Agriculture Association of Textile Chemical and Critical Reviews Journal (2025) 178-185

AATCC Review

01 June 2025: Received
19 July 2025: Revised
28 July 2025: Accepted
26 August 2025: Available Online

https://aatcc.peerjournals.net/

Original Research Article

Open Access

Impact of integrated nutrient management on mustard productivity and soil fertility in a long-term rice–mustard cropping system

Vikram Bharati*[1], R. S. Singh[1], Meka Shivaram Reddy[1], S. S. Prasad[3], Brijesh Kumar[2], C. S. Choudhary[3], Rajendra Prasad[1], Amrendra Kumar[1] and H. C. Chaudhary[3]

[1]*Department of Agronomy, Dr. RPCAU, Pusa Bihar 848 125, India*
[2]*Department of Soil Science, Dr. RPCAU, Pusa Bihar 848125, India*
[3]*Department of Plant Pathology, Dr. RPCAU, Pusa Bihar 848125, India*

ABSTRACT

Rice–mustard cropping systems dominate large tracts of the Indo-Gangetic Plains, playing a crucial role in food and nutritional security. However, intensive cultivation without adequate nutrient replenishment has led to declining soil fertility and stagnating crop yields. Despite the known benefits of Integrated Nutrient Management (INM), long-term empirical evidence assessing its sustainability in rice–mustard systems is limited, particularly in the alluvial soils of eastern India. Addressing this gap is vital for developing specific nutrient strategies that enhance productivity while preserving soil health. This study aimed to evaluate the long-term effects of INM on mustard yield, soil fertility, and system sustainability in a rice–mustard cropping system. A ten-year field experiment was conducted at TCA, Dholi, Bihar. The experiment consisted of ten nutrient management treatments, including control, varying levels of NPK fertilizers, combinations with secondary and micronutrients (S, Zn, B) and the inclusion of organic manure (FYM @ 2.5 t ha^{-1}), laid out in a randomized block design with three replications. Results revealed significant differences among treatments in terms of growth, yield and economic returns of mustard. The treatment T4 (150% NPK) recorded the higher seed yield (1870 kg ha^{-1}), net returns (₹141578ha^{-1}) and benefit–cost ratio (1.43), which were statistically at par with T8 (100% NPK + FYM @ 2.5 t ha^{-1}), followed by treatments supplemented with micronutrients. Long-term INM application enhanced soil fertility, with the highest organic carbon (0.50%) recorded under 100% NPK + FYM treatment. Integrated nutrient management proves to be a sustainable strategy for enhancing mustard yield, profitability, and soil health in the intensive rice–mustard system of alluvial soils.

Keywords: *Economics, Integrated nutrient management, rice–mustard system, soil fertility, yield, Long term*

Introduction

Rice is the staple food for more than half of the world's population [3]. It is the most significant and extensively cultivated food crop grown extensively in tropical and subtropical regions, which provides half of the daily food for one of every three people on the earth. About 70% of the global population consumes rice as an essential food while more than two billion people in Asia alone, obtain 60-70% of their energy intake from rice and its products [47]. In India, during the year 2023–24, the total cultivated area under rice was 47.82 million hectares, with a total production of 137.82 million tonnes and an average productivity of 2.88 tonnes per hectare [10] and it is the second-highest producer contributing 22% of global rice production. Rice cultivation in traditional systems commonly involves puddling, a process of repeated wet tillage that creates a soft and compacted soil layer to facilitate water retention and suppress weeds. While puddling is advantageous for rice establishment, it has detrimental effects on the soil's physical structure. Specifically, puddling disrupts natural soil aggregates, decreases macro porosity and leads to the formation of a hard pan in the subsurface layers [30]. This results in poor soil aeration and restricted water infiltration, which negatively impact the growth of succeeding upland crops such as mustard, which require well-aerated and structured soils for optimal root development.

Oilseeds play a vital role in global agriculture as key sources of edible oils, biofuels, and industrial raw materials [9]. In India, they contribute about 5% to the gross national product and 10% to the total value of agricultural output [28]. As an oilseed crop, mustard holds considerable economic value on a global scale. Mustard (*Brassica juncea* L.) is cultivated during the dry winter season and features a deep taproot system, reducing its dependence on irrigation water. Among the seven edible oilseeds cultivated in India, it is the third prominent oilseed crop, after groundnut and soybean. Rajasthan, Uttar Pradesh, Gujarat, Madhya Pradesh, Haryana, West Bengal, Bihar, Punjab and Assam are the key states where it is predominantly grown. Indian mustard (*Brassica juncea*) occupies three-quarters of the area under brassica cultivation in India. During the 2023-24 agricultural year in India, mustard is cultivated on 9.18 million hectares, with a total production of 13.25 million tonnes. The productivity of mustard stands at 1444 kg ha^{-1}. Mustard is a major oilseed crop in India, covering 30.41% of the oilseed area and contributing 33.42% to total production [11]. With an oil content of 36–43% [42], it is widely used for cooking, condiments, hair oils, medicines and industrial greases. Its green parts serve as fodder, and its microgreens are rich in

Corresponding Author: **Vikram Bharati*

DOI: https://doi.org/10.21276/AATCCReview.2025.13.04.178

vitamins A and C, supporting eye health and immunity. They also supply important minerals such as calcium and iron, which are crucial for bone health and the production of red blood cells. Additionally, these microgreens are packed with antioxidants, including glucosinolates, which aid in liver detoxification and help in cancer prevention. Moreover, they are a good source of fiber, promoting healthy digestion and supporting gut health. Mustard oil cake is used as a cost-effective protein supplement for livestock and is beneficial for milking cows [28]. It is typically blended with other feed ingredients such as green fodder, straw, grains, or silage or through fermentation or heat treatment (such as steaming or boiling) to reduce bitterness (sinigrin) and glucosinolate levels, making the oil cake more palatable and easier to digest for cattle. This helps to reduce the possible harmful effects of substances like glucosinolates and sinigrin, which may affect cattle's health if taken in high quantities. In the tanning industry, mustard oil is used for softening leather.

