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Development, validation and future prospects of soil test crop response based targeted yield equations for millets

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Abstract

Millets are climate-resilient and nutritionally rich crops that play a vital role in ensuring food and nutritional security in India, particularly under rainfed and marginal farming conditions. However, their productivity is often constrained by imbalanced and non-site-specific fertilizer application. The Soil Test Crop Response (STCR) approach, based on the targeted yield concept, provides a scientific framework for precise nutrient management by integrating soil test values, crop nutrient requirements and fertilizer inputs to achieve predetermined yield targets. In India, extensive research has been conducted on the development of STCR-based targeted yield equations for major millets such as sorghum, pearl millet and finger millet across diverse agro-ecological regions. These equations have been validated through field and on-farm trials, demonstrating their ability to achieve yield targets within acceptable limits while improving nutrient use efficiency and economic returns. The integration of organic sources under the Integrated Plant Nutrient System (IPNS) further enhances soil health and reduces dependency on chemical fertilizers. Despite these advancements, the application of STCR in millets remains limited, particularly for small millets and under rainfed conditions. Variability in soil types and lack of awareness among farmers also pose challenges to its widespread adoption. Future prospects include the integration of STCR with precision agriculture tools, digital soil mapping and climate-smart nutrient management strategies. Therefore, the STCR-based targeted yield approach offers a promising pathway for sustainable intensification of millet production in Indian agriculture.

Keywords: Climate resilient crops, fertilizer prescription equations, nutrient management, soil test crop response, targeted yield approach

Introduction

Millets are among the oldest cultivated cereal crops and are increasingly recognized as climate-resilient and nutritionally rich grains, particularly suited for dryland and rainfed agriculture. They are widely grown across Asia, Africa and parts of the Americas, playing a crucial role in ensuring food and nutritional security for millions of people. Globally, millets are cultivated in more than 100 countries, with India, Nigeria and Niger being the leading producers. The total global production of millets was about 30.1 million tonnes in 2021, of which India alone contributed nearly 41%, highlighting its dominant role in millet cultivation (Kheya *et al.*, 2023)^[12].

The International Year of Millets (2023) serves as a global platform to highlight the crop's ecological, nutritional and economic advantages. By fostering collaboration between scientific research and policy-making, the initiative aims to catalyze stakeholder engagement, optimize millet production systems and drive public demand for these sustainable grains. Millets are often referred to as “nutri-cereals” due to their superior nutritional profile compared to major cereals like rice and wheat. They are rich in carbohydrates (60–70%), proteins (7–12%), dietary fibre and essential micronutrients such as calcium, iron, zinc and magnesium. For instance, finger millet is exceptionally high in calcium (about 364 mg/100 g), while pearl millet is rich in iron (up to 6.4 mg/100 g) and sorghum provides significant dietary fibre and energy (Ankita, 2025)^[1]. According to the Food and Agriculture Organization, millets also contain important vitamins such as thiamin, niacin, and vitamin B6, along with minerals like phosphorus, magnesium, and zinc, making them highly beneficial for human health (FAO, 2023)^[8].

Despite their nutritional and ecological advantages, millet productivity in India remains relatively low due to imbalanced fertilization practices and the use of generalized fertilizer recommendations. In this context, the Soil Test Crop Response (STCR) approach offers a scientific framework for precise nutrient management. The STCR-based targeted yield concept aims to achieve a predetermined yield by integrating soil test values, crop nutrient requirements and fertilizer inputs. This approach enables the formulation of site-specific fertilizer recommendations, thereby improving nutrient use efficiency, crop productivity and economic returns.

In India, extensive research has been conducted on the development and validation of STCR-based targeted yield equations for various millet crops such as sorghum, pearl millet and finger millet under different agro-ecological conditions. These studies have demonstrated that STCR not only enhances yield predictability but also maintains soil fertility, particularly when combined with organic sources under Integrated Plant Nutrient System (IPNS). However, the application of this approach to minor millets and diverse soil types is still limited, necessitating further research and technological integration. Therefore, understanding the development, validation and future prospects of STCR-based targeted yield equations for millets is essential for achieving sustainable intensification and nutritional security in Indian agriculture.

