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Soil Quality Index as a Predictor of Maize–Wheat System Productivity Under Long-Term Nutrient Management

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Abstract

The long-term effects of integrated nutrient management (INM) on crop performance and soil health—particularly within sub-humid environments—remain insufficiently explored. This research aimed to quantify the relationship between the soil quality index (SQI) and overall system productivity. The SQI represents a numerical indicator of soil functioning and its biological and chemical integrity, while system productivity reflects the economic yield generated by the cropping system. A long-term experiment initiated in 1972 formed the foundation for this study, which was conducted from 2019 to 2021 and included eleven nutrient management treatments. These comprised the following treatments: inorganic fertilizers alone (100% NPK, 150% NPK, 100% NP, 100% N, and 100% NPK without sulfur); combinations of organic and inorganic inputs (50% NPK + FYM and 100% NPK + FYM); lime with inorganic fertilizers (100% NPK + lime); zinc with inorganics (100% NPK + Zn); hand weeding with inorganics (100% NPK + HW); an unfertilized control. The study was implemented in a maize–wheat rotation under the sub-humid climatic conditions of Palampur, Himachal Pradesh, India. System productivity was estimated using wheat grain equivalent yield, and SQI values were generated from selected soil properties. These indicators—along with the sustainable yield index (SYI)—were applied to assess the effectiveness of each treatment. The results showed that the 100% NPK + FYM combination produced the highest SQI, followed by 100% NPK + lime, whereas the 100% N treatment yielded the lowest value. Overall, the findings highlight the crucial role of adopting sustainable nutrient management practices to maintain soil quality and optimize productivity in sub-humid agricultural systems.

Keywords: maize–wheat; long-term experiment; system productivity; soil quality; sustainable yield index



Academic Editor: Claude Hammecker

Received: 13 September 2025

Revised: 29 December 2025

Accepted: 9 January 2026

Published: 20 January 2026

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1. Introduction

Soil quality represents “the fitness of a specific kind of soil to function within its capacity and within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation” [1]. Soil quality assessment generally relies on physical, chemical, and biological indicators, and the interaction among these parameters reflects the complex functional state of the soil system [2]. Among the available evaluation approaches, the Soil Quality Index (SQI) has emerged as the most widely accepted method because it quantitatively integrates multiple soil attributes and can be applied across diverse soil types and management conditions [3,4]. SQI has been extensively used to assess the effects of agricultural practices [5] and crop production systems [6] on overall soil health [7], demonstrating its usefulness in comparing management strategies and identifying pathways for improvement. Consequently, employing SQI provides a scientific basis for guiding sustainable agricultural production [8].

The maize–wheat cropping system is one of the dominant cereal-based systems practiced in the Alfisols of the sub-humid Northwestern Himalayas, serving as a major source of food and income for farmers in the region [9]. However, the continuous cultivation of maize followed by wheat, without sufficient diversification, has led to gradual yield stagnation because of the exhaustive nature of this cereal–cereal sequence, which progressively depletes soil nutrients [10,11]. Several studies have shown that long-term reliance on chemical fertilizer application while neglecting organic inputs accelerates the depletion of soil organic matter [12–15], induces secondary and micronutrient deficiencies, and ultimately results in declining soil fertility [16] and crop productivity [17]. Compared to diversified or organically enriched fertilization systems used elsewhere, the prevalent fertilizer-dependent maize–wheat model in this region has limited resilience and reduced capacity to sustain soil health in the long run. Therefore, maintaining the health of cultivated soils has become critical to meet the rising food demand of an ever-increasing population [18].

Continuous cropping and associated management practices—such as the application of chemical fertilizers, manures, and soil amendments—have a strong influence on soil quality and the long-term sustainability of cropping systems [19,20]. Several studies have documented substantial adverse effects of imbalanced or fertilizer-dependent management on key soil properties, including soil aggregation, porosity, fertility, and biological activity [19]. Likewise, ref. [20] reported marked reductions in soil organic matter, deterioration of soil structure, and a decline in soil pH under continuous inorganic fertilization. In contrast, integrated nutrient management—through the combined use of chemical fertilizers with straw, manure, or increased rates of organic inputs—has shown strong restorative effects, resulting in 24.1–44.4% increases in soil organic carbon and 22.8–47.7% increases in total nitrogen in the upper 0–10 cm soil layer compared with fertilizer-only treatments [21]. Singh et al. (1990) [21] further demonstrated that substituting 30% of chemical fertilizers with straw and organic manure substantially enhanced soil quality by 12.6–56.9% and improved yield by 4.21–12.7%. These changes in soil properties highlight the necessity of using soil quality indicators to evaluate the impacts of contrasting management practices. In this context, the Sustainable Yield Index (SYI) provides an effective means of quantifying the long-term stability and sustainability of cropping systems based on actual yield performance over multiple years [21,22]. Additionally, the biological relevance of SQI as an evaluation tool is supported by its strong positive correlation with crop yield [23], and long-term fertilizer experiments remain a robust platform for assessing management-induced trends in soil health and productivity [24].