Despite being one of the leading producers, India, with its vast population, struggles to meet the domestic demand for edible oils [24]. As a result, the country spends a significant amount of foreign exchange on importing edible oils, with a total import quantity of 15.96 million tonnes valued at ₹ 131967 crore in the year 2023-24 [38]. Bihar relies heavily on mustard for cooking. However, there is less cultivation of oilseed crops throughout India. The pressure on crop land area in Bihar is high due to the state's large population, low farmer land holdings and limited agricultural land availability. Mustard was grown on an area of 96.98 thousand hectares, producing 122.4 thousand tonnes, with a productivity of 1263 kg ha^{-1}. This production does not meet the demand for mustard oil. The area of cultivation and production of mustard clearly shows that there is a large potential for expansion. To bridge the gap between demand and supply, productivity needs to be enhanced. A promising approach to increasing yields is by cultivating mustard with nutrient management strategies that sustain soil fertility.

Indian agriculture Indian agriculture largely depends on rice-based cropping systems, with the rice–mustard sequence being one of the most dominant, particularly in the Indo-Gangetic Plains and eastern India [5]. This system is also widely practiced across South and Southeast Asia. However, continuous cultivation of rice followed by mustard without appropriate nutrient management often leads to nutrient imbalances and a gradual decline in soil fertility and crop productivity [39]. Rice, being a nutrient-exhaustive crop, significantly depletes essential soil nutrients such as nitrogen (N), phosphorus (P) and potassium (K), especially when fertilization is inadequate [42]. Furthermore, rice cultivation practices like puddling and prolonged submergence degrade soil structure, leading to compaction and reduced porosity, which negatively impact the root development and nutrient uptake of the subsequent mustard crop. Despite these challenges, residual soil moisture following rice harvest can be beneficial for mustard germination and early growth, especially under rainfed conditions (Sharma et al., 2005). Additionally, the incorporation of rice residues and the application of organic amendments such as farmyard manure (FYM) have been shown to enhance soil organic carbon, microbial activity and the availability of micronutrients like zinc (Zn) and boron (B), thereby supporting improved mustard yields [8].

To address these challenges, long-term fertility experiments (LTFE) were conducted to evaluate the effects of different nutrient management practices on soil health and crop performance over time.

Therefore, this research was conducted to assess the impact of integrated nutrient management on soil fertility dynamics and the productivity of mustard in a rice–mustard cropping system. The findings are expected to guide sustainable nutrient strategies for long-term soil and crop productivity.

MATERIALS AND METHOD

2.1 Experimental Site

A long-term field experiment was conducted during the *rabi* seasons from 2011–12 to 2020–21 at the Agricultural Research Farm, Tirhut College of Agriculture (TCA), Dholi, Dr. Rajendra Prasad Central Agricultural University, Pusa. The site falls under Agro-climatic Zone I of Bihar and is situated on the southern bank of the Burhi Gandak River. The geographical coordinates of the site are 25°59′44″ N latitude and 85°35′30″ E longitude, with an elevation of 58.13 meters above mean sea level.

2.2 Soil Characteristics

Soil samples were collected from the experimental site at a depth of 0–15 cm using a screw auger. To ensure representativeness, samples were taken from multiple locations across the field and composited. The collected soil was then divided into two subsamples for separate analyses. One subsample was subjected to mechanical analysis to determine its physical properties, including the particle size distribution (percentages of sand, silt and clay). The other subsample was air-dried at ambient room temperature. After drying, the soil was gently ground to disaggregate clumps and passed through a 2 mm sieve to obtain a homogeneous sample suitable for subsequent chemical analyses. The soil texture analysis revealed that the soil contained 49.75% sand, 39.36% silt and 10.87% clay, classifying it as sandy loam according to the USDA soil textural classification triangle. In addition to the physical attributes, the chemical characteristics of the soil were assessed. The soil pH was 8.14, indicating a slightly alkaline reaction, and the electrical conductivity (EC) was 0.27 dS m^{-1}, suggesting non-saline conditions. The organic carbon content was 0.33%, reflecting a moderate level of organic matter. The concentrations of available macronutrients were 131.45 kg ha^{-1} for nitrogen (N), 19.12 kg ha^{-1} for phosphorus (P) and 64.87 kg ha^{-1} for potassium (K). Among the secondary and micronutrients, the soil had 11.51 mg kg^{-1} of available sulfur (S), 0.53 mg kg^{-1} of available zinc (Zn) and 0.34 mg kg^{-1} of available boron (B).

2.3. Climate and Weather Conditions

The experimental site is located in a subtropical climate characterized by moderate annual rainfall, hot dry summers, and cool winters. The region receives an average annual precipitation of 1275 mm, with approximately 1015 mm occurring during the southwest monsoon season, typically from mid-July to September. During the crop season, weekly maximum temperatures ranged from 14.7°C to 31.8°C, while minimum temperatures varied between 6.5°C and 16.8°C. Relative humidity showed considerable variation, with weekly highs between 95% and 100% and lows ranging from 45% to 85%.

2.4. Experimental Design

The experiment was laid out in a randomized complete block design (RCBD) with three replications. A total of ten different fertilizer treatments were applied, with each treatment replicated three times, resulting in 30 plots in total.

The total plot size was 5.0 m × 3.0 m, with a net plot size of 4.8 m × 2.4 m. The mustard variety Rajendra Suflam was used for the study. The Essential macronutrients nitrogen (N), phosphorus (P) and potassium (K) were supplied through urea, diammonium phosphate (DAP) and muriate of potash (MOP), respectively. The recommended fertilizer dose applied was 80:40:40 kg NPK per hectare. Mustard seeds were sown at a seed rate of 5 kg ha^{-1}. To enhance nutrient uptake and use efficiency, a split-application strategy for nitrogen was adopted. At the time of sowing, 50% of the recommended nitrogen dose was applied along with the full doses of phosphorus and potassium. The remaining 50% of nitrogen was top-dressed during the first irrigation. In addition to the primary nutrients, treatments also included the application of sulphur, boron, zinc and farmyard manure (FYM). The detailed experimental layout is presented in Table 1.

Table 1. Details of treatments.

Treatment	Configuration
T1	Control
T2	50% Recommended NPK
T3	100% Recommended NPK
T4	150% NPK
T5	100% NPK + Sulfur @ 40 kg ha^{-1}
T6	100% NPK + Zinc @ 25 kg $ZnSO_4$ ha^{-1}
T7	100% NPK + Boron @ 1 kg ha^{-1}
T8	100% NPK + FYM @ 2.5 t ha^{-1}
T9	100% NP
T10	100% N

2.5. Field Operation and Crop Cultivation Practice

After the harvest of the preceding crop, the experimental field was prepared using a tractor-drawn mouldboard plough. Residual crop roots and debris were manually removed to facilitate proper tillage. This was followed by 2–3 passes with a tractor-drawn cultivator to further break down soil clods. Subsequent harrowing and levelling operations were carried out to achieve a fine tilth and uniform soil surface conducive to optimal seedbed conditions. Irrigation channels and earthen bunds were precisely constructed according to the experimental layout to ensure efficient water conveyance, controlled distribution. Pre-sowing irrigation was applied to ensure adequate soil moisture for uniform germination. To maintain a consistent plant population across plots, gap filling was performed shortly after emergence to replace non-germinated or dead seedlings. Approximately 15–20 days after sowing (DAS), manual thinning was carried out to achieve a uniform spacing of 30 × 10 cm, following complete germination. Weed control was managed manually, with two hand-weeding operations conducted during the crop growth period to maintain weed-free conditions. Irrigation was scheduled at critical growth stages: immediately after sowing, at 30 DAS, during the flowering stage, and at 60 DAS, in addition to the pre-sowing irrigation. The crop remained free from major diseases throughout the growing season. However, to manage aphid infestation identified as the primary insect pest a single application of Dimethoate 30 EC was administered at a rate of 1000 mL ha^{-1}, diluted in 800 litres of water, during early pod formation. Harvesting was carried out manually using sickles once the majority of plants reached physiological maturity. The harvested plants were left to dry in the field for approximately one week. After sufficient drying, the biomass from each net plot was bundled and weighed. Threshing was performed manually by beating the dried plants with sticks. Seed yield was determined by weighing the clean seeds separated from the chaff. Straw yield was calculated by subtracting the seed yield from the total biological yield.

2.6. Analytical methods:

Soil chemical properties were assessed following standard procedures. Soil pH and electrical conductivity (EC) were determined in a 1:2.5 (w/v) soil-water suspension (Jackson, 1973). Organic carbon content was analyzed using the Walkley and Black wet digestion method (1934). Available nitrogen was estimated by the alkaline permanganate method (Subbiah and Asija, 1956) and available phosphorus was determined using Olsen's method with 0.5 M $NaHCO_3$ extractant (Olsen *et al*., 1954). Available potassium was extracted with neutral normal ammonium acetate and measured using a flame photometer (Hanway and Heidel, 1952). Sulfur was extracted using 0.15% $CaCl_2$ and turbidity was measured at 420 nm (Williams and Steinbergs, 1959) while available zinc was determined using atomic absorption spectrophotometry (Lindsay and Norvell, 1978) and boron by the hot water extraction method (John *et al*., 1975).

2.7. Data Collection

Seed yield (kg ha^{-1})

At physiological maturity, mustard plants were harvested from the designated net plot area, deliberately excluding border rows to minimize border effects and ensure data accuracy. The harvested plant material was sun-dried to a uniform moisture level suitable for threshing. Seeds were manually threshed, thoroughly cleaned to remove inert matter and foreign particles, and weighed using a calibrated digital balance. The seed yield per plot was recorded in kilograms and standardized to a uniform moisture content (typically 8–10 %) to account for variability in seed moisture levels. The plot-wise seed yield was subsequently extrapolated to a per-hectare basis (kg ha^{-1}).

Mustard Equivalent Yield (kg ha^{-1})

The mustard equivalent yield (MEY) was used to standardize the total system productivity by converting the rice grain yield into its mustard equivalent based on prevailing market prices. This approach facilitates a unified yield expression across component crops with differing economic values. MEY was calculated using the formula:

$$\text{MEY (kg/ha)} = Ym + \left(\frac{Yc \times Pc}{Pm}\right)$$

Where: Ym = Yield of mustard (kg ha^{-1}), Yc = Yield of the companion or intercrop (kg ha^{-1}), Pc = Market price of the companion or intercrop (Rs kg^{-1}) and Pm = Market price of mustard (Rs kg^{-1})

System productivity was determined by dividing the total MEY by the duration (in days) of the cropping system, representing the average daily yield output:

$$\text{System productivity (kg/ha/day)} = \frac{\text{Total MEY (kg/ha)}}{Duration\ of\ the\ system\ (days)}$$

Sustainable Yield Index (SYI) was calculated. SYI is a quantitative indicator used to assess the sustainability and consistency of crop yields across seasons or years. It provides insight into both productivity and resilience of the system under variable environmental and management conditions. The index was computed using the following formula:

$$SYI = \frac{(\bar{Y} - \sigma)}{Ymax}$$

Where: $\bar{Y}$ = Mean yield over years (kg ha^{-1}) σ = Standard deviation of yield (kg ha^{-1})
Ymax = Maximum observed yield in the dataset (kg ha^{-1})

2.8. Economic Analysis

Gross returns (₹ ha^{-1}) were calculated based on the prevailing market prices of both grain and straw yields, representing the total revenue generated per hectare. These values reflect gross income and do not account for production costs. Net returns (₹ ha^{-1}) were obtained by deducting the total cost of cultivation from the gross returns, thereby representing the actual profit realized per unit area after accounting for all input expenses. The benefit–cost ratio (BCR) was computed by dividing net returns by the total cost of cultivation. A BCR value greater than 1 indicates economic viability and a positive return on investment, thus serving as a key indicator of the profitability of the cropping system.