Spatial distribution and agro-environmental conditions influencing millet cultivation in India

Millet cultivation in India is widely distributed across diverse agro-climatic regions, particularly in arid and semi-arid zones where other cereals fail to perform well. India is the largest producer of millets, contributing about 38–41% of global production, which highlights its importance in both national and global food systems. Geographically, millet cultivation is concentrated in states such as Rajasthan, Maharashtra, Karnataka, Gujarat, Uttar Pradesh and Madhya Pradesh. Rajasthan alone accounts for nearly 36% of the total millet cultivated area in the country, making it the leading state in terms of acreage (Banerjee *et al.*, 2025) [3]. Different millet species showed region-specific distribution (for example, pearl millet) dominates in the dry northwestern plains, sorghum is mainly grown in the Deccan Plateau, and finger millet is concentrated in southern and hilly regions like Karnataka and Uttarakhand (Warisa *et al.*, 2025 a) [28].

The agro-environmental adaptability of millets is one of their key strengths. These crops are well suited to low rainfall conditions (300–600 mm annually), poor soil fertility and high temperature stress, making them ideal for marginal and rainfed areas (Warisa *et al.*, 2025 b) [28]. Millets can grow in a wide range of soils, including sandy, loamy and shallow soils. It requires minimal external inputs compared to crops like rice and wheat. Their deep root systems and efficient water-use mechanisms allow them to withstand drought conditions, ensuring stable yields even under climate variability. As a result, millets are increasingly recognized as climate-resilient crops that can support sustainable agriculture and livelihood security in vulnerable regions of India.

The targeted yield approach, developed under the Soil Test Crop Response (STCR) framework, is a scientific method of fertilizer recommendation aimed at achieving a pre-determined crop yield by considering both soil fertility and crop nutrient demand. This concept was first proposed by Ramamoorthy and co-workers in 1967 [17] and has since been widely used in India for developing precise, site-specific nutrient management strategies.

Principles of Targeted Yield Approach (STCR)

The core principle of this approach is that fertilizer application should be directly linked to a specific yield target, rather than applying a blanket recommendation (Ramamoorthy *et al.*, 1967) [17]. It assumes that for producing a unit quantity of yield, a crop requires a definite amount of nutrients, known as the nutrient requirement (NR). The total nutrient uptake by the crop is met through two main sources: the indigenous supply from the soil and the applied fertilizers. Therefore, the fertilizer dose is calculated by accounting for the contribution from soil (CS%) and the contribution from fertilizers (CF%), ensuring that only the deficit nutrients are supplied externally (ICAR, 2014) [11].

Another important principle is soil test-based nutrient management, where initial soil analysis is essential to determine available nutrient status. Based on this, fertilizer prescription equations are developed to estimate the exact quantity of nutrients required to achieve the targeted yield. These equations help in maintaining balanced fertilization, improving nutrient use efficiency, and avoiding both under- and over-application of fertilizers (FAO, 2023) [9].

The targeted yield approach is also site-specific and adaptable, as it considers variations in soil type, climate, and cropping systems. Furthermore, it can be integrated with organic nutrient sources under the Integrated Plant Nutrient System (IPNS), which enhances soil health and sustainability (Santhi *et al.*, 2002 a) [20]. However, this approach ensures higher productivity, economic efficiency and long-term soil fertility, making it highly relevant for sustainable agriculture, especially in nutrient-exhaustive cropping systems like millets.

Soil test-based fertilizer recommendations using the targeted yield approach under both chemical fertilizers alone and integrated plant nutrient systems (IPNS)

Initially, fertilizer use for achieving higher yields was based on empirical estimates of nutrient availability from soil and added fertilizers, commonly referred to as the “prescription method” proposed by Truog (1960). Later, during 1965–67, Ramamoorthy *et al.* (1967) [17] provided a strong theoretical foundation along with field-based evidence showed that Liebig’s law of minimum applies equally to nitrogen (N), phosphorus (P) and potassium (K) in high-yielding crops such as wheat, rice and pearl millet. This finding contradicted the earlier belief that the law was mainly applicable to nitrogen, while phosphorus and potassium were thought to follow the percentage sufficiency concept given by Mitscherlich and Baule and later modified by Mitscherlich and Bray. Among the different approaches used for fertilizer recommendation, the targeted yield method is considered unique because it not only suggests fertilizer doses based on soil test values but also indicates the level of yield that farmers can expect, provided that proper crop management practices are followed (Velayutham, 1979) [27].

This approach considers three key parameters such as the nutrient requirement (NR) of a crop to produce a unit quantity of economic yield, the percentage contribution of nutrients from the soil (Cs) based on soil test values, and the percentage contribution from applied fertilizers (Cf). These parameters are used to establish a relationship between the target yield (T), soil nutrient status (S), and fertilizer requirement (F), which is expressed through a standard fertilizer prescription equation.

$$F = \{ (NR \times 100 T) / Cf \} - \{ (Cs \times STV) / Cf \}$$

Under Integrated Plant Nutrient System (IPNS) conditions, an additional factor is the contribution of nutrients from organic

sources (Co) also included. In such cases, the fertilizer requirement is adjusted by accounting for nutrients supplied through organic manures along with soil and fertilizer sources.

$$FN = \{(NR \times 100 T) / Cf\} - \{(Cs \times SN) / Cf\} - \{(Co \times ON) / Cf\}$$

This methodology, combined with an inductive experimental approach, is known as the “Inductive-cum-Targeted Yield Approach.” It forms the scientific basis of the All India Coordinated Research Project for Soil Test Crop Response, sponsored by the Indian Council of Agricultural Research.

Fertilizer recommendations for sustaining soil fertility using the targeted yield approach

To sustain soil fertility over time, it is important to select suitable yield targets along with proper fertilizer management practices. This ensures that both goals achieving high crop yields and maintaining soil health are met across successive cropping seasons. Ramamoorthy and Mahajan (1974)^[16] showed that the desired yield target and the corresponding fertilizer requirement can be calculated using specific equations that relate soil nutrient supply, fertilizer contribution and crop nutrient demand. In these equations, t represents the target yield ($q\ ha^{-1}$), n is the ratio of nutrient contribution from soil to fertilizer, r denotes the nutrient requirement per unit yield ($kg\ per\ 100\ kg\ produce$), m is the ratio between nutrient requirement and fertilizer contribution, s refers to the soil test value ($kg\ ha^{-1}$), and Fd indicates the fertilizer dose ($kg\ ha^{-1}$). These relationships help determine the appropriate fertilizer application needed to achieve the set yield target while maintaining soil fertility. At present, long-term experiments and demonstrations are being conducted at various STCR centers to identify optimal fertilizer doses that can ensure maximum yield without degrading soil health.

Site-Specific Nutrient Management

Site-Specific Nutrient Management (SSNM) is an advanced approach to fertilizer management in which nutrients are applied according to the specific requirements of a crop in a particular field, rather than following blanket recommendations. The concept is based on the idea that soil fertility and crop nutrient demand vary across locations, and therefore, nutrient application should be tailored to match this variability for achieving optimum yield and efficiency. SSNM focuses on supplying nutrients such as nitrogen (N), phosphorus (P) and potassium (K) in the right amount, at the right time and in the right proportion. It considers three major components: (i) the indigenous nutrient supply from the soil, (ii) the crop's nutrient requirement for a targeted yield and (iii) the efficiency of applied fertilizers. (Chaudhari *et al.*, 2020)^[4]. By integrating these factors, SSNM ensures that crops receive adequate nutrition without excessive or insufficient fertilizer use. This makes it closely related to the targeted yield approach used in Soil Test Crop Response (STCR) studies. A key feature of SSNM is the use of nutrient omission plots, where one nutrient is deliberately omitted to assess its limiting effect on crop growth. This helps in identifying which nutrients are deficient and require supplementation. In addition, SSNM promotes balanced fertilization, preventing nutrient imbalances that can reduce crop productivity and degrade soil health over time. Modern SSNM practices incorporate tools and technologies such as soil testing, plant tissue analysis, leaf color charts (for nitrogen management) and decision-support systems like nutrient expert, developed by the International Rice Research

Institute (Richards *et al.*, 2015)^[19]. Advanced approaches also use GPS, GIS and remote sensing to monitor spatial variability in soil properties and crop performance, enabling precise nutrient application at a micro-level. The benefits of SSNM are well documented. It improves crop yield, nutrient use efficiency and economic returns, while reducing fertilizer losses and environmental pollution. Studies have shown that SSNM can increase yields by 10–20% while reducing fertilizer use compared to conventional practices (Dobermann *et al.*, 2002)^[5]. It also contributes to long-term soil fertility and sustainability, which is particularly important in intensive cropping systems. However, the adoption of SSNM is sometimes constrained by factors such as limited access to soil testing facilities, lack of technical knowledge among farmers, and the need for decision-support tools. Despite these challenges, SSNM is increasingly recognized as a key strategy for sustainable agriculture, especially in countries like India where soil variability is high.

Soil test-based fertilizer recommendations for achieving targeted yields in millets

The Soil Test Crop Response (STCR), combined with the Integrated Plant Nutrition System (IPNS), represents the standard approach for precision nutrient management in Indian agriculture. For millets, which are often grown in nutrient-poor, rainfed soils, this "prescription-based" fertilization ensures that yield targets are met while maintaining soil health.



Fig 1: Soil test-based optimization pathway for achieving targeted yield through STCR approach

The general form of the fertilizer prescription equation (FPE) for any nutrient (N, P, or K) is:

$$FN = (NR \times T) - (CS \times SN) - (CO \times ON)$$

Where;

FN: Fertilizer nutrient to be applied (kg/ha)

NR: The amount of nutrient needed to produce 1 quintal (100

kg) of grain

T: Targeted yield (q/ha)

CS: Percent contribution from the soil available nutrient

SN: Soil test value for the available nutrient (kg/ha)

CO: Percent contribution from the organic source (e.g., FYM)

ON: Nutrient content in the organic source (kg/ha)

Table 1: Soil Test Based Integrated Fertilizer Prescription Parameters for Millets

Crop	Soil type	Nutrient requirement (kg/q)	Soil contribution (Cs%)	Fertilizer contribution (Cf%)	Organic matter contribution (Co/Cfym%)	Fertilizer savings under IPNS	Source
Sorghum (Jowar)	Red sandy loam (Irugur series)	N:4.86 P ₂ O ₅ :1.63 K ₂ O:4.56	N:0.98 P ₂ O ₅ :0.87 K ₂ O:0.59	N:34.56 P ₂ O ₅ :26.41 K ₂ O:65.19	N:0.98 P ₂ O ₅ :0.90 K ₂ O:0.76	Significant reduction in NPK doses. e.g., N reduced from 84 to 30 kg/ha with 10 t/ha FYM at 4 t/ha target	http://www.tnau.ac.in report
Finger millet (Ragi)	Alfisol (Kndicpaleustalfs)	N:2.76 P ₂ O ₅ :0.49 K ₂ O:2.55	N:14.48 P ₂ O ₅ :10.42 K ₂ O:19.13	N:30.29 P ₂ O ₅ :30.48 K ₂ O:109.33	N:19.24 P ₂ O ₅ :9.92 K ₂ O:40.48	Savings of 9.61% N, 7.06% P ₂ O ₅ and 56.42% K ₂ O with 7.5 t/ha FYM	Basavaraja <i>et al.</i> , 2017 [2]
	Alfisol (Typic Rhodustalf)	N:4.80 P ₂ O ₅ :2.30 K ₂ O:4.40	N:14.86 P ₂ O ₅ :19.18 K ₂ O:18.95	N:44.16 P ₂ O ₅ :32.79 K ₂ O:59.75	N:28.47 P ₂ O ₅ :11.77 K ₂ O:33.78	Significant reduction in NPK doses. e.g., N reduced from 70 to 37 kg/ha with 12.5 t/ha FYM at 3 t/ha target.	Mhoamed <i>et al.</i> , 2023
Pearl Millet	Inceptisol (Typic Ustropept)	N:2.81 P ₂ O ₅ :1.33 K ₂ O:2.53	N:26.36 P ₂ O ₅ :38.51 K ₂ O:10.33	N:45.44 P ₂ O ₅ :44.14 K ₂ O:87.45	N:27.55 P ₂ O ₅ :16.04 K ₂ O:40.15	Savings of 38 kg N, 22 kg P ₂ O ₅ and 25 kg K ₂ O per hectare with 12.5 t/ha FYM.	Ravikiran <i>et al.</i> , 2018c [18]

Table 2: Nutrient requirement, contribution from soil and fertilizer for achieving targeted yield

Parameter	Nitrogen	Phosphorus	Potassium
NR (kg/q)	4.0	1.8	2.2
CS (%)	30	35	25
CF (%)	50	30	60

These equations are developed through field experiments under the inductive-cum-targeted yield model and provide fertilizer recommendations that help achieve yield targets within $\pm 10\%$ accuracy. When integrated with organic sources under the Integrated Plant Nutrient System (IPNS), fertilizer doses can be further optimized, reducing chemical input and improving soil health (Muralidharudu *et al.*, 2011a) [14].

Validation and productivity impact of STCR-based targeted yield approach

Validation is an essential step in the Soil Test Crop Response (STCR) approach to ensure that the developed fertilizer prescription equations are accurate, reliable, and field-

applicable. It is usually carried out through on-farm trials across different locations and seasons, where the actual yield obtained is compared with the pre-set target yield.

A well-validated STCR equation is expected to achieve yields within $\pm 10\%$ of the target yield, which is considered acceptable under field conditions (Santhi *et al.*, 2002b) [21]. Validation studies conducted under the Indian Council of Agricultural Research – AICRP-STCR program have consistently shown good agreement between targeted and actual yields.

The adoption of STCR-based fertilizer recommendations has shown significant improvements in:

- Crop yield (20–40% increase)
- Nutrient use efficiency
- Economic returns (higher B:C ratio)
- Soil fertility sustainability

It is mainly due to balanced nutrient application and precise matching of nutrient supply with crop demand.

Table 3: Validation Results of STCR in Millets

Crop	Target Yield (q ha ⁻¹)	Actual Yield (q ha ⁻¹)	Deviation (%)	Fertilizer Saving (%)
Sorghum	50	47–52	$\pm 6\%$	15–20%
Finger Millet	40	38–42	$\pm 5\%$	10–18%
Pearl Millet	45	42–48	$\pm 7\%$	12–22%

Source: Santhi *et al.* (2002c) [22] and Muralidharudu *et al.* (2011b) [14]

Table 4: Productivity and Economic Impact of millets

Treatment Type	Yield (q ha ⁻¹)	Increase over Control (%)	B:C Ratio
Control (No fertilizer)	20	—	1.2
Farmer Practice	28	40%	1.6
STCR-Based	36	80%	2.2
STCR-IPNS	38	90%	2.4

Source: Dey and Das (2014) [6]

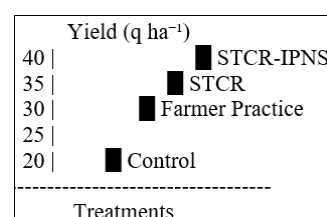
**Fig 2:** Yield Comparison between conventional, STCR alone and STCR-IPNS technologies

Table 5: Validation results of millets in different states

Crop	State	Parameter	Value	Source
Finger millet	Tamil Nadu	Target Yield (q ha ⁻¹)	40	Shanthi <i>et al.</i> (2010)
		Actual Yield (q ha ⁻¹)	38–42	
		Deviation (%)	±5%	
		Fertilizer Saving (%)	12–18%	
		B:C Ratio	2.1–2.3	
Sorghum	Karnataka	Target Yield (q ha ⁻¹)	50	Dey and Shanthi (2014) ^[7]
		Actual Yield (q ha ⁻¹)	46–52	
		Deviation (%)	±6%	
		Fertilizer Saving (%)	15–20%	
	Maharashtra	B:C Ratio	2.0–2.4	
		Target Yield (q ha ⁻¹)	50	
		Actual Yield (q ha ⁻¹)	46–51	
		Deviation (%)	±5%	
Pearl millet	Andhra Pradesh	Fertilizer Saving (%)	15–22%	Muralidharudu <i>et al.</i> (2011b) ^[14]
		B:C Ratio	2.2–2.6	
		Fertilizer Saving (%)	45	
			42–47	
		B:C Ratio	±6%	

In Karnataka, STCR validation studies have been conducted under rainfed conditions, especially for sorghum in Alfisols and Vertisols. STCR experiments in Andhra Pradesh have focused on pearl millet under rainfed and semi-arid conditions. Results indicate strong validation of targeted yield equations and improved nutrient efficiency.

Table 6: Comparative summary across states

State	Yield Increase (%)	Fertilizer Saving (%)	Accuracy (Deviation)
Tamil Nadu	80–94%	12–18%	±5%
Karnataka	50–112%	15–20%	±6%
Andhra Pradesh	44–105%	12–20%	±6%
Maharashtra	40–100%	15–22%	±5%

Conclusion

The Soil Test Crop Response (STCR) based targeted yield approach has emerged as a scientifically robust and practically viable strategy for optimizing nutrient management in millet cultivation across India. By integrating soil test values, crop nutrient requirements and fertilizer contributions, this approach ensures precise and balanced fertilization tailored to specific yield targets. The development of STCR equations for major millets such as sorghum, pearl millet and finger millet across diverse agro-ecological regions has provided a strong foundation for site-specific nutrient management. Validation studies conducted under field and on-farm conditions have consistently demonstrated that STCR-based recommendations can achieve targeted yields within ±5–10% deviation, while significantly improving nutrient use efficiency, crop productivity and economic returns. The incorporation of organic sources under the Integrated Plant Nutrient System (IPNS) further enhances soil health, reduces dependency on chemical fertilizers and supports long-term sustainability. Despite these advantages, the widespread adoption of STCR in millet systems is constrained by factors such as limited soil testing facilities, lack of awareness among farmers and the location-specific nature of fertilizer prescription equations. Moreover, research on small millets and micronutrient-based STCR formulations remains inadequate. From a future perspective, the integration of STCR with precision agriculture tools, digital soil mapping and

decision-support systems offers promising opportunities to enhance its applicability and scalability. Therefore, the STCR-based targeted yield approach holds significant potential for achieving sustainable intensification of millet production, ensuring food and nutritional security while maintaining soil fertility in Indian agriculture.

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