Long-term fertilizer experiments serve as an indispensable platform for understanding the complex interactions among soil, plants, climate, and management practices, and

for determining how these interactions influence yield sustainability over time [25,26]. Because changes in soil quality index values occur gradually, long-term trials provide the most reliable framework for assessing the relationship between soil properties and crop yield as management practices evolve. Evidence from such studies has been instrumental in formulating strategies aimed at maintaining soil quality while simultaneously enhancing crop productivity [17,24]. Researchers across diverse agroecosystems have already evaluated the soil quality index under long-term fertilization scenarios using multiple indexing approaches [27–31], highlighting the relevance and applicability of SQI as a decision-support tool. Building upon this scientific foundation, the present research integrates long-term soil and yield assessments to generate insights that can guide sustainable intensification of the maize–wheat system in the Alfisols of the Northwestern Himalayas.

Long-term field studies indicate that relying solely on chemical fertilizers or organic inputs is insufficient to maintain soil health or sustain crop yields over extended periods. Rather, integrating organic manures with mineral fertilizers has proven essential for enhancing soil productivity, improving system resilience, and lowering dependence on synthetic nutrient sources [32,33]. Despite the global recognition of integrated nutrient management as a balanced approach for sustaining soil fertility, limited information is available on how five decades of continuous cropping and fertilization influence soil quality and maize–wheat productivity in sub-humid Alfisols.

In light of the limited information available on long-term nutrient management effects, we hypothesized that decades of applying inorganic fertilizers together with farmyard manure (FYM) and lime would markedly enhance soil functional status and the productivity of the cropping system in this region. Accordingly, this study was structured to achieve the following goals:

- Investigate the principal physical, chemical, and biological characteristics of the soil;
- Determine the Sustainable Yield Index (SYI) and evaluate the productivity of the maize–wheat rotation; and
- Develop a soil quality index (SQI) after five decades of uninterrupted nutrient inputs involving fertilizers, FYM, and lime.

The distinct contribution of this research lies in its integration of the soil quality index with productivity outcomes in the maize–wheat system, enabling evaluation of management impacts under diverse nutrient regimes in sub-humid Alfisols. Establishing such linkages offers valuable predictive potential for estimating crop yields from soil quality dynamics, with applicability to comparable cropping systems and agro-ecological regions.

2. Materials and Methods

2.1. Experimental Site

A long-term experiment on the maize–wheat cropping system was initiated in 1972 as part of the All India Coordinated Research Project (AICRP) at the experimental farms of CSK Himachal Pradesh Krishi Vishwavidyalaya in Palampur. The study location is situated in a sub-humid belt of the Northwestern Himalayan region, at an elevation of about 1290 m, and geographically positioned at 32°6′ N latitude and 76°3′ E longitude. The climate of this region features moderately warm summers (March–June) and relatively cool winters (December–February).

Most of the annual precipitation is received from the southwest monsoon between June and September, with rainfall during the study period (2010–2021) fluctuating widely from 0 to 1229 mm (Figure 1). Over the experimental years, average monthly maximum temperatures ranged from 13.8 to 33.8 °C, whereas minimum temperatures varied between 3.0 and 20.7 °C (Figure 1). The experimental soil is classified within the Alfisol group, specifically as illitic Typic Hapludalfs.

