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Site-Specific Nutrient Management Improves Productivity and Profitability of a Maize–Mustard Cropping System under Semi-Arid Conditions of Bundelkhand Region

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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

A field experiment was conducted during the *kharif 2022* and *rabi* 2022–2023 seasons at the Research Farm of Rani Lakshmi Bai Central Agricultural University, Jhansi, Uttar Pradesh, India, to evaluate the effects of different nutrient-management strategies on crop productivity, system productivity, production efficiency, land-use efficiency, and economics of a maize (*Zea mays* L.)–mustard (*Brassica juncea* L.) cropping system under semi-arid conditions. The experiment was laid out in a randomized block design with seven nutrient-management treatments comprising 100% of the recommended dose of fertilizers (RDF), organic farming, natural farming, integrated nutrient management (INM), site-specific nutrient management (SSNM), farmers' practice, and 75% RDF integrated with green manuring, with three replications. Site-specific nutrient management (SSNM), comprising 100% of the recommended nutrients supplemented with Zn @ 5 kg ha^{-1}, B @ 1 kg ha^{-1}, S @ 60 kg ha^{-1}, and Fe @ 1 kg ha^{-1}, recorded the highest growth and yield attributes in both crops. In maize, SSNM produced the maximum plant height (205.46 cm), grain yield (4660 kg ha^{-1}), straw yield (9735 kg ha^{-1}), and biological yield (14396 kg ha^{-1}). Similarly, in mustard, it recorded the highest plant height (248.77 cm), siliquae $plant^{-1}$ (353.33), seed yield (2026 kg ha^{-1}), stover yield (4968 kg ha^{-1}), and biological yield (6994 kg ha^{-1}). The same treatment also resulted in the highest mustard equivalent yield (3702 kg ha^{-1}), production efficiency (14.76 kg ha^{-1} day^{-1}), and land-use efficiency (68.68%). Economic analysis revealed that SSNM generated the maximum gross and net returns from both maize (₹128,441 and ₹77,051 ha^{-1}, respectively) and mustard (₹127,829 and ₹83,417 ha^{-1}, respectively), whereas the highest benefit:cost ratio in mustard (1.96) was recorded under 75% RDF integrated with green manuring. The findings demonstrate that site-specific nutrient management integrating balanced macro- and micronutrient application substantially enhanced crop productivity, system efficiency, and profitability of the maize–mustard cropping system and can be recommended as a sustainable nutrient management strategy for the semi-arid Bundelkhand region.

Keywords: Site-specific nutrient management; maize–mustard cropping system; integrated nutrient management; balanced fertilization; micronutrients; mustard-equivalent yield; production efficiency; land-use efficiency; crop productivity; farm profitability.

1. Introduction

The maize–mustard cropping system represents a strategically important cereal–oilseed production system in India, particularly in regions where crop diversification and efficient resource utilization are essential for sustaining agricultural productivity. Maize (*Zea mays* L.) is a highly productive C_4 cereal crop characterized by efficient photosynthetic carbon assimilation, rapid biomass accumulation, and adaptability to diverse agro-climatic conditions. Indian mustard (*Brassica juncea* L. Czern & Coss.) is a major oilseed crop contributing substantially to edible oil production and nutritional security. The sequential cultivation of maize followed by mustard enhances land-use efficiency and offers considerable potential for improving farm income and cropping-system productivity. However, both maize and mustard are nutrient-exhaustive crops that remove substantial quantities of nitrogen (N), phosphorus (P), potassium (K), sulphur (S), and micronutrients from the soil (Sarkar et al., 2018). Continuous cultivation without adequate nutrient replenishment can therefore lead to progressive depletion of soil fertility, reduced nutrient availability, and a decline in crop productivity.

Historically, chemical fertilizers have played a central role in increasing crop yields by supplying readily available nutrients to crops. The application of NPK fertilizers, along with sulphur and micronutrients, has contributed significantly to enhanced agricultural production. Nevertheless, long-term and imbalanced use of chemical fertilizers has raised concerns regarding nutrient-use inefficiency, soil degradation, a decline in soil organic carbon, and environmental contamination through nutrient losses by leaching, volatilization, and runoff. These challenges are particularly critical in intensive cropping systems, where the demand for nutrients is high and the natural regenerative capacity of the soil may be insufficient to maintain long-term productivity. Balanced nutrient management, supported by the efficient use of crop inputs, is therefore important for sustaining field-crop productivity while reducing avoidable environmental burdens (Bashir et al., 2022).

In response to these limitations, organic farming has emerged as an alternative nutrient-management strategy that emphasises the use of organic manures, composts, crop residues, and biological inputs. Organic amendments contribute to improved soil physical, chemical, and biological properties by enhancing soil organic matter, nutrient buffering capacity, microbial activity, and water-holding capacity (Das & Varma, 2010; M. Kumar et al., 2021). However, sole dependence on organic nutrient sources may not always satisfy the nutrient demand of high-yielding cropping systems such as maize–mustard, particularly where the availability of bulky organic manures is limited.

Natural farming, popularly known as Zero Budget Natural Farming (ZBNF), has gained increasing attention as a low-input sustainable agricultural approach. This system utilises locally available biological resources, including microbial formulations such as Beejamrutha and Jeevamrutha, to stimulate soil microbial activity, nutrient mineralisation, and nutrient cycling. Natural farming also promotes the use of indigenous botanical formulations for pest and disease management, thereby reducing dependence on synthetic agrochemicals. By strengthening soil biological processes and reducing external input requirements, natural farming has the potential to enhance the ecological sustainability of cropping systems.

Among the various nutrient-management approaches, integrated nutrient management (INM) has emerged as an effective strategy for synchronising nutrient supply with crop demand while simultaneously improving soil health. INM combines inorganic fertilisers with organic amendments and micronutrients to ensure balanced nutrient availability and sustained crop productivity. Vermicompost, a valuable organic amendment used in INM, supplies essential macro- and micronutrients in a slow-release form and improves soil structure, aeration, water-holding capacity, and microbial activity (Garg et al., 2006; Suthar, 2007). The integration of organic and inorganic nutrient sources has been reported to enhance nutrient-use efficiency, maintain soil fertility, and improve crop yields compared with sole application of chemical fertilisers.

