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Site-Specific Nutrient Management in Safflower (*Carthamus tinctorius* L.) A Review of Research Advances, Adoption Challenges, and Future Priorities for Marathwada, Maharashtra

Shruti Balaji Yerawad[1]
Vishal B. Awasarmal[2]
Vivek Balaji Choudhary[3]

[1]M.Sc. Scholar, Department of Agronomy, College of Agriculture, Parbhani, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani – 431 401, Maharashtra, India
[2]Associate Professor, Department of Agronomy, College of Agriculture, Parbhani, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani – 431 401, Maharashtra, India
[3]M.Sc. Scholar, Department of Seed Science and Technology, College of Agriculture, Parbhani, Vasantrao Naik Marathwada Krishi Vidyapeeth, Parbhani – 431 401, Maharashtra, India

*Corresponding Author
Shruti Balaji Yerawad*

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INTRODUCTION

Safflower (*Carthamus tinctorius* L.) is one of the oldest oilseed crops of the Indian subcontinent, grown chiefly on residual soil moisture after monsoon withdrawal across the rainfed black-soil tracts of peninsular India. Maharashtra and Karnataka together account for most of India's safflower area and production, with the crop in Maharashtra concentrated overwhelmingly in Marathwada, where it follows *kharif* soybean, cotton or fallow (Shinde *et al.,* 2024).

Average productivity in Maharashtra remains well below research-station levels, a gap attributed to post-rainy moisture stress, delayed sowing, and — critically — blanket fertilizer recommendations that take no account of field fertility, soil-test status, or residual nutrients from a preceding legume (Shinde *et al.,* 2024). Site-Specific Nutrient Management (SSNM) was developed to correct this mismatch by basing fertilizer prescriptions on a field's attainable yield, indigenous nutrient supply, and expected response to added nutrients (Dobermann & Cassman, 2002). This review synthesizes SSNM principles and operational approaches for safflower, research evidence from Marathwada, adoption constraints, and priorities for future research.

2. Safflower in Maharashtra and Marathwada

Safflower occupies roughly a fifth of a million hectares in Maharashtra, the great majority in Marathwada's medium-deep to deep Vertisols — soils with high clay content, moderate-to-high native potassium but frequently low available nitrogen and low-to-medium phosphorus (Meshram *et al.,* 2018). Sown in September–October on conserved moisture following *kharif* soybean, the crop matures largely on receding profile moisture. Moisture stress at flowering and seed-filling, delayed sowing, and a widespread reliance on a single blanket N-P dose that ignores field-to-field fertility and residual legume nutrients

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3. Concept and Principles of SSNM

SSNM holds that fertilizer nutrients should supplement, not substitute for, nutrients already available from soil, water, organic sources and crop residues, with the dose calculated to close the gap between a field's indigenous nutrient supply and the uptake required for a realistic, field-specific attainable yield (Dobermann & Cassman, 2002). Field-specific potassium and phosphorus balances have proven an effective basis for adjusting requirements across systems with variable residue retention (Buresh *et al.,* 2010). First formalized in irrigated rice- and maize-based systems, the approach was later operationalized into tools such as Nutrient Expert, which uses a QUEFTS-type framework to translate yield history, soil type and cropping sequence into a balanced N-P-K recommendation without extensive soil testing (Pampolino *et al.,* 2012). In safflower, the same logic is implemented mainly through Soil Test Crop Response (STCR) equations relating targeted yield to fertilizer requirement, adjusted for soil-test value (Fig. 1).

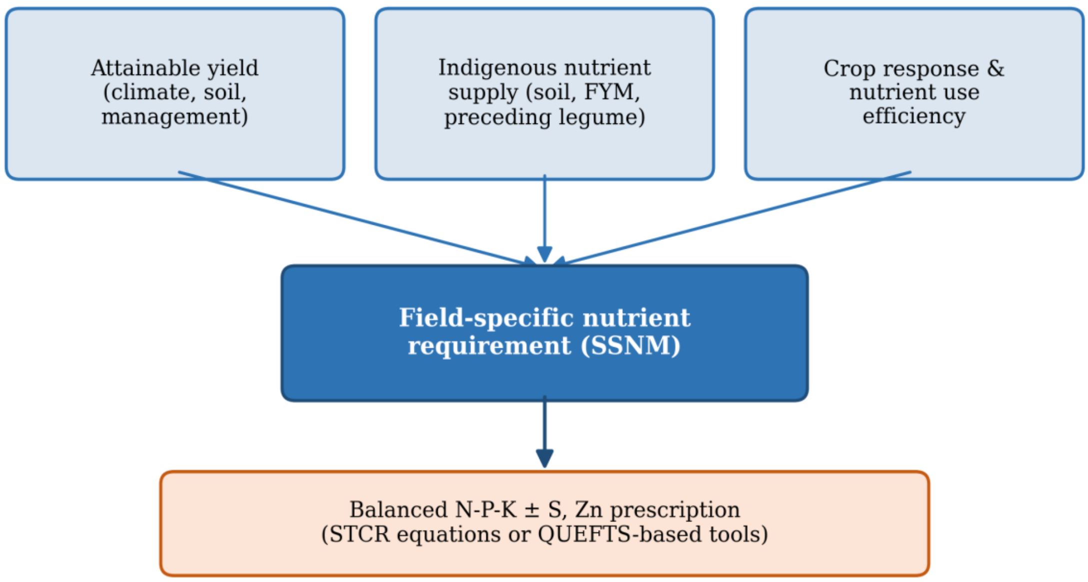

Fig. 1. Conceptual framework of Site-Specific Nutrient Management, integrating attainable yield, indigenous nutrient supply and crop response into a field-specific fertilizer prescription.

4. Approaches for Operationalizing SSNM in Safflower

4.1 The STCR approach

STCR remains the most widely used route to SSNM in safflower. Equations of the form F = a·T − b·S (F = fertilizer requirement, T = targeted yield, S = soil-test value) were developed under the AICRP on STCR and validated at VNMKV, Parbhani. For a targeted yield of ~1.5 t ha^{-1}, full (100%) STCR-based application has consistently out-yielded both an unfertilized control and reduced (50–75%) doses while improving system economics (Shinde *et al.,* 2024). At Tandur, STCR-based fertilizer supplemented with zinc and sulphur produced the highest growth, yield and gross returns, though the highest net returns and B:C ratio occurred without added FYM — underlining the need to weigh input cost against yield gain when stacking organic amendments onto an already fertility-matched dose (Sudhakar *et al.,* 2020).

4.2 QUEFTS-based and Nutrient Expert-type tools

Unlike STCR, QUEFTS-based tools estimate indigenous nutrient supply from readily available proxies — soil type, cropping history, expected unfertilized yield — making them attractive where routine soil testing is limited (Pampolino *et al.,* 2012). These tools are well validated for cereals; a safflower-specific calibration remains far less developed, a clear gap relative to major cereal crops (Fig. 2).

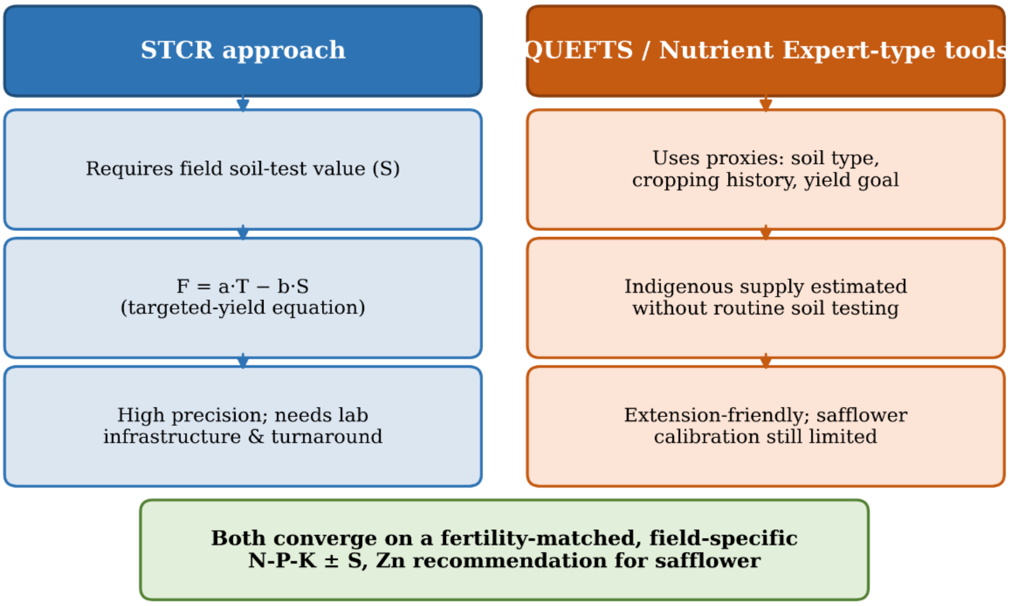

Fig. 2. Comparison of the STCR and QUEFTS/Nutrient Expert-type approaches to operationalizing SSNM, converging on a common fertility-matched fertilizer prescription.

4.3 Integration with organic sources and micronutrients

A fertility-matched inorganic dose performs still better with sulphur and zinc, to which safflower on Vertisols is frequently responsive, and with farmyard manure, which additionally improves soil physical and biological condition (Sudhakar *et al.,* 2020). Long-term Vertisol trials at VNMKV comparing continuous inorganic fertilization with combined NPK-plus-FYM in the soybean–safflower rotation show the combined treatment sustains higher yield of both crops while improving soil quality indices, supporting an integrated rather than purely inorganic SSNM framing (Meshram *et al.,* 2018; Khandare *et al.,* 2026).

5. Research Advances in SSNM for Safflower

At the AICRP research farm, VNMKV Parbhani, full (100%) STCR-based fertilization produced the highest safflower yield after both normal- and short-duration soybean, with the short-duration sequence — permitting earlier safflower sowing — recording a modestly higher yield, underlining the interaction between sowing time, residual moisture and fertilizer efficiency (Shinde *et al.,* 2024). At the system level, safflower-equivalent yield and system profitability responded significantly to STCR-based fertilization level, with soybean cultivar duration a comparatively secondary determinant (Shinde *et al.,* 2024). Long-term multi-cycle Vertisol trials further show that fertility-matched application sustained with organic amendment improves the sustainable-yield index and an integrated soil-quality index relative to unbalanced or purely inorganic fertilization, indicating that SSNM combined with organic inputs can raise productivity without compromising long-term soil quality (Meshram et al., 2018; Khandare et al., 2026), as illustrated in Fig. 3.

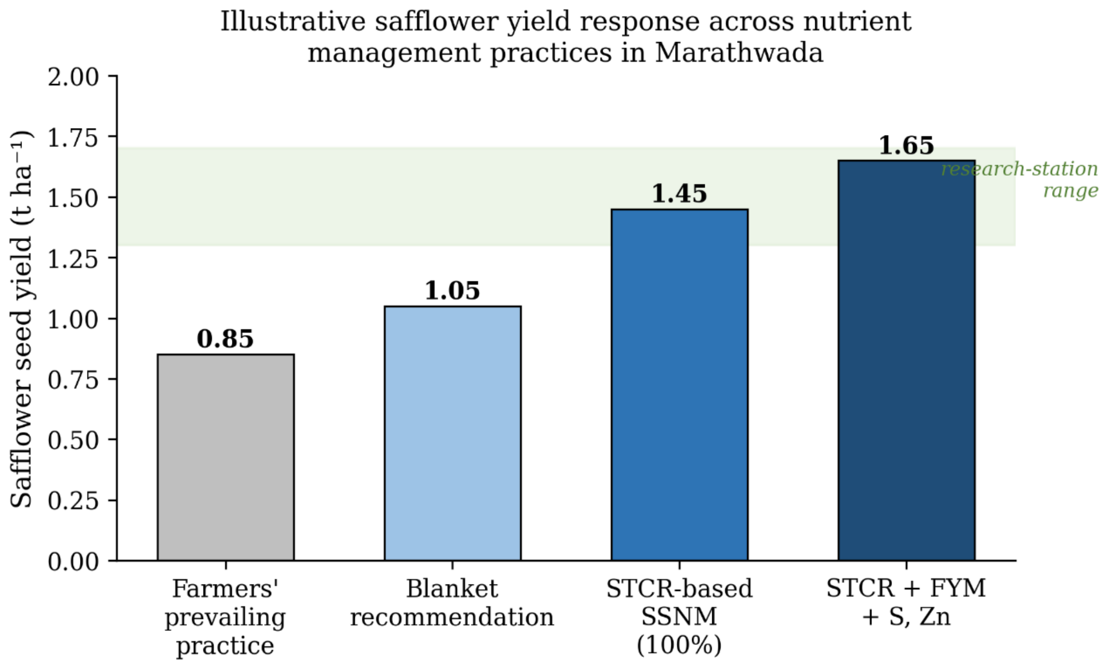

Fig. 3. Illustrative safflower seed-yield response across nutrient management practices in Marathwada, based on ranges reported in the reviewed literature (Shinde et al., 2024; Sudhakar et al., 2020).

6. Challenges in Adoption

Adoption is constrained on several fronts. Agro-ecologically, the rainfed system means attainable yield — and hence the SSNM prescription — varies sharply with residual moisture and late-season dry spells, while small, fragmented holdings make field-by-field soil testing logistically demanding, and safflower as a minor oilseed receives lower input priority than soybean or cotton. Institutionally, STCR prescriptions depend on a current field soil test and extension staff able to translate results correctly, yet laboratory capacity in Marathwada remains limited and transfer into routine soil health card advisories is uneven. Technologically, omission-plot data quantifying indigenous N, P and K supply across Marathwada's soil-rainfall domains remain thin relative to cereals (Pampolino *et al.,* 2012), constraining both a safflower-specific Nutrient Expert-type tool and the calibration of sensor- or remote-sensing-based diagnostics.

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7. Future Research Priorities

Six priorities emerge for closing Marathwada's safflower yield gap through SSNM (Fig. 4): (1) expanding omission-plot and nutrient-response trials across major soil-rainfall domains to underpin a QUEFTS-based, Nutrient Expert-type tool for rainfed safflower (Pampolino et al., 2012); (2) extending SSNM from the single crop to the full soybean–safflower system, quantifying residual N and P carry-over (Shinde *et al.,* 2024); (3) developing drought-contingent, moisture-adjusted prescriptions that scale fertilizer investment to realistically attainable seasonal yield; (4) deeper integration of organic and inorganic sources, quantifying the fertilizer-substitution value of FYM and residues under long-term Vertisol management (5) strengthening institutional delivery — soil-testing capacity, STCR-based soil health card advisories, and farmer/input-dealer decision-support formats; and (6) exploratory evaluation of low-cost sensor- and satellite-based diagnostics (leaf-colour charts, SPAD, vegetation indices) for in-season nitrogen monitoring.

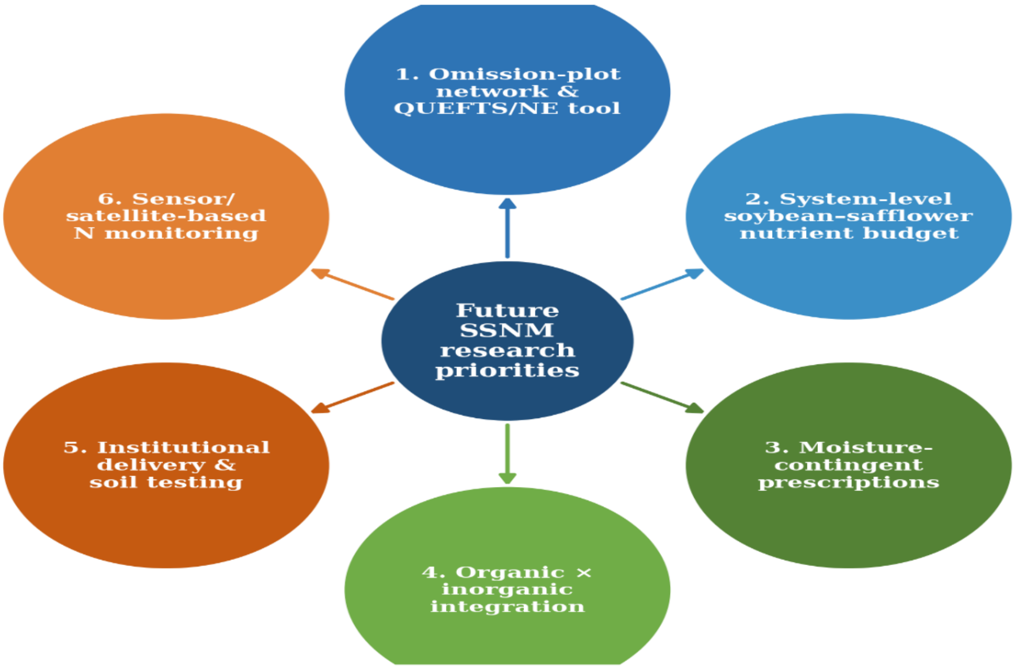

Fig. 4. Roadmap of six priority research directions for strengthening Site-Specific Nutrient Management in safflower

CONCLUSION

Site-Specific Nutrient Management offers a scientifically sound and, on the evidence available from Marathwada, an economically rewarding alternative to blanket fertilizer recommendations for safflower. STCR-based prescriptions, particularly when supplemented with sulphur, zinc and organic manure, have consistently improved seed yield, cropping-system profitability and, over the long term, indicators of soil quality on the region's dominant Vertisols. Nonetheless, safflower still lacks the breadth of omission-plot data, system-level nutrient budgets, moisture-contingent prescriptions and simplified decision-support tools that now underpin SSNM in major cereal crops, and the institutional pathway for delivering even the existing STCR prescriptions to individual farm holdings in Marathwada remains constrained by soil-testing capacity and extension reach. Addressing these gaps through the research priorities outlined here would help translate the demonstrated research-station benefits of

SSNM into a measurable, region-wide narrowing of Marathwada's persistent safflower yield gap.

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