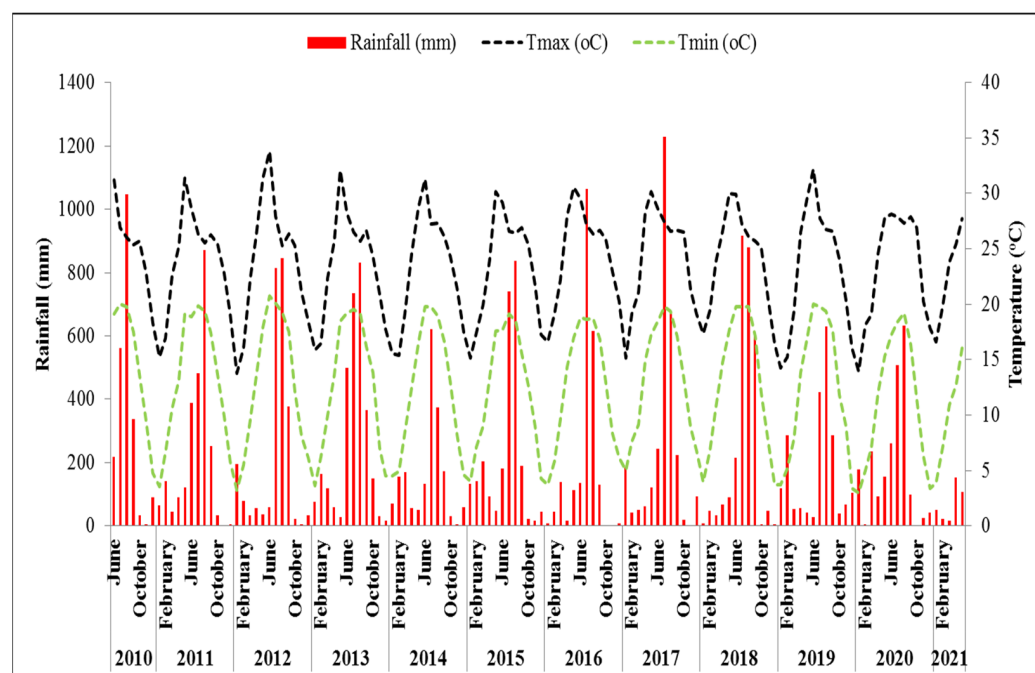


Figure 1. Monthly mean rainfall and maximum and minimum temperature at the experimental site from 2010 to 2021.

2.2. Experimental Design and Treatments

Initially, the long-term experiment included ten nutrient management treatments, which remained unchanged up to the 1980–81 cropping season. During the 1981 kharif season, a new treatment consisting of 100% NPK without sulfur was added, increasing the total number of treatments to eleven. All treatments were arranged in a randomized complete block design (RCBD) with three replications, resulting in 33 plots overall. Full details of the treatment structure are presented in Supplementary Materials, Table S1.

2.3. Agronomic Management of the Maize–Wheat System

The fertilizer rates used for the 100% NPK treatment followed the state’s recommended nutrient schedule, providing 120 kg N, 60 kg P, and 40 kg K per hectare for maize and 120 kg N, 60 kg P, and 30 kg K per hectare for wheat. As routine soil analyses showed a progressive buildup of available phosphorus, the P doses in both the 100% and 150% NPK treatments were reduced by 50%, and farmyard manure (FYM) was added to the 50% NPK treatment starting in June 2011. Throughout the experiment, urea, single superphosphate (SSP), and muriate of potash (MOP) were used as the respective sources of nitrogen, phosphorus, and potassium. In the sulfur-free treatment [100% NPK (–S)], diammonium phosphate (DAP) replaced SSP to assess the impact of P fertilization without sulfur.

FYM was applied only to the maize crop at a rate of 10 t ha^{−1} (dry basis), reflecting typical local agricultural practice. The manure contained 1.03% nitrogen, 0.47% phosphorus, and 0.85% potassium, in addition to 689 mg kg^{−1} Fe, 312 mg kg^{−1} Mn, 52 mg kg^{−1} Zn, and 23 mg kg^{−1} Cu. At sowing, the entire amounts of SSP and MOP, along with half of the urea, were incorporated into the soil. The remaining nitrogen was delivered as two topdressings—one at the knee-high and another at the pre-tasseling stage for maize, and similarly at maximum tillering and flowering for wheat.

Until 2011, zinc sulfate (ZnSO₄) was applied annually to both maize and wheat at 25 kg ha^{−1} in the 100% NPK + Zn treatment. Lime (finely ground CaCO₃, passed through a 100-mesh sieve) was supplied at 900 kg ha^{−1} to maize only under the 100% NPK + lime

treatment until 1979, aiming to maintain soil pH near 6.5. In later years, lime was reapplied only when soil pH declined below 6.3.

Maize and wheat were cultivated annually at the same experimental location from 1972 through 2021, with maize planted in June and wheat in November, completing 48 uninterrupted cropping cycles. The designated treatments were applied to the same plots each year for both crops to maintain consistency. Each experimental plot measured 15.0 m² (5.0 m × 3.0 m).

For maize, a single pre-sowing irrigation was provided, after which the crop's water needs were met almost entirely by ample rainfall throughout the growing season (Figure 1). Wheat, however, received supplemental irrigation from a tube well at key growth stages—crown root initiation, tillering, late jointing, flowering, and the dough stage.

Prior to planting, the soil was tilled to a depth of 0.15 m. Weed control in maize involved a pre-emergence application of atrazine at 1.125 kg ha⁻¹. A post-emergence herbicide, Vesta (Clodinafop Propargyl 15% + Metsulfuron Methyl 1% WP), was applied at 442.5 g ha⁻¹ in all plots except the 100% NPK + HW treatment, where weeds were removed manually and the biomass incorporated into the soil. Additionally, hand hoeing was performed 45 days after sowing.