Site-specific nutrient management (SSNM) represents a precision nutrient-management approach that aligns fertiliser application with crop nutrient requirements and indigenous soil nutrient supply. By applying nutrients in the right amount, at the right time, and in the right proportion, SSNM improves fertiliser-use efficiency, reduces nutrient losses, and enhances crop productivity and profitability (Bana et al., 2020; Cao et al., 2017; Pampolino et al., 2012; Pooniya et al., 2015; Timsina et al., 2021). In nutrient-exhaustive cropping systems such as maize–mustard, SSNM can contribute significantly to optimising nutrient use and sustaining soil fertility (Shahi et al., 2022). Field-scale evidence in maize indicates that soil-test- and targeted-yield-based SSNM can improve grain yield and gross returns relative to farmers' fertiliser practice (Pandit et al., 2022). Recent studies further indicate that precision nutrient tools can align fertiliser application more closely with crop demand in maize, while sensor-guided nitrogen management can improve mustard productivity and profitability (Sairam et al., 2025; Meena et al., 2024).

Green manuring is another important strategy for enhancing soil fertility and reducing dependence on chemical fertilisers. It is a traditional cultivation practice that has played a significant role in improving soil fertility and crop yield in agricultural systems (Gao et al., 2020). Green manure crops contribute organic matter to the soil, improve soil structure, stimulate microbial activity, and enhance nutrient cycling, particularly nitrogen availability. Several field studies have demonstrated that green manuring can reduce chemical nitrogen fertiliser input and reactive nitrogen losses while maintaining crop yield (Fontaine et al., 2020; Gao et al., 2020; Mohanty et al., 2020; Xie et al., 2016). Therefore, integrating green manuring with reduced fertiliser doses may provide an environmentally sustainable and resource-efficient option for maintaining productivity in maize–mustard cropping systems. Long-term research in a maize–mustard rotation has shown that precise nutrient management combined with conservation-oriented crop establishment can improve equivalent yield, soil microbial dynamics, and water–energy performance (Lakhena et al., 2025). Nevertheless, the comparative performance of recommended fertilisation, organic farming, natural farming, INM, SSNM, farmers' practice, and reduced fertiliser integrated with green manuring within a single maize–mustard sequence has not been clearly established under the semi-arid conditions of Bundelkhand.

Considering the high nutrient demand of maize and mustard and the need for sustainable nutrient-management strategies, a comparative evaluation of different nutrient-management approaches is essential. The present study was undertaken to assess the performance of different nutrient-management systems in the maize–mustard cropping system. The study aimed to identify a nutrient-management strategy capable of improving crop productivity, nutrient availability, soil fertility, nutrient-use efficiency, and overall sustainability of the cropping system.

2. Materials and Methods

2.1 Weather Parameters

The experimental site is located in the semi-arid subtropical region of Bundelkhand, characterised by hot summers and cool, dry winters. During the kharif season (July–October 2022), maize was cultivated under southwest monsoon conditions, during which the region received the majority of its annual rainfall, ensuring favourable moisture availability for crop establishment and vegetative growth. In contrast, the succeeding mustard crop was grown during the rabi season (October 2022–March 2023) under predominantly dry weather conditions with comparatively low temperatures, which favoured flowering, siliqua formation, and seed development.

Throughout the experimental period, the maximum air temperature ranged from approximately 28 to 43°C, whereas the minimum temperature varied between 6 and 25°C. The coolest period occurred during December and January, while temperatures gradually increased from February onwards. Rainfall during the rabi season was negligible except for occasional winter showers, whereas nearly 85–90% of the annual rainfall occurred during the southwest monsoon. The long-term average annual rainfall of Jhansi ranges between 714 and 846 mm. Meteorological observations recorded at the Agro-meteorological Observatory, ICAR-Indian Grassland and Fodder Research Institute, Jhansi (India), were used to characterize the prevailing weather conditions during the study.

2.2 Experimental Site and Soil Characteristics

A field experiment was conducted during the kharif (2022) and rabi (2022–23) seasons at the Research Farm of Rani Lakshmi Bai Central Agricultural University (RLBCAU), Jhansi, Uttar Pradesh, India, under a maize (*Zea mays* L.)–mustard (*Brassica juncea* L.) cropping system. The experimental farm is situated in the Bundelkhand Agro-climatic Zone (Central Plateau and Hills Region) at 25°30′30″–25°31′00″ N latitude and 78°33′30″–78°34′00″ E longitude, with an elevation of 284 m above mean sea level.

Prior to the initiation of the experiment, composite soil samples were collected from the 0–15 cm soil layer and analysed following standard laboratory procedures. The soil was clay loam in texture with a pH of 7.16–7.74, electrical conductivity of 0.24–0.27 dS m^{-1}, and organic carbon content of 0.21%. The initial soil fertility status indicated low available nitrogen (122–132 kg ha^{-1}), low to medium available phosphorus (10.5–10.8 kg ha^{-1}), medium available potassium (265.4–271.3 kg ha^{-1}), and low available sulphur (8.0–8.4 mg kg^{-1}).

2.3 Experimental Design and Treatment Details

The experiment was laid out in a Randomized Block Design (RBD) comprising seven nutrient-management treatments with three replications. The gross plot size was 12.0 × 3.5 m, while the net plot size measured 10.8 × 3.0 m. The same nutrient-management treatments were maintained throughout the maize–mustard cropping sequence to assess their cumulative effects on crop productivity, system productivity, resource-use efficiency, and economic returns.