2.9. Statistical Analysis

The observations underwent statistical analysis using the Randomized Block Design (RBD). Mean differences were tested using the F-test at a 5% level of significance (LOS). The Critical Difference (CD) at a 5% level of probability was employed for comparing the treatments [35].

3.0. Results and Discussion

3.1 Effect of Fertility Levels on Seed Yield, Mustard Equivalent Yield (MEY), System Productivity and Sustainable Yield Index (SYI)

The seed yield of mustard was significantly influenced by different nutrient management practices under the rice–mustard cropping system (Table 2). The maximum seed yield was observed in the treatment receiving 150% of the recommended NPK (T4), which produced 1870 kg ha^{-1}. However, this yield was statistically at par with the treatment receiving 100% recommended NPK in conjunction with farmyard manure (FYM @ 2.5 t ha^{-1}; T8), which yielded 1737 kg ha^{-1}. The lowest yield (510 kg ha^{-1}) was observed in the control (T1), indicating a strong yield response to balanced nutrient application. The enhanced yield under T4 can be attributed to increased nutrient availability and uptake, supporting robust plant growth and development. In contrast, the high performance of T8 underscores the synergistic effects of integrating organic manure with mineral fertilizers, which improve nutrient release patterns, enhance soil microbial activity, and promote better nutrient use efficiency. Secondary and micronutrient additions, such as sulfur, zinc and boron, significantly improved yield over 100% NPK alone, highlighting the importance of balanced fertilization beyond primary nutrients. These findings are in line with the results reported by Meena *et al.*, [22], Mukhi *et al.*, [25].

Mustard equivalent yield (MEY) varied significantly across the different nutrient management treatments. The highest MEY (5430 kg ha^{-1}) was recorded with 150% Recommended NPK (T4), which was statistically comparable to T8 (100% NPK + FYM @ 2.5 t ha^{-1}), which produced 5187 kg ha^{-1} of MEY. This was followed by 100% NPK + Sulfur @ 40 kg ha^{-1} (T5) with 4956 kg ha^{-1}. The lowest MEY was observed in the control (T1: 1606 kg ha^{-1}), reflecting the necessity of external nutrient input to maintain productivity in intensive cropping systems. The superiority of 150% NPK suggests that a higher dose of balanced fertilization not only enhances mustard yield but also contributes to increased system productivity in a rice–mustard rotation. The integration of FYM with 100% NPK (T8) also recorded a significantly higher MEY, indicating the beneficial effects of combining organic and inorganic nutrient sources. These results corroborate findings by Deekshith *et al.*, [7].

The highest system productivity (17.8 kg ha^{-1}) was recorded under 150% Recommended NPK (T4), followed closely by 100% NPK + FYM @ 2.5 t ha^{-1} (T8) with 17.0 kg ha^{-1} and 100% NPK + Sulfur @ 40 kg ha^{-1} (T5) with 16.2 kg ha^{-1}. These treatments outperformed the standard 100% NPK (T3: 15.1 kg ha^{-1}), indicating the additive effects of micronutrient and organic amendments in enhancing system output. The lowest productivity was observed in the control (T1: 5.3 kg ha^{-1}) and nutrient-deficient treatments such as 50% NPK (T2: 8.0 kg ha^{-1}) and 100% N (T10: 8.0 kg ha^{-1}). These results are consistent with those reported by Chhaba *et al.*, [37].

The Sustainability Yield Index (SYI), which reflects the stability and reliability of yield over time, was notably affected by different nutrient management treatments. The highest SYI (0.84) was recorded under 100% NPK + FYM @ 2.5 t ha^{-1} (T8), closely followed by 150% Recommended NPK (T4) with an SYI of 0.81, indicating highly stable and productive systems. Treatments involving micronutrient supplementation such as 100% NPK + Sulfur (T5), Zinc (T6) and Boron (T7) also registered high SYI values ranging from 0.75 to 0.76, demonstrating the importance of secondary and micronutrients in improving yield consistency and resilience. The standard 100% NPK (T3) treatment recorded a respectable SYI of 0.72, while the omission of essential nutrients led to a marked decline in sustainability indices. For instance, 100% N (T10) and the control (T1) recorded the lowest SYI values (0.31 and 0.28, respectively), highlighting the yield instability associated with nutrient-deficient or imbalanced fertilization practices. 50% NPK (T2) and 100% NP (T9) produced intermediate SYI values (0.51), underscoring the limited long-term productivity of under-fertilized systems. The superiority of integrated nutrient management (T8) in terms of SYI can be attributed to improvements in soil physical, chemical and biological properties, which promote nutrient availability and buffering against environmental variability. Similarly, higher SYI under 150% NPK suggests that even elevated nutrient inputs can contribute to sustainable productivity when balanced fertilization is maintained.

3.2. Economic Evaluation of Nutrient Management Treatments

The economic evaluation of nutrient management treatments revealed significant differences in system gross return, net return and benefit-cost (B:C) ratio (Table 3). Among the treatments, T4 (150% Recommended NPK) achieved the highest gross return (₹240,263 ha^{-1}) and net return (₹141,578 ha^{-1}), with a benefit–cost ratio of 1.43. However, these values were statistically at par with T8 (100% NPK + FYM @ 2.5 t ha^{-1}), which recorded a gross return of ₹229,510 ha^{-1}, a net return of ₹123,893 ha^{-1}, and a B:C ratio of 1.17. Although slightly lower in economic returns than T4 and T8, the treatments T5 (100% NPK + Sulfur @ 40 kg ha^{-1}), T6 (100% NPK + Zinc @ 25 kg $ZnSO_4$ ha^{-1}) and T7 (100% NPK + Boron @ 1 kg ha^{-1}) also recorded noteworthy profitability, with net returns ranging between ₹110,922 to ₹117,671 ha^{-1} and B:C ratios from 1.10 to 1.16. These results highlight the importance of secondary and micronutrient supplementation in enhancing mustard productivity and economic viability, especially under long-term intensive cropping. Conversely, lower input treatments such as control (T1) and 100% N (T10) resulted in poor economic performance, with T1 showing negative net returns (₹–14,638 ha^{-1}) and a negative B:C ratio (–0.17). This highlights the economic risks of nutrient omission or unbalanced fertilization.

3.3 Effect of Fertility Levels on SOC and Available Primary Nutrients

3.3.1 Soil Organic Carbon (SOC)

The effect of different nutrient management treatments had a statistically significant ($P \leq 0.05$) on soil organic carbon was given in table 4. The highest SOC content (0.50%) was recorded under the treatment T8 (100% NPK + FYM @ 2.5 t ha^{-1}). This result can be attributed to the continuous addition of organic carbon through FYM, which enhanced microbial activity, root biomass return and overall organic matter buildup in the soil. The second-highest SOC value (0.42%) was recorded in T4 (150% NPK), which suggests that higher doses of balanced inorganic fertilizers can moderately improve SOC by increasing crop biomass and root exudates, thus indirectly contributing to soil carbon inputs. However, the effect was comparatively lower than that achieved with the integrated use of FYM. The lowest SOC (0.31%) was recorded in T1 (Control), reflecting the adverse impact of continuous cropping without nutrient inputs on soil health.

3.3.2 Available Nitrogen (kg ha^{-1})

Available nitrogen levels were significantly affected by nutrient management strategies (Table 4). The maximum available N (169.30 kg ha^{-1}) was recorded under T4 (150% NPK), followed closely by T8 (158.59 kg ha^{-1}). This can be attributed to the higher N input and enhanced mineralization from both inorganic and organic sources. In contrast, the lowest available N was observed under T7 (106.62 kg ha^{-1}), indicating possible nutrient mining or immobilization effects. The increase in available N under T8 also reflects the synergistic effect of integrated nutrient management (INM) through FYM, which not only supplements nitrogen but also improves soil microbial activity and nutrient turnover. These results corroborate the findings of Arulmozhiselvan *et al*., [2].

3.3.3 Available Phosphorus (kg ha^{-1})

The available phosphorus content showed significant differences across treatments (Table 4). The highest P_2O_5 content (27.24 kg ha^{-1}) was recorded under T4 (150% NPK), followed by T8 (26.69 kg ha^{-1}). The increase in P_2O_5 availability in these treatments could be due to sufficient P application and improved root activity and solubilization under balanced nutrient conditions. The lowest P_2O_5 content was found in the control (T1), indicating depletion due to crop uptake without replenishment. Organic sources in T8 likely enhanced P_2O_5 solubilization through microbial activity and organic acid production. These results are consistent with Sarkar *et al*., [30].

3.3.4 Available Potassium (kg ha^{-1})

Available potassium content also varied significantly among treatments (Table 4). The maximum available K_2O (123.36 kg ha^{-1}) was recorded in T4 (150% NPK), followed by T8 (110.67 kg ha^{-1}), reflecting the positive effect of higher K input and improved nutrient cycling under integrated management. The lowest K_2O values were observed under T1 (61.87 kg ha^{-1}) and T10 (64.89 kg ha^{-1}), suggesting K_2O depletion under nutrient-deficient treatments. The improved K_2O status under T8 may also be due to mineralization from FYM and enhanced K_2O retention due to better soil physical conditions. These results align with the findings of Manna *et al*., [20].

3.4. **Influence of Nutrient Management on Secondary and Micronutrient Availability**

The availability of secondary and micronutrients like sulfur (S), zinc (Zn) and boron (B) was significantly influenced by the nutrient management practices, as depicted in Figure 1.

3.4.1 Sulfur (mg kg^{-1})

A marked improvement in available sulfur content was recorded in the treatment receiving 100% NPK + Sulfur @ 40 kg ha^{-1} (T5), which registered the highest sulfur level (14.00 mg kg^{-1}), significantly surpassing all other treatments. This distinct increase can be attributed to the direct application of elemental sulfur, enhancing soil sulfur status. Other treatments ranged between 9.60 and 11.80 mg kg^{-1}, with the lowest value observed under T10 (100% N), indicating sulfur deficiency when S is not supplemented. Treatments receiving integrated nutrient management (T8) or balanced fertilization (T3, T4) showed moderate improvements in sulfur availability.

3.4.2 Zinc (mg kg^{-1})

The zinc content in soil was significantly influenced by the nutrient management practices (Figure 1). The highest available zinc concentration was observed in the treatment receiving 100% NPK + Zinc @ 25 kg $ZnSO_4$ ha^{-1} (T6), which recorded 0.68 mg kg^{-1}. This value was significantly higher than all other treatments. Other treatments, including those with balanced fertilization (T3: 100% NPK) and organic amendments (T8: 100% NPK + FYM), showed moderate Zn levels ranging between 0.55 and 0.57 mg kg^{-1}, which were statistically at par. The lowest zinc content (0.45 mg kg^{-1}) was found under T10 (100% N), indicating a depletion of micronutrients under imbalanced fertilization practices Meena *et al*., [23].

3.4.3 Boron (mg kg^{-1})

Boron content showed a significant increase in T7 (100% NPK + Boron @ 1 kg ha^{-1}), which recorded the highest B level (0.38 mg kg^{-1}), significantly higher than the rest. The next best treatment was T8 (0.33 mg kg^{-1}), indicating that organic inputs may also contribute to micronutrient availability. In contrast, the lowest B content (0.24 mg kg^{-1}) was observed in T10, again showing the adverse effect of nutrient omission on soil micronutrient status.

Table 2. Pooled data of seed yield, mustard equivalent yield, system productivity and sustainable yield index of Indian mustard under different fertility levels (2011-2021)

Treatments	Seed yield (kg ha^{-1})	Mustard Equivalent yield (kg ha^{-1})	System productivity (kg ha^{-1} day^{-1})	Sustainable yield index
T_1: Control	510	1606	5.3	0.28
T_2: 50% Recommended NPK	1037	2452	8	0.51
T_3: 100% Recommended NPK	1558	4597	151	0.72
T_4: 150% NPK	1870	5430	17.8	0.81
T_5: 100% NPK + Sulfur @ 40 kg ha^{-1}	1614	4956	16.2	0.76
T_6: 100% NPK + Zinc @ 25 kg $ZnSO_4$ ha^{-1}	1607	4831	15.8	0.76
T_7: 100% NPK + Boron @ 1 kg ha^{-1}	1543	4695	15.4	0.75
T_8: 100% NPK + FYM @ 2.5 t ha^{-1}	1737	5187	17	0.84
T_9: 100% NP	1159	3084	10.1	0.51
T_{10}: 100% N	814	2433	8	0.31
SEm (±)	48	132		
CD (P≤0.05)	136	391		

Table 3. Pooled data of gross return, net return and benefit-cost ratio of Indian mustard under different fertility levels (2011-2021)

Treatments	System Gross Return (Rs. ha^{-1})	System Net Return(Rs. ha^{-1})	B:C ratio
T_1: Control	71051	-14638	-0.17
T_2: 50% Recommended NPK	108486	19562	0.22
T_3: 100% Recommended NPK	203432	107815	1.13
T_4: 150% NPK	240263	141578	1.43
T_5: 100% NPK + Sulfur @ 40 kg ha^{-1}	219288	117671	1.16
T_6: 100% NPK + Zinc @ 25 kg $ZnSO_4$ ha^{-1}	213772	112155	1.1
T_7: 100% NPK + Boron @ 1 kg ha^{-1}	207739	110922	1.15
T_8: 100% NPK + FYM @ 2.5 t ha^{-1}	229510	123893	1.17
T_9: 100% NP	13645	43233	0.46
T_{10}: 100% N	107662	18616	0.21
SEm (±)	5827	5827	0.09
CD (P≤0.05)	17315	17315	0.28

Table 4. Effect of different fertility levels on organic carbon (SOC %), Available nitrogen, phosphorus and potassium (kg ha^{-1}) after mustard harvest soil (2011-2021)

Treatments	SOC %	Available N (kg ha^{-1})	Available P_2O_5 (kg ha^{-1})	Available K_2O (kg ha^{-1})
T_1: Control	0.31	129.62	18.88	61.87
T_2: 50% Recommended NPK	0.34	136.73	23.92	81.06
T_3: 100% Recommended NPK	0.35	149.27	24.16	99.36
T_4: 150% NPK	0.42	169.30	27.24	123.36
T_5: 100% NPK + Sulfur @ 40 kg ha^{-1}	0.39	139.30	25.34	98.92
T_6: 100% NPK + Zinc @ 25 kg $ZnSO_4$ ha^{-1}	0.38	144.26	24.42	97.61
T_7: 100% NPK + Boron @ 1 kg ha^{-1}	0.36	106.62	24.19	101.11
T_8: 100% NPK + FYM @ 2.5 t ha^{-1}	0.5	158.59	26.69	110.67
T_9: 100% NP	0.33	150.10	23.21	68.15
T_{10}: 100% N	0.33	141.27	21.22	64.89
SEm (±)	0.044	8.345	1.224	4.828
CD (P ≤0.05)	0.045	24.988	3.664	14.455
CV	7.103	10.143	8.859	9.219

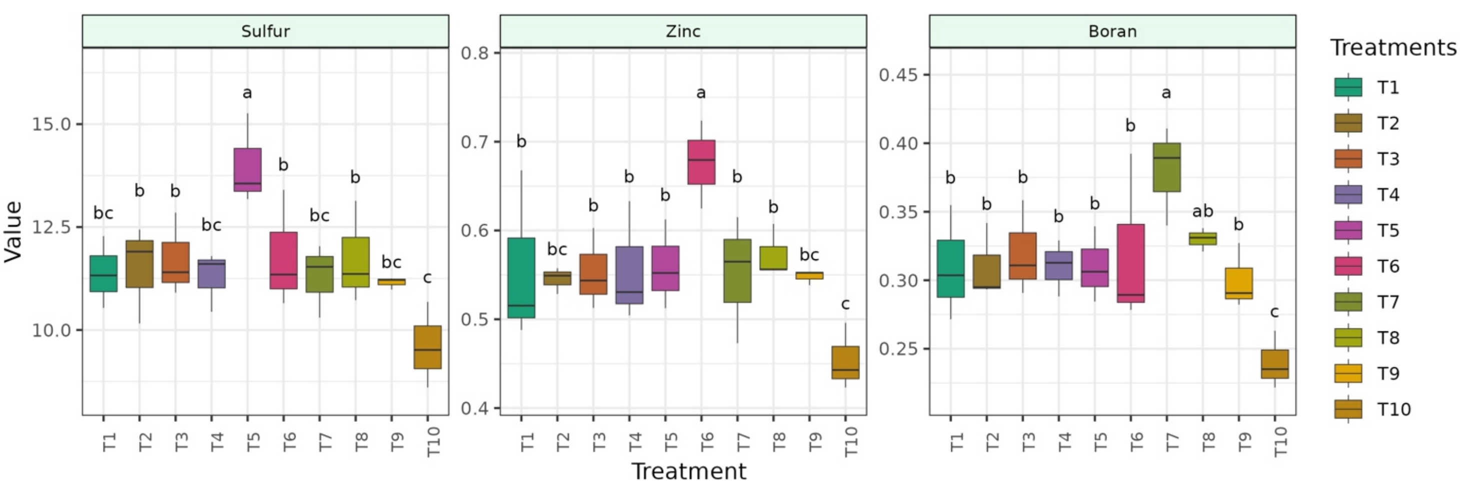

Fig. I Impact of different fertility levels on soil Available Sulphur (mg kg^{-1}), zinc (mg kg^{-1}) and Boran (mg kg^{-1}) after mustard harvest

Conclusion

This long-term study highlights the effectiveness of integrated nutrient management (INM) in enhancing mustard productivity and sustaining soil fertility in a rice–mustard system. The highest seed yield, system productivity and economic benefits were achieved with 150% NPK (T4), while 100% NPK + FYM (T8) was equally effective, showing superior improvements in soil organic carbon (0.50%) and nutrient availability. Inclusion of secondary and micronutrients (S, Zn, B) further enhanced crop performance and soil health, emphasizing the need for balanced fertilization. Overall, INM practices proved superior to sole chemical fertilizer use, offering a sustainable approach to improve yield, nutrient use efficiency and soil quality. Adopting INM in similar agro-ecological regions can support long-term productivity and resource conservation, ensuring the sustainability of intensive cropping systems.

Acknowledgement

Acknowledgements: The authors would like to thank the Department of Agronomy, Tirhut College of Agriculture (TCA), Dholi, Dr. Rajendra Prasad Central Agricultural University (RPCAU), Pusa, for hosting the long-term experiment in collaboration with AICRP- Mustard, ICAR- IIRMR- Sewar, Bharatpur, Rajasthan- 321303. We are grateful to the Indian Council of Agricultural Research (ICAR) for providing the necessary financial support to conduct the research work. We are also grateful to technical and field staff involved in maintaining the experiment from 2011 to 2021. Special appreciation is due to the laboratory staff for their assistance in soil and plant analysis.

Conflict of interest: The authors declare that they have no conflict of interest.

References

1. Ahlawat, I. P. S., Yadav, D. S., and Singh, S. (2021). Integrated nutrient management in oilseed-based cropping systems. *Indian Journal of Fertilisers*, 17(7), 602–608.

2. Arulmozhiselvan, K., Elayarajan, M., and Sathya, S. (2013). Effect of Long Term Fertilization and Manuring on Soil Fertility, Yield and Uptake by Finger Millet on Inceptisol. *Madras Agricultural Journal*, 100.

3. Bouman BAM. How much water does rice use? Rice Today. 2009; 8:28-29.

4. Choudhary, A., Sharma, R., and Singh, V. (2022). Effect of integrated nutrient management on sustainability and productivity in oilseed cropping systems. *Indian Journal of Agronomy*, 67(2), 145–150.

5. Das, T. K., Bhattacharyya, R., Sudhishri, S., Sharma, A. R., and Bandyopadhyay, K. K. (2014). Conservation agriculture in mustard-based cropping systems in India: a review. *International Journal of Agricultural Sustainability*, 12(4), 369–384. https://doi.org/10.1080/14735903.2014.916582

6. Choudhary, M., Meena, R. H., and Sahu, R. (2018). Effect of nutrient management on soil properties and crop productivity in mustard. *Annals of Agricultural Research*, 39(1), 55–61.

7. Deekshith H. N., Mankotia B. S., and Manuja S. 2023. " Napus)". *International Journal of Plant & Soil Science* 35 (19):1458-66. https://doi.org/10.9734/ijpss/2023/v35i183446.

8. Dwivedi, B. S., Shukla, A. K., Yadav, R. L., and Meena, M. C. (2003). Improving mustard productivity and soil health through integrated nutrient management in rice-based systems. *Fertiliser News*, 48(10), 45–54.

9. Food and Agriculture Organization of the United Nations (FAO). (2023). World Food and Agriculture – Statistical Yearbook 2023. Rome. https://doi.org/10.4060/cc8166en

10. Hanway, J.J. & Heidal, H. (1952). *Soil Analysis Methods as Used in Iowa State College Soil Testing Laboratory* [Iowa State College of Agriculture bulletin], Vol . 1–31.

11. Indiastat.com. https://www.indiastatagri.com/table/agriculture/area-production-productivity- Rice-indi/17372.

12. Indiastat.com. https://www.indiastatagri.com/table/agriculture/area-production-productivity- rapeseed-mustard-indi/17372.

13. Jackson, M.L. (1973). *Soil Chemical Analysis*. Prentice Hall of India, Pvt. Ltd, pp. 498–512.

14. John, M. K., Chuah, H. H., & Neufeld, J. H. (1975). Comparison of boron extraction methods from soils. *Soil Science*, 119(3), 228–236.

15. Kumar, S., Agrawal, S. Jilani, N., Kole, P., Kaur, G. and Mishra, A. (2023) Effect of integrated nutrient management practices on growth and productivity of rice: A review. *Pharma Innovation Journal*, 12(5):2648-2662.

16. Kumar, A., Verma, S., and Mishra, B. (2020). Effect of organics and inorganics on nutrient availability and yield of mustard. *Indian Journal of Agronomy*, 65(3), 365–370.

17. Kumar, S., Yadav, R. L., and Meena, R. K. (2020). Influence of organics and fertilizers on yield, quality and economics of Indian mustard (*Brassica juncea*). *Journal of Oilseed Brassica*, 11(1), 48–52.

18. Kumar, S., Yadav, R. L., and Meena, R. K. (2020). Influence of organics and fertilizers on yield, quality and economics of Indian mustard (*Brassica juncea*). *Journal of Oilseed Brassica*, 11(1), 48–52.

19. Lindsay, W. L., and Norvell, W. A. (1978). Development of a DTPA soil test for zinc, iron, manganese, and copper. *Soil Science Society of America Journal*, 42(3), 421–428.

20. Manna, M. C., Swarup, A., Wanjari, R. H., Ravankar, H. N., Mishra, B., Saha, M. N. and Sarap, P. A. (2005). Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. *Field crops research*, 93(2-3), 264-280.

21. Meena, A. L., Pandey, R. N., Kumar, D., Dotaniya, M. L., Sharma, V. K., Singh, G. and Bhanu, C. (2020). Impact of 12-year-long rice based organic farming on soil quality in terms of soil physical properties, available micronutrients and rice yield in a typic Ustochrept soil of India. *Communications in Soil Science and Plant Analysis*, 51(18), 2331-2348.

22. Meena, B. S., Narolia, R. S., Nagar, G., Meena, S. N. and Meena, D. S. (2022). Effect of sowing window, planting geometry and nutrient-management on yield, nutrient uptake and economics of Indian mustard in Vertisols of south-eastern Rajasthan. *Indian Journal of Agronomy*, 67(1), 50-57.

23. Meena, R. S., Yadav, R. L. and Singh, S. (2018). Long-term effect of nutrient management on productivity and soil fertility in mustard-based cropping systems. *Indian Journal of Agronomy*, 63(3), 297–302.

24. Ministry of Agriculture & Farmers Welfare. (n.d.). *National Mission on Edible Oils – Oil Palm (NMEO-OP)*. Government of India. https://nmeo.dac.gov.in

25. Mukhi, S.K., S.S. Sardar, N. Bar, and P.J. Mishra. 2024. Effect of Integrated Nutrient Management Practices on Growth, Yield, Quality and Economics of Indian Mustard (*Brassica Juncea* L.). *Journal of Experimental Agriculture International* 46 (11):405-13. https://doi.org/10.9734/jeai/2024/v46i113063.

26. Nayak, A., Maity, S. K. and Khanda, C. (2020). Improving N, P, K content, other properties of soil and system productivity through integrated nutrient management practices in SRI hybrid rice-mustard cropping sequence in Eastern India. *ORYZA-An International Journal on Rice*, 57(4), 296-301. [1]

27. Olsen, S.R., Cole, C.V., Watanabe, F.S. and Dean, L.A. (1954). *Estimation of Available Phosphorous in Soil by Extraction with Sodium Bicarbonate USDA*. circular no. 939.

28. Rai, S., Maurya, K.K., Kushwaha, S., Mishra, P., Nath, T and Singh, R. (2014). Response of Indian mustard (*Brassica juncea L.*) as influenced by different doses and sources of sulphur. *Plant Archives* 14 (2): 855-858.

29. Rathore, R. S., Meena, M. C. and Choudhary, A. K. (2019). Effect of nutrient management on system productivity and soil fertility in mustard-based cropping systems. *Journal of Oilseed Brassica*, 10(2), 118–122.

30. Sarkar, S., Dhar, A., Dey, S., Chatterjee, S. K., Mukherjee, S., Chakraborty, A. and Mainuddin, M. (2024). Natural and organic input-based integrated nutrient-management practices enhance the productivity and soil quality index of rice–mustard–green gram cropping system. *Land*, 13(11), 1933.

31. Sharma, P. K., Singh, D. K. and Lal, M. (2005). Effect of preceding rice crop management on mustard yield and soil fertility. *Journal of Oilseeds Research*, 22(1), 95–98.

32. Sharma, R. P., Verma, S. and Singh, A. (2019). Effect of integrated nutrient management on productivity and soil fertility under mustard-based cropping system. *Indian Journal of Agronomy*, 64(2), 179–184.

33. Sharma, S. D. and De Datta, S. K. (1985). Effects of puddling on soil physical properties and processes. In *Soils and Rice*. International Rice Research Institute, Los Baños, Philippines.

34. Shekhawat, K., Rathore, S. S., Premi, O. P., Kandpal, B. K. and Chauhan, J. S. (2012). Advances in Agronomic Management of Indian Mustard (*Brassica juncea*): An Overview. *International Journal of Agronomy*, 2012, 1–14.

35. Stigler S. Fisher and the 5% level. Chance. 2008;21(4):12-12.

36. Subbiah, B.V. and Asija, G.L. (1956) A rapid procedure for determination of available nitrogen in soils. *Current Science*, 25, 259–260.

37. Tekchand Chhaba, T. C., Devendra Singh, D. S., & Jat, B. L. (2017). Response of mustard to potassium in combination with other nutrients.

38. The Economic Times. https://economictimes indiatimes.com/news/ economy/ foreign-trade/indias-edible-oil-imports -dip-3-pc-to-159-6-lakh-tonnes-in-2023-24

39. Tiwari, K. N., Pathak, A. N. and Dwivedi, B. S. (2002). Research achievements on long-term fertilizer experiments in India. *Fertiliser News*, 47(4), 15–25.

40. Walkley, A. & Black, I.A. (1934) Estimation of organic carbon by chromic acid titration method. *Soil Science*, 37, 29–38. DOI: 10.1097/00010694-193401000-00003.

41. Williams, C. H. and Steinbergs, A. (1959). Soil sulphur fractions and their relationship to plant availability. *Australian Journal of Agricultural Research*, 10(2), 340–352. https://doi.org/10.1071/AR9590340

42. Yadav, R. L., Dwivedi, B. S., Pandey, P. S., Prasad, K. and Singh, R. M. (2000). Long-term effects of integrated nutrient management on soil properties and yield of rice–wheat system. *Indian Journal of Agronomy*, 45(1), 30–35.