At maturity, grain and biomass yields were recorded for both crops. Grain moisture was assessed after oven-drying the samples at 60 °C. Maize grain yields were adjusted to a standard moisture content of 15.5%, whereas stover yields were reported on an air-dry basis. For wheat, grain and straw yields were also expressed on an air-dry weight basis. The quantities of fertilizers and FYM supplied to maize and wheat under each treatment during the 2019–2021 seasons are presented in the Supplementary Materials, Table S2.

2.4. Initial Soil Status of the Experiment

At the outset of the experiment in 1972, the soil was moderately acidic, with a pH of 5.8. The baseline soil organic carbon (SOC) concentration measured 7.9 g kg⁻¹, and the available macronutrient levels were 736 kg ha⁻¹ of nitrogen (N), 12 kg ha⁻¹ of phosphorus (P), and 194.2 kg ha⁻¹ of potassium (K). Exchangeable calcium and magnesium were present at 5.30 and 1.30 cmol(p⁺) kg⁻¹, respectively. DTPA-extractable micronutrients were quantified as 26.0 mg kg⁻¹ Fe, 24.3 mg kg⁻¹ Mn, 1.9 mg kg⁻¹ Zn, and 0.4 mg kg⁻¹ Cu. The physical profile of the soil indicated a bulk density of 1.31 Mg m⁻³ and a porosity of 45.36% (Table 1).

Table 1. Initial Soil Status.

S. No.	Soil Characteristics	Values/Terminology
A.	Physical characteristics	
	Bulk density	1.31 Mg/m ³
	Porosity	45.36%
B.	Chemical characteristics	
	Soil pH	5.80
	Organic carbon (g kg ⁻¹)	7.90
	Available Nitrogen (kg ha ⁻¹)	736
	Available Phosphorus (kg ha ⁻¹)	12.0
	Available Potassium (kg ha ⁻¹)	194.20
	Exchangeable calcium (Ca) (c mol (p ⁺) kg ⁻¹)	5.30
	Exchangeable Magnesium (Mg) (c mol (p ⁺) kg ⁻¹)	1.30

2.5. Soil Sampling and Analysis

After the wheat crops were harvested in 2020 and 2021, soil samples were collected from each replicated plot at two depths: 0–0.15 m (surface) and 0.15–0.30 m (subsurface), using a core sampler for all eleven treatments. In each plot, four randomly selected sampling spots were chosen after clearing surface residues, and the soil retrieved from these points was combined to form a composite sample. The mixed soil was air-dried in the shade, gently crushed with a wooden pestle to break apart clods, and sieved through a 2 mm mesh. The resulting material was stored in labeled polyethylene bags for subsequent laboratory analyses.

For the assessment of mean weight diameter (MWD), aggregates retained between 4 mm and 8 mm mesh sizes were used. Additional soil samples for biological measurements were collected during the peak growth stage of the crop, transported promptly to the laboratory, and processed immediately to preserve microbial integrity.

A suite of standardized analytical procedures was used to measure soil physical, chemical, and biological characteristics. The bulk density of intact soil cores from the 0–0.15 m and 0.15–0.30 m layers was determined using the core sampling method [34]. Particle density and porosity were then calculated through conventional empirical relationships [35]. The water holding capacity (WHC) was quantified using Keen boxes [36], aggregate stability was expressed as mean weight diameter (MWD) measured via wet-sieving [37], and saturated hydraulic conductivity was determined following the constant-head approach [38].

Soil organic carbon was quantified using the dichromate oxidation technique [39]. Available nitrogen was measured using the alkaline KMnO_4 distillation method [40]. Phosphorus availability was assessed by extraction with Olsen's reagent [41] and subsequent colorimetric determination using the ascorbic acid procedure. Available sulfur was extracted with a 0.15% CaCl_2 solution, and turbidity readings were taken spectrophotometrically [42]. Ammonium acetate (neutral 1N) was used to extract exchangeable Ca and available K, and both were analyzed with a flame photometer [43].

Microbial biomass carbon (MBC) and nitrogen (MBN) were estimated using the chloroform fumigation–extraction method [44], incorporating correction coefficients of $K_c = 0.45$ for MBC [45] and $K_c = 0.54$ for MBN [46]. Dehydrogenase activity (DHA) was measured based on the reduction of triphenyl tetrazolium chloride to triphenyl formazan [47]. All biological measurements were expressed on an oven-dry soil weight basis.

2.6. Sustainability Yield Index

The sustainability yield index was computed using the method given below:

$$SYI = \frac{\bar{Y} - \sigma}{Y_{\max}} \quad (1)$$

where $\bar{Y}$ = average yield of a treatