is therefore conditional rather than universal: STCR is a suitable foundation for sustainable fodder-maize nutrient management when its coefficients are derived for the fodder endpoint, the soil-test method and the relevant production environment. Grain- or cob-based equations should not be transferred numerically to whole-plant fodder without revalidation. Green-fodder targets should be paired with dry-matter and nutrient-removal measurements, and high-biomass harvests require explicit attention to K balance. Organic nutrient credits can reduce unnecessary mineral fertiliser, but they must reflect actual material quality and residual effects. Nitrogen is best treated as a dynamic nutrient, making a pre-season STCR base combined with in-season crop sensing a promising but still validation-dependent extension.

Sustainable implementation ultimately depends on repeated calibration, realistic target setting and feedback from farmer fields. A technically precise equation cannot compensate for unrepresentative soil sampling, unreliable analytical data, water-limited target selection or delayed fertiliser application. The next generation of fodder-maize STCR should therefore be evaluated as an integrated decision system rather than as a stand-alone formula. Its success should be judged by reliable dry-matter production and feed quality, efficient nutrient use, profitability, maintenance of soil fertility and reduced nutrient surplus across seasons.

11. Limitations

This critical narrative review is intrinsically vulnerable to selection and interpretive bias despite the use of an explicit search strategy, source verification and structured evidence appraisal. The evidence base is heterogeneous in soil type, cultivar, crop endpoint, experimental duration, nutrient source and efficiency metric, which limits direct comparison and prevents a meaningful quantitative synthesis. Much of the STCR evidence is concentrated in India and in grain-maize or sweet-corn systems, whereas direct fodder-specific calibration and multi-location validation remain relatively sparse. Several relevant long-term studies evaluate balanced or integrated nutrient management rather than STCR specifically and were therefore used only to inform sustainability mechanisms, not to attribute effects uniquely to STCR. English-language and accessible full-text evidence was prioritised, so locally important studies outside these constraints may have been missed. Rapid development of sensor-guided management and newly published fertility-gradient work also means that the evidence base may change as full calibration and validation studies become available.

Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that no competing interests exist.

References

Amin, M. E.-M. H. (2011). Effect of different nitrogen sources on growth, yield and quality of fodder maize (*Zea mays* L.). *Journal of the Saudi Society of Agricultural Sciences, 10*(1), 17–23. https://doi.org/10.1016/j.jssas.2010.06.003

Anitha, G., Visveswaran, S., Rani, B., Rajasree, G., Gopinath, P. P., Raj, K. K., Swaroop, R., Safeer, M. M., Rohith, A. K., & Esakkimuthu, M. (2026). Development of fertility gradients and STCR based nutrient management for fodder maize in the southern laterite soils of Kerala. *International Journal of Advanced Biochemistry Research, 10*(4S), 536–539. https://doi.org/10.33545/26174693.2026.v10.i4Sg.8151

Baethge, C., Goldbeck-Wood, S., & Mertens, S. (2019). SANRA—A scale for the quality assessment of narrative review articles. *Research Integrity and Peer Review, 4*, Article 5. https://doi.org/10.1186/s41073-019-0064-8

Bender, R. R., Haegele, J. W., Ruffo, M. L., & Below, F. E. (2013). Nutrient uptake, partitioning, and remobilization in modern, transgenic insect-protected maize hybrids. *Agronomy Journal, 105*(1), 161–170. https://doi.org/10.2134/agronj2012.0352

Bhagat, R., Walia, S. S., Dheri, G. S., Singh, S. P., Saini, K. S., & Ravisankar, N. (2026). Exploring optimal integrated nutrient management combinations in potato-fodder maize-maize rotation to improve agronomic parameters, productivity and nutrient uptakes under Inceptisols of north-western India. *Journal of Agriculture and Food Research, 25*, 102553. https://doi.org/10.1016/j.jafr.2025.102553

Bhaumik, S., Rajeev, Kumar, S., Fayaz, S., Choudhary, M., Narender, K., & Sharma, S. (2025). Impact of nutrients on the development and yield of fodder maize (*Zea mays* L.): A review. *Agricultural Reviews, 46*(2), 302–308. https://doi.org/10.18805/ag.R-2631

Brar, B. S., Singh, J., Singh, G., & Kaur, G. (2015). Effects of long term application of inorganic and organic fertilizers on soil organic carbon and physical properties in maize-wheat rotation. *Agronomy, 5*(2), 220–238. https://doi.org/10.3390/agronomy5020220

Ciampitti, I. A., & Vyn, T. J. (2012). Physiological perspectives of changes over time in maize yield dependency on nitrogen uptake and associated nitrogen efficiencies: A review. *Field Crops Research, 133*, 48–67. https://doi.org/10.1016/j.fcr.2012.03.008

Coumaravel, K., Santhi, R., & Maragatham, S. (2013). Soil test crop response correlation studies under integrated plant nutrition system for hybrid maize on an Alfisol. *Madras Agricultural Journal, 100*(7–9), 660–664. https://doi.org/10.29321/MAJ.10.001378

Das, D., Dwivedi, B. S., Datta, S. P., Datta, S. C., Meena, M. C., Dwivedi, A. K., Singh, M. V., Chakraborty, D., & Jaggi, S. (2021). Long-term differences in nutrient management under intensive cultivation alter potassium supplying ability of soils. *Geoderma, 393*, 114983. https://doi.org/10.1016/j.geoderma.2021.114983

Dhawan, G., Dheri, G. S., & Gill, A. A. S. (2022). Long-term use of balanced fertilization decreases nitrogen losses in a maize-wheat system on Inceptisol of north India. *Archives of Agronomy and Soil Science, 68*(3), 395–412. https://doi.org/10.1080/03650340.2020.1836347

Ferrari, R. (2015). Writing narrative style literature reviews. *Medical Writing, 24*(4), 230–235. https://doi.org/10.1179/2047480615Z.000000000329

Gholami, A., Maleki, A., Mirzaeiheydari, M., & Babaei, F. (2024). Effect of nitrogen fertilizer and zinc sulfate on growth, physiological, biochemical and nutrient use efficiency in fodder maize under irrigation regimes. *Journal of Plant Nutrition, 47*(19), 3701–3720. https://doi.org/10.1080/01904167.2024.2383653

Goswami, R., Dutta, S., Banerjee, H., Chakraborty, S., Ray, K., Majumdar, K., & Timsina, J. (2026). Typology-based evaluation of Nutrient Expert for sustainable maize intensification in smallholder farms of eastern India. *Farming System, 4*(2), 100193. https://doi.org/10.1016/j.farsys.2025.100193

Green, B. N., Johnson, C. D., & Adams, A. (2006). Writing narrative literature reviews for peer-reviewed journals: Secrets of the trade. *Journal of Chiropractic Medicine, 5*(3), 101–117. https://doi.org/10.1016/S0899-3467(07)60142-6

Hasanain, M., Singh, V. K., Rathore, S. S., Shekhawat, K., Singh, R. K., Dwivedi, B. S., Upadhyaya, P. K., & Singh, S. (2021). Effect of site-specific nutrient management in conservation agriculture-based maize in north-western India. *Indian Journal of Agronomy, 66*(2), 136–142. https://doi.org/10.59797/ija.v66i2.2849

Hazra, K. K., Nath, C. P., Singh, U., Praharaj, C. S., Kumar, N., Singh, S. S., & Singh, N. P. (2019). Diversification of maize-wheat cropping system with legumes and integrated nutrient management increases soil aggregation and carbon sequestration. *Geoderma, 353*, 308–319. https://doi.org/10.1016/j.geoderma.2019.06.039

Kumar, B., Ram, H., & Schoenau, J. (2024). Agronomic biofortification of fodder maize (*Zea mays* L.) with Zn for improving herbage productivity and its quality. *Agronomy, 14*(5), 912. https://doi.org/10.3390/agronomy14050912

Kumar, D., Singh, M., Kumar, S., Meena, R. K., Yadav, M. R., Makarana, G., Kushwaha, M., Dutta, S., Kumar, R., & Rajesh. (2022). Productivity and quality enhancement in fodder maize (*Zea mays*) cultivars through nutrient management strategies. *The Indian Journal of Agricultural Sciences, 92*(1), 126–130. https://doi.org/10.56093/ijas.v92i1.120875

Kumar, D., Singh, M., Meena, R. K., Kumar, S., Meena, B. L., Yadav, M. R., Makarana, G., & Kushwaha, M. (2023). Productivity and profitability improvement of fodder maize under combined application of indigenously prepared panchagavya with organic and inorganic sources of nutrient. *Journal of Plant Nutrition, 46*(14), 3519–3534. https://doi.org/10.1080/01904167.2023.2206433

Kumar, R., Singh, M., Meena, B. S., Kumar, S., Yadav, M. R., Parihar, C. M., Ram, H., Meena, R. K., Meena, V. K., & Kumar, U. (2017a). Quality characteristics and nutrient yield of fodder maize (*Zea mays*) as influenced by seeding density and nutrient levels in Indo-Gangetic Plains. *The Indian Journal of Agricultural Sciences, 87*(9), 1203–1208. https://doi.org/10.56093/ijas.v87i9.74205

Kumar, R., Singh, M., Meena, B. S., Ram, H., Parihar, C. M., Kumar, S., Yadav, M. R., Meena, R. K., Kumar, U., & Meena, V. K. (2017b). Zinc management effects on quality and nutrient yield of fodder maize (*Zea mays*). *The Indian Journal of Agricultural Sciences, 87*(8), 1013–1017. https://doi.org/10.56093/ijas.v87i8.73070

Kumar, V., Singh, A. K., Jat, S. L., Parihar, C. M., Pooniya, V., Singh, B., & Sharma, S. (2015). Precision nutrient and conservation agriculture practices for enhancing productivity, profitability, nutrient-use efficiencies and soil nutrient status of maize (*Zea mays*) hybrids. *The Indian Journal of Agricultural Sciences, 85*(7), 926–930. https://doi.org/10.56093/ijas.v85i7.50124

Kurbah, I., Dixit, S. P., Mehta, S., & Sharma, S. K. (2024). Effect of continuous FYM and fertilizer applications over nine years utilizing STCR based targeted yield equations on transfer and uptake of micronutrients in an acid Alfisol under a maize-wheat cropping system. *Journal of Plant Nutrition, 47*(19), 3542–3556. https://doi.org/10.1080/01904167.2024.2380489

Li, Z., Gao, W., Jiang, C., Lu, Y., Kamran, M., & Yang, X. (2025). Appropriate nitrogen application rate with decreased basal/topdressing ratio improves yield, quality, water productivity, and N-use efficiency of forage maize in a rainfed region. *Agricultural Water Management, 317*, 109629. https://doi.org/10.1016/j.agwat.2025.109629

Maertens, M., Oyinbo, O., Abdoulaye, T., & Chamberlin, J. (2023). Sustainable maize intensification through site-specific nutrient management advice: Experimental evidence from Nigeria. *Food Policy, 121*, 102546. https://doi.org/10.1016/j.foodpol.2023.102546

Mohan, S., Singh, M., & Kumar, R. (2015). Effect of nitrogen, phosphorus and zinc fertilization on yield and quality of kharif fodder—A review. *Agricultural Reviews, 36*(3), 218–226. https://doi.org/10.5958/0976-0741.2015.00025.2

Nisar, S., Mavi, M. S., Singh, J., & Dey, P. (2023). Integrated nutrient management in spring-maize improves yield, nutrient use efficiency and minimizes greenhouse gas intensity. *Archives of Agronomy and Soil Science, 69*(13), 2522–2536. https://doi.org/10.1080/03650340.2022.2160977

Pooniya, V., Jat, S. L., Choudhary, A. K., Singh, A. K., Parihar, C. M., Bana, R. S., Swarnalakshmi, K., & Rana, K. S. (2015). Nutrient Expert assisted site-specific-nutrient-management: An alternative precision fertilization technology for maize-wheat cropping system in South-Asian Indo-Gangetic Plains. *The Indian Journal of Agricultural Sciences, 85*(8), 996–1002. https://doi.org/10.56093/ijas.v85i8.50796

Rangaiah, K. M., Nagaraju, B., Kasturappa, G., Nagendrachari, A. N., Kadappa, B. P., Narayanaswamy, U. K. S., Hussain Sab, M. S., Veerabadraiah, G. G., Srivastava, S., & Dey, P. (2024). Inductive cum targeted yield model-based integrated fertilizer prescription for sweet corn (*Zea mays* L. Saccharata) on Alfisols of Southern India. *PLOS ONE, 19*(8), e0307168. https://doi.org/10.1371/journal.pone.0307168

Ray, K., Banerjee, H., Bhattacharyya, K., Dutta, S., Phonglosa, A., Pari, A., & Sarkar, S. (2018). Site-specific nutrient management for maize hybrids in an Inceptisol of West Bengal, India. *Experimental Agriculture, 54*(6), 874–887. https://doi.org/10.1017/S001447971700045X

Reddy, K. J., Chandrashekara, C. P., Rajyalakshmi, B., Biradar, D. P., Rajakumar, G. R., & Kanannavar, P. S. (2025). Development of soil test crop response (STCR) and STCR-integrated plant nutrition supply (IPNS) models to achieve targeted yields of maize (*Zea mays* L.) in Vertisols of northern Karnataka. *Indian Journal of Agricultural Research, 59*(1), 44–49. https://doi.org/10.18805/IJARe.A-6210

Shekara, B. G., Chikkarugi, N. M., Sannagoudar, M. S., Jinger, D., Halli, H. M., Gupta, G., Chand, S., Paramesh, V., Rajanna, G. A., Aravindan, S., & Mahesha, H. S. (2025). Optimizing yield, quality, and nitrogen use efficiency in fodder maize through precision N-management. *Discover Applied Sciences, 7*, 812. https://doi.org/10.1007/s42452-025-07232-6

Shyam, C. S., Rathore, S. S., Shekhawat, K., Singh, R. K., Padhan, S. R., & Singh, V. K. (2021). Precision nutrient management in maize (*Zea mays*) for higher productivity and profitability. *The Indian Journal of Agricultural Sciences, 91*(6), 933–935. https://doi.org/10.56093/ijas.v91i6.114303

Singh, A. K., Jat, S. L., Parihar, C. M., Kumar, M., Singh, C. S., Hallikeri, S. S., Sreelatha, D., Manjulatha, G., & Mahala, D. M. (2020). Precision nutrient management for enhanced yield and profitability of maize (*Zea mays*). *The Indian Journal of Agricultural Sciences, 90*(5), 952–956. https://doi.org/10.56093/ijas.v90i5.104369

Velayutham, M. (2017). The law of optimum—A unified concept in plant nutrition bridging the law of minimum and the law of the maximum. *Madras Agricultural Journal, 104*(10–12), 309–314. https://doi.org/10.29321/MAJ.10.201779

Venkatesh, M. S., Hazra, K. K., Ghosh, P. K., & Singh, K. K. (2022). Improving productivity of maize-lentil rotation in alkaline Fluvisol following soil test crop response (STCR)-targeted yield approach of nutrient management. *Archives of Agronomy and Soil Science, 68*(7), 929–943. https://doi.org/10.1080/03650340.2020.1864338

Wang, X., Miao, Y., Dong, L., Mi, G., Batchelor, W. D., & Kusnierek, K. (2025). Precision nitrogen management for maize based on crop modeling, remote sensing and machine learning. *Computers and Electronics in Agriculture, 239*, 111124. https://doi.org/10.1016/j.compag.2025.111124

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