The treatments were as follows:

Treatment	Description
T_1	100% Recommended dose of fertilizers (RDF)
T_2	Organic farming
T_3	Natural farming
T_4	Integrated nutrient management (75% RDF + 25% nutrients through organic source) + recommended Zn, Fe and B
T_5	Site-specific nutrient management (100% RDF + Zn @ 5 kg ha^{-1} + B @ 1 kg ha^{-1} + S @ 60 kg ha^{-1} + Fe @ 10 kg ha^{-1})
T_6	Farmers' practice
T_7	75% RDF + Green manuring

The recommended fertiliser dose (RDF) for maize was 120:60:40 kg $N:P_2O_5:K_2O$ ha^{-1}, whereas mustard received 120:60:60:40 kg $N:P_2O_5:K_2O:S$ ha^{-1}.

2.4 Crop Establishment and Nutrient Application

The maize hybrid DMH-122 was sown on 14 July 2022, followed by Indian mustard cultivar Giriraj, which was sown on 19 October 2022 after the harvest of maize. Recommended agronomic practices, including optimum seed rate, spacing, irrigation scheduling, weed management, and plant protection measures, were adopted uniformly across all treatments.

Nitrogen, phosphorus, potassium, and sulphur were supplied through urea (46% N), diammonium phosphate (DAP; 18:46:0), muriate of potash (MOP; 60% K_2O), and gypsum (18% S), respectively. Zinc, boron, and iron were applied through zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$; 21% Zn), borax ($Na_2B_4O_7 \cdot 10H_2O$; 10.5% B), and ferrous sulphate heptahydrate ($FeSO_4 \cdot 7H_2O$; 19% Fe), respectively.

Under the RDF treatment, the full dose of phosphorus, potassium, sulphur, and half of the nitrogen was applied as a basal application at sowing, while the remaining nitrogen was top-dressed in two equal splits at appropriate crop growth stages. Nutrient applications under organic farming, natural farming, integrated nutrient management, site-specific nutrient management, and green-manuring treatments were carried out according to their respective treatment schedules. Organic inputs and green manure were incorporated into the soil before sowing to facilitate decomposition and synchronised nutrient release.

2.5 Crop Observations and Yield Estimation

Five representative plants were randomly selected and tagged from the net plot area of each treatment for recording growth and yield observations.

For maize, observations included plant height, number of leaves per plant, chlorophyll content (SPAD value), cob characteristics, grain yield, stover yield, biological yield, and harvest index. For mustard, observations comprised plant height, number of primary and secondary branches, chlorophyll content, number of siliquae per plant, number of seeds per siliqua, test weight, seed yield, stover yield, biological yield, and harvest index.

Both crops were harvested manually at physiological maturity from the net plot area. The harvested produce was sun-dried, threshed separately for each treatment, and cleaned prior to recording yield. Grain yield of maize and seed yield of mustard were adjusted to a standard moisture content and expressed on a hectare basis (kg ha^{-1}). Biological yield was calculated as the sum of economic yield and stover yield, whereas harvest index was computed as the ratio of economic yield to biological yield and expressed as a percentage.

2.6 Mustard Equivalent Yield (MEY) and Efficiency Indices

Mustard Equivalent Yield (MEY): Mustard equivalent yield (MEY) was calculated by converting the yield of each crop into the equivalent yield of mustard based on their economic value. The MEY was calculated using the following equation:

$$\text{MEY} = \text{Mustard yield} + \left(\frac{\text{Maize yield} \times \text{Price of maize}}{\text{Price of mustard}}\right)$$

The total productivity of the maize–mustard cropping system was calculated on the basis of the support price of the main produce during the study period and the prevailing market prices for the inputs.

Production efficiency (PE): Production efficiency was calculated as the ratio of mustard equivalent yield to the total duration of the cropping system and expressed as kg ha^{-1} day^{-1}:

$$PE = \frac{MEY\ (kg\ ha^{-1})}{Total\ duration\ of\ the\ cropping\ system\ (days)}$$

Land use efficiency (LUE): Land use efficiency was calculated to determine the extent of land occupation by the cropping system during the experimental year and expressed as a percentage (%):

$$LUE = \frac{Total\ duration\ of\ crop\ occupation\ (days)}{365} \times 100$$

Economic Analysis: The economics of the maize–mustard cropping system were assessed by calculating gross return (GR), net return (NR), and benefit:cost (B:C) ratio using the prevailing market prices of produce and inputs during the study period. The following standard formulae were used:

$$GR = Yield\ of\ produce \times Market\ price$$

$$NR = GMR - Cost\ of\ cultivation$$

$$B{:}C\ ratio = \frac{NMR}{Cost\ of\ cultivation}$$

The cost of cultivation included expenditure on seeds, fertilisers, organic inputs, micronutrients, labour, irrigation, plant protection measures, and other field operations.

2.7 Statistical Analysis

The experimental data obtained from maize, mustard, and system productivity parameters were subjected to analysis of variance (ANOVA) using R statistical software (version 4.3.1). The significance of treatment effects was tested using Fisher's least significant difference (LSD) test at $P \leq 0.05$. Treatment means were compared, and results were interpreted based on statistical significance. Graphical visualisations were generated using the ggplot2, GGally, agricolae, and dplyr packages.

3. Results and Discussion

3.1 Growth Attributes of Maize and Mustard

Nutrient management strategies significantly influenced the growth attributes of both maize and mustard (Table 1). The SSNM-based treatment (T_5) recorded the highest values for all measured growth parameters, indicating the superior effectiveness of balanced and site-specific nutrient application.

In maize, T_5 produced the tallest plants at harvest (205.46 cm), the maximum number of leaves at anthesis (15.60 plant^{-1}), and the highest chlorophyll content (22.94 SPAD). These values were significantly higher than those recorded under organic (T_2) and natural farming (T_3) treatments, which showed comparatively lower growth performance. Similarly, in mustard, T_5 resulted in the highest plant height (248.77 cm), the maximum number of primary branches (10.43 plant^{-1}), the maximum number of secondary branches (13.77 plant^{-1}), and the highest chlorophyll content (22.05 SPAD).

The superior growth under T_5 may be attributed to the synchronised supply of macro- and micronutrients, including N, P, K, S, Zn, Fe, and B, which ensured nutrient availability throughout critical growth stages. Adequate nitrogen supply promotes chlorophyll synthesis, photosynthetic activity, cell division, and cell elongation, thereby enhancing plant height and biomass accumulation (Mohanty et al., 2015). The inclusion of micronutrients likely improved enzymatic activity and nutrient metabolism, resulting in enhanced chlorophyll content and vegetative growth. Similar improvements in crop growth under site-specific nutrient management have been reported by Bana et al. (2020) in rice, Mohanty et al. (2015) in wheat, and Swamy et al. (2016) in maize.

3.2 Yield Attributes of Maize and Mustard

Yield attributes of both crops were significantly affected by nutrient management practices (Table 2). In maize, T_5 recorded the highest number of cobs plant^{-1} (1.309), the maximum cob weight (224.20 g), and the highest test weight (478.76 g). These values were significantly superior to those obtained under T_2 and T_3, indicating the beneficial effect of balanced nutrient application on reproductive development.

In mustard, T_5 also produced the highest number of siliquae plant^{-1} (353.33), the maximum seed count (17.97 seeds siliqua^{-1}), and the highest test weight (6.93 g). The enhanced reproductive performance under T_5 suggests improved assimilate production and translocation towards sink organs due to adequate nutrient availability during flowering and grain-filling stages.

The improvement in yield attributes under SSNM may be attributed to enhanced nutrient-use efficiency and balanced nutrient supply, which support better floral initiation, grain formation, and seed development. Adequate nitrogen availability during critical growth stages enhances assimilate production, while sulphur and boron play important roles in protein synthesis, pollen viability, and seed set. Similar findings have been reported by Dass et al. (2013), Kaur et al. (2015), and Sreelatha et al. (2012), who observed significant increases in yield attributes under balanced nutrient management practices.

3.3 Yield Performance of Maize and Mustard

The application of SSNM significantly improved the yield performance of both maize and mustard (Table 3). In maize, T_5 recorded the highest grain yield (4660 kg ha^{-1}), straw yield (9735 kg ha^{-1}), and biological yield (14,396 kg ha^{-1}). The harvest index was also highest under T_5 (32.28%), indicating efficient partitioning of assimilates towards grain production.

In mustard, T_5 produced the highest seed yield (2026 kg ha^{-1}), stover yield (4968 kg ha^{-1}), and biological yield (6994 kg ha^{-1}). Although harvest index differences among treatments were not statistically significant, T_5 recorded the numerically highest value (28.85%).

The substantial yield enhancement under T_5 can be attributed to improved nutrient uptake, enhanced photosynthetic efficiency, and balanced nutrient availability throughout the crop growth period. Site-specific nutrient management ensures that nutrients are supplied according to crop demand, thereby reducing nutrient losses and improving fertiliser recovery efficiency. Similar yield improvements under SSNM have been reported by Pampolino et al. (2012) in maize–wheat systems and Pasuquin et al. (2014) in Southeast Asia. The present findings also agree with the observations of Mehta et al. (2011), who reported higher grain yield and harvest index under site-specific nutrient management.

3.4 Yield Performance of Maize and Mustard

The application of SSNM significantly improved the yield performance of both maize and mustard (Table 3 and Fig. 1). In maize, T_5 recorded the highest grain yield (4660 kg ha^{-1}), straw yield (9735 kg ha^{-1}), and biological yield (14,396 kg ha^{-1}). The harvest index was also highest under T_5 (32.28%), indicating efficient partitioning of assimilates towards grain production.

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3.5 Economic Analysis

Economic analysis revealed that nutrient management strategies significantly influenced the profitability of the maize–mustard cropping system (Table 4). In maize, T_5 generated the highest gross return (₹128,441 ha^{-1}), net return (₹77,051 ha^{-1}), and benefit:cost ratio (1.50). In mustard, T_5 also recorded the highest gross return (₹127,829 ha^{-1}) and net return (₹83,417 ha^{-1}). However, the highest benefit:cost ratio in mustard was observed under T_7 (1.96), indicating that the combination of 75% of the recommended dose with green manuring provided a highly cost-effective nutrient management option.

The superior economic performance of T_5 was primarily due to higher crop yields and greater marketable produce, which outweighed the additional cost of micronutrient application. The high B:C ratio under T_7 suggests that partial substitution of inorganic fertilisers with green manuring can reduce input costs while maintaining satisfactory productivity. Comparable improvements in profitability and resource-use efficiency under conservation agriculture, residue mulching, and balanced nutrient management have been reported by Choudhary and Behera (2021), A. Kumar et al. (2021), and Sarkar et al. (2018).

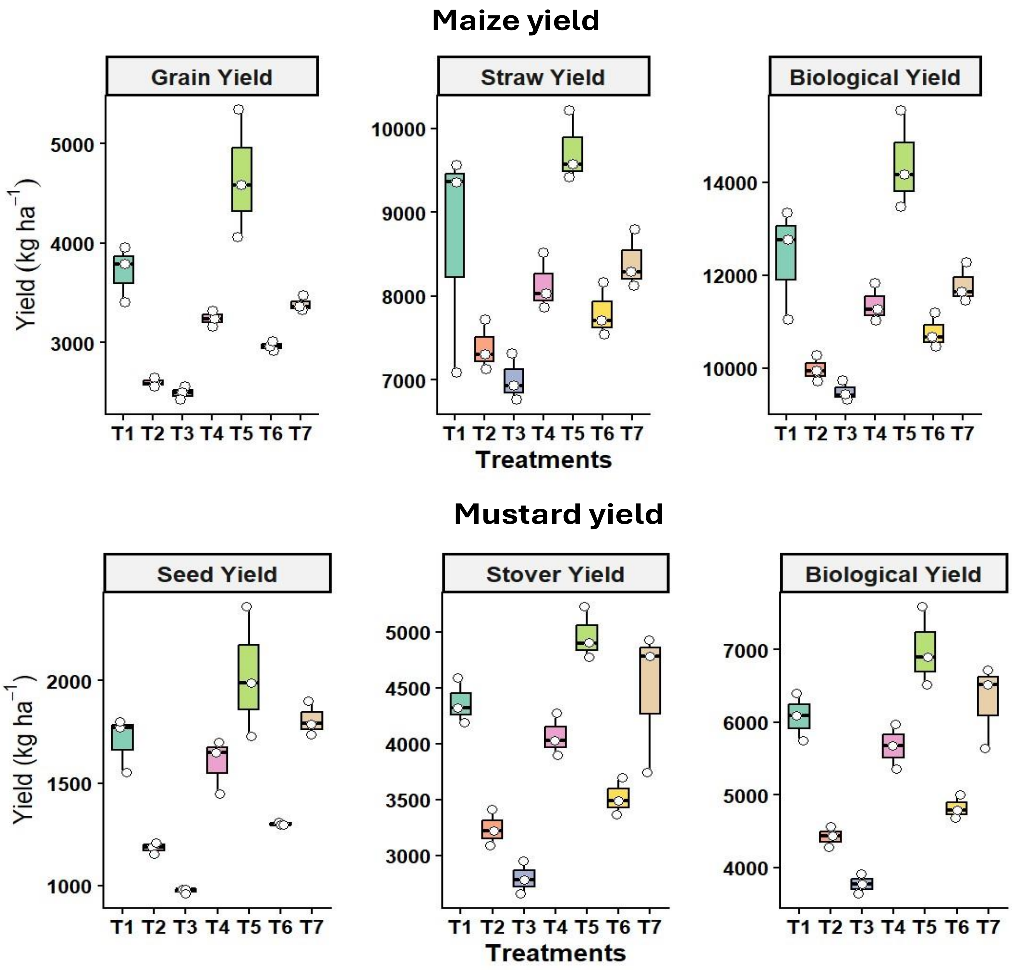


Fig. 1. Effect of treatments on maize yield and Mustard yield. Boxplots showing variation in (A) Grain yield (kg ha^{-1}) of maize, (B) Straw yield (kg ha^{-1}) of maize (C) Biological yield (kg ha^{-1}) of maize, D) Seed yield (kg ha^{-1}) of mustard, (E) Stover yield (kg ha^{-1}) of mustard and (F) Biological yield (kg ha^{-1}) of mustard as influenced by different treatments. Box represents interquartile range, line inside box represents median, and whiskers represent minimum and maximum values. T1-T7 = Treatment 1 to Treatment 7

3.6 System Productivity and Efficiency

System productivity and efficiency parameters were significantly influenced by nutrient management practices (Table 5 and Fig. 2). The highest mustard equivalent yield (3702.66 kg ha^{-1}), production efficiency (14.76 kg ha^{-1} day^{-1}), and land-use efficiency (68.68%) were recorded under T_5. These values were significantly higher than those obtained under organic and natural farming treatments.

The enhanced system productivity under T_5 reflects the cumulative effect of higher yields in both maize and mustard, efficient nutrient utilisation, and improved crop growth dynamics. Site-specific nutrient management optimises nutrient availability according to crop requirements, thereby improving resource-use efficiency and sustaining higher productivity across the cropping sequence. Similar improvements in system productivity under SSNM-based fertiliser application have been reported by Chivenge et al. (2022), M. Kumar et al. (2021), Pampolino et al. (2012), and Shahi et al. (2022).

Table 1. Effect of different nutrient management strategies on growth attributes parameters of maize and mustard

Treatment	Maize			Mustard			
	Plant height at harvest (cm)	Number of leaves at anthesis (no. plant^{-1})	Chlorophyll content at anthesis (SPAD value)	Plant height at harvest (cm)	Primary branches at harvest (no. plant^{-1})	Secondary branches at harvest (no. plant^{-1})	Chlorophyll content at anthesis (SPAD value)
T_1	197.19 ± 11.63^{ab}	15.13 ± 1.26^{ab}	21.85 ± 0.77^{ab}	223.69 ± 7.26^{abc}	7.43 ± 0.29^{bc}	10.02 ± 0.50^{b}	20.06 ± 1.36^{ab}
T_2	162.71 ± 10.76^{cd}	12.60 ± 0.19^{cd}	14.99 ± 0.51^{de}	210.78 ± 13.39^{bc}	5.99 ± 0.21^{d}	7.43 ± 0.15^{d}	16.14 ± 0.50^{d}
T_3	154.42 ± 2.69^{d}	11.73 ± 0.18^{d}	14.21 ± 0.62^{e}	201.92 ± 8.78^{c}	4.89 ± 0.21^{e}	6.00 ± 0.22^{e}	14.87 ± 0.19^{d}
T_4	174.91 ± 0.27^{bcd}	13.93 ± 0.22^{abc}	19.45 ± 0.65^{c}	216.25 ± 3.78^{bc}	7.27 ± 0.60^{c}	8.68 ± 0.44^{c}	19.04 ± 0.62^{bc}
T_5	205.46 ± 9.79^{a}	15.60 ± 0.27^{a}	22.94 ± 0.63^{a}	248.77 ± 6.73^{a}	10.43 ± 0.60^{a}	13.77 ± 0.72^{a}	22.05 ± 0.70^{a}
T_6	168.45 ± 2.43^{cd}	13.60 ± 0.22^{bc}	17.02 ± 0.82^{d}	212.60 ± 1.82^{bc}	6.74 ± 0.12^{cd}	8.33 ± 0.14^{cd}	16.98 ± 0.58^{cd}
T_7	182.03 ± 4.26^{bc}	14.40 ± 0.23^{ab}	20.15 ± 1.05^{bc}	232.51 ± 11.53^{ab}	8.33 ± 0.34^{b}	10.98 ± 0.39^{b}	21.28 ± 0.79^{ab}

(Values are mean ± standard deviation. Means followed by different superscript letters within a column differ significantly at $P < 0.05$)

Table 2. Effect of different nutrient management strategies on yield attributes of maize and mustard

Treatment	Maize			Mustard		
	Number of cobs plant^{-1}	Cob weight (g cob^{-1})	Test weight (g)	Siliquae plant^{-1}	Seeds siliqua^{-1}	Test weight (g)
T_1	1.247 ± 0.132^{ab}	192.77 ± 13.68^{bc}	407.23 ± 6.85^{bc}	297.88 ± 15.39^{bc}	16.02 ± 0.74^{abc}	5.98 ± 0.29^{b}
T_2	1.039 ± 0.006^{c}	167.88 ± 2.37^{cd}	386.55 ± 5.92^{cd}	241.33 ± 1.32^{de}	15.09 ± 0.73^{bc}	4.06 ± 0.03^{cd}
T_3	1.039 ± 0.006^{c}	160.34 ± 6.04^{d}	362.55 ± 12.45^{d}	228.03 ± 4.40^{e}	14.47 ± 0.44^{c}	3.33 ± 0.07^{d}
T_4	1.109 ± 0.005^{bc}	183.86 ± 2.18^{bcd}	398.82 ± 6.47^{bcd}	277.12 ± 5.43^{bcd}	15.99 ± 0.84^{abc}	5.48 ± 0.26^{b}
T_5	1.309 ± 0.008^{a}	224.20 ± 8.00^{a}	478.76 ± 27.14^{a}	353.33 ± 35.95^{a}	17.97 ± 0.35^{a}	6.93 ± 0.58^{a}
T_6	1.039 ± 0.006^{c}	175.87 ± 2.27^{cd}	390.60 ± 6.10^{bcd}	260.28 ± 2.00^{cde}	15.58 ± 0.51^{bc}	4.46 ± 0.02^{c}
T_7	1.169 ± 0.006^{abc}	208.84 ± 15.35^{ab}	429.07 ± 7.87^{b}	314.48 ± 12.70^{ab}	16.84 ± 0.60^{ab}	5.79 ± 0.42^{b}

(Values are mean ± standard deviation. Means followed by different superscript letters within a column differ significantly at $P < 0.05$)

Table 3. Effect of different nutrient management strategies on yield of maize and mustard

Treatment	Maize				Mustard			
	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Biological yield (kg ha^{-1})	Harvest index (%)	Seed yield (kg ha^{-1})	Stover yield (kg ha^{-1})	Biological yield (kg ha^{-1})	Harvest index (%)
T_1	3711 ± 162.80^{b}	8670 ± 794.22^{ab}	12382 ± 692.93^{b}	30.26 ± 2.81^{ab}	1707 ± 78.06^{b}	4368± 117.89^{b}	6075± 186.99^{bc}	28.08 ± 0.59^{a}
T_2	2592± 25.31^{de}	7383 ± 174.23^{cd}	9976 ± 161.87^{de}	26.01 ± 0.57^{c}	1185 ± 15.62^{cd}	3238± 92.74^{de}	4423 ± 82.66^{d}	26.83 ± 0.76^{a}
T_3	248 ± 38.16^{e}	7003 ± 164.47^{d}	9492 ± 127.22^{e}	26.24 ± 0.74^{c}	975 ± 7.05^{d}	2797± 85.18^{e}	3772 ± 78.95^{e}	25.87 ± 0.71^{a}
T_4	3236 ± 45.10^{c}	8134 ± 195.16^{bcd}	11370 ± 238.49^{bc}	28.47 ± 0.23^{abc}	1598± 76.03^{b}	4068 ± 110.40^{bc}	5667 ± 180.37^{c}	28.19 ± 0.58^{a}
T_5	4660 ± 371.24^{a}	9735 ± 247.09^{a}	14396 ± 614.51^{a}	32.28 ± 1.20^{a}	2026 ± 182.81^{a}	4968 ± 134.63^{a}	6994 ± 316.64^{a}	28.85 ± 1.30^{a}
T_6	2961 ± 28.77^{cd}	7804 ± 185.69^{bcd}	10765 ± 213.94^{cd}	27.52 ± 0.28^{bc}	1301 ± 4.77^{c}	3518 ± 98.20^{cd}	4819 ± 94.75^{d}	27.03 ± 0.60^{a}
T_7	3384 ± 44.59^{bc}	8404 ± 203.23^{bc}	11788 ± 247.78^{bc}	28.71 ± 0.22^{abc}	1809 ± 47.35^{ab}	4487 ± 372.93^{ab}	6297 ± 330.50^{b}	28.99 ± 2.33^{a}

(Values are mean ± standard deviation. Means followed by different superscript letters within a column differ significantly at $P < 0.05$)

Table 4. Effect of different nutrient management strategies on economics of maize and mustard

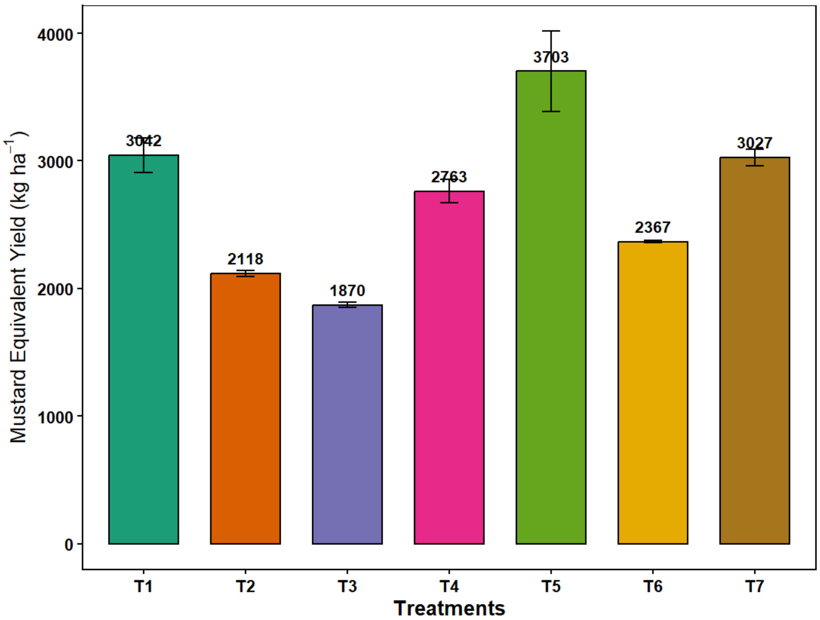
Treatment	Maize				Mustard			
	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	Benefit:cost ratio	Cost of cultivation (₹ ha^{-1})	Gross return (₹ ha^{-1})	Net return (₹ ha^{-1})	Benefit:cost ratio
T_1	47827	105777 ± 2470.77^{b}	57950 ± 2470.77^{b}	1.21 ± 0.05^{b}	40849	108339± 4596.42^{bc}	67489 ± 4596.42^{b}	1.65 ± 0.11^{bc}
T_2	42623	78931± 572.16^{ef}	36308 ± 572.16^{e}	0.85 ± 0.01^{de}	35645	75959 ± 667.66^{d}	40314± 667.66^{cd}	1.13 ± 0.02^{de}
T_3	39123	75441± 180.61^{f}	36318 ± 180.61^{e}	0.93 ± 0.01^{cd}	31345	62931 ± 177.63^{e}	31586± 177.63^{d}	1.01 ± 0.01^{e}
T_4	56076	94407± 1606.94^{cd}	38331± 1606.94^{de}	0.69 ± 0.03^{e}	49098	101379± 4483.13^{c}	52281 ± 4483.13^{c}	1.07 ± 0.09^{e}
T_5	51390	128441 ± 8201.34^{a}	77051± 8201.34^{a}	1.50 ± 0.16^{a}	44412	127829 ± 10429.74^{a}	83417 ± 10429.74^{a}	1.88 ± 0.24^{ab}
T_6	41863	87760± 1263.63^{de}	45896 ± 1263.63^{cd}	1.10 ± 0.03^{bc}	34885	83263± 233.10^{d}	48377± 233.10^{c}	1.39 ± 0.01^{cd}
T_7	45653	98333 ± 1646.75^{bc}	52679 ± 1646.75^{bc}	1.15 ± 0.03^{b}	38675	114344 ± 1497.63^{b}	75669 ± 1497.63^{ab}	1.96 ± 0.04^{a}

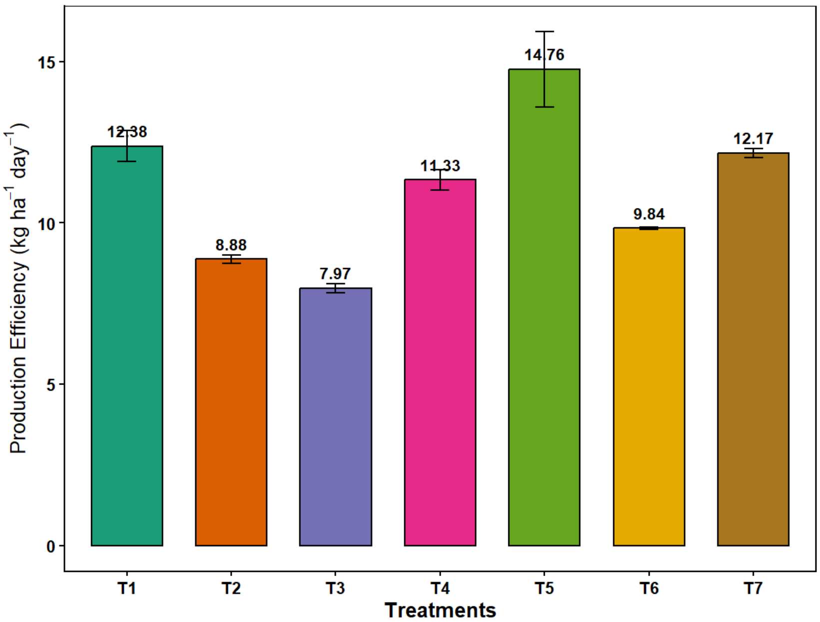
(Values are mean ± standard deviation. Means followed by different superscript letters within a column differ significantly at $P < 0.05$)

Table 5. Effect of different nutrient management strategies on system productivity and efficiency parameters in maize-mustard cropping system

Treatment	Mustard equivalent yield ($kg\ ha^{-1}$)	Production efficiency ($kg\ ha^{-1}\ day^{-1}$)	Land use efficiency (%)
T_1	3042.28 ± 135.99^{b}	12.38 ± 0.48^{b}	67.31 ± 0.40^{c}
T_2	2118.29 ± 24.42^{cd}	8.88 ± 0.13^{cd}	65.39 ± 0.40^{f}
T_3	1870.03 ± 20.18^{d}	7.97 ± 0.13^{d}	64.29 ± 0.40^{g}
T_4	2762.81 ± 91.65^{b}	11.33 ± 0.31^{b}	66.76 ± 0.40^{d}
T_5	3702.66 ± 316.32^{a}	14.76 ± 1.18^{a}	68.68 ± 0.40^{a}
T_6	2366.88 ± 7.22^{c}	9.84 ± 0.04^{c}	65.94 ± 0.40^{e}
T_7	3026.93 ± 63.30^{b}	12.17 ± 0.14^{b}	68.13 ± 0.64^{b}

(Values are mean ± standard deviation. Means followed by different superscript letters within a column differ significantly at $P < 0.05$)





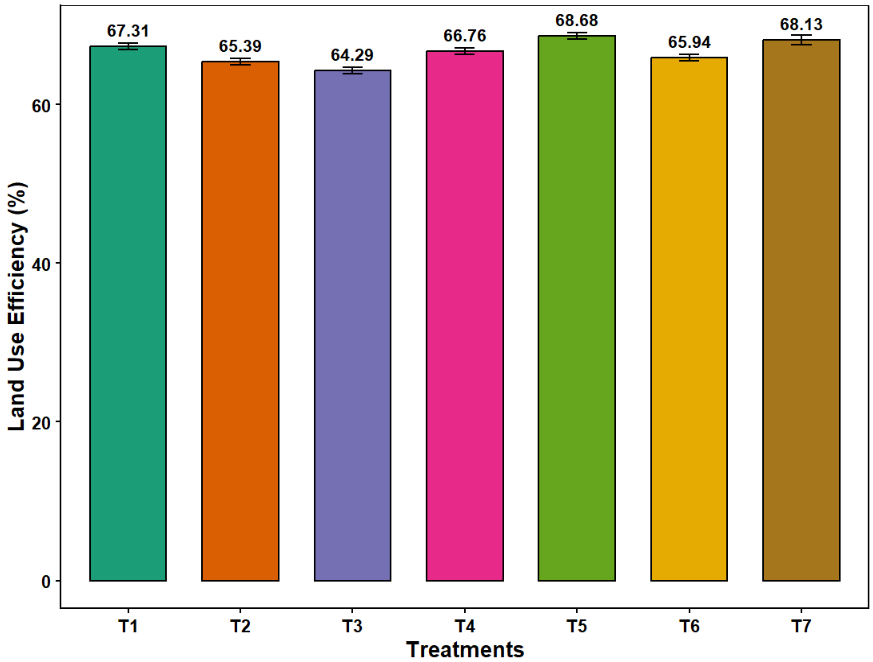


Fig. 2. Effect of treatments on system productivity and efficiency parameters. Bar diagram showing (A) Mustard Equivalent Yield (kg ha⁻¹), (B) Production Efficiency (kg ha⁻¹ day⁻¹) and (C) Land Use Efficiency (%) of maize-mustard cropping system as influenced by different treatments. Vertical bars represent ± standard deviation. T1-T7 = Treatment 1 to Treatment 7

The superior performance of T_5 across growth, yield, economic, and system productivity parameters demonstrates the importance of balanced nutrient management in intensive cropping systems. The combined application of macronutrients with sulphur and micronutrients (Zn, Fe, and B) likely enhanced several physiological and biochemical processes, including chlorophyll synthesis, enzyme activation, pollen viability, seed formation, and assimilate translocation.

Nitrogen plays a central role in chlorophyll formation and photosynthesis, while phosphorus supports energy transfer and root development. Potassium regulates stomatal function and assimilate transport, whereas sulphur contributes to protein synthesis. Micronutrients such as zinc, iron, and boron are essential for enzyme activity, chlorophyll biosynthesis, and reproductive development. The balanced supply of these nutrients under T_5 ensured continuous nutrient availability during critical growth stages, leading to enhanced crop performance.

Furthermore, SSNM minimises nutrient losses through leaching and volatilisation by matching fertiliser application with crop demand. This synchronisation improves nutrient recovery efficiency and agronomic efficiency, thereby increasing crop productivity while reducing environmental risks. Similar conclusions regarding enhanced nutrient-use efficiency under SSNM have been reported by Cao et al. (2017), Chivenge et al. (2022), and Timsina et al. (2021).

4. Conclusion

The present investigation demonstrated that nutrient management strategies significantly influenced the productivity, profitability, and system efficiency of the maize–mustard cropping system under the semi-arid conditions of Bundelkhand. Among the evaluated treatments, site-specific nutrient management (SSNM) comprising 100% of the recommended nutrients + Zn @ 5 kg ha^{-1} + B @ 1 kg ha^{-1} + S @ 60 kg ha^{-1} + Fe @ 1 kg ha^{-1} (T_5) consistently outperformed all other treatments. It recorded the highest maize plant height (205.46 cm), grain yield (4660 kg ha^{-1}), straw yield (9735 kg ha^{-1}), and biological yield (14,396 kg ha^{-1}). Likewise, in mustard, T_5 produced the maximum plant height (248.77 cm), siliquae plant^{-1} (353.33), seeds siliqua^{-1} (17.97), test weight (6.93 g), seed yield (2026 kg ha^{-1}), stover yield (4968 kg ha^{-1}), and biological yield (6994 kg ha^{-1}).

The superior crop performance under SSNM translated into the highest mustard equivalent yield (3702 kg ha^{-1}), production efficiency (14.76 kg ha^{-1} day^{-1}), and land-use efficiency (68.68%), indicating improved resource-use efficiency and enhanced cropping system productivity. Economic analysis further revealed that SSNM generated the maximum gross return of ₹128,441 ha^{-1} and net return of ₹77,051 ha^{-1} in maize, while in mustard it recorded the highest gross return (₹127,829 ha^{-1}) and net return (₹83,417 ha^{-1}). However, the highest benefit:cost ratio (1.96) was obtained with 75% RDF integrated with green manuring (T_7) owing to its lower cost of cultivation.

Overall, the results indicate that site-specific nutrient management with balanced application of macro- and micronutrients is the most effective strategy for maximising crop productivity, improving nutrient-use efficiency, enhancing system productivity, and increasing farm profitability in the maize–mustard cropping system. Therefore, SSNM supplemented with sulphur, zinc, iron, and boron can be recommended after further multi-season and multilocation trials as a sustainable nutrient management practice for the semi-arid agro-ecological conditions of Bundelkhand and other regions with similar soil and climatic conditions.

5. Limitation

The experiment was conducted at one location during a single maize–mustard cropping sequence in 2022–2023; therefore, seasonal and site-specific variability could not be assessed. The study primarily evaluated crop performance, system efficiency, and economic returns, without examining long-term changes in soil fertility, nutrient balances, or environmental nutrient losses. Consequently, the findings should be validated through multi-season and multi-location trials before being generalized to other agro-ecological conditions.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). 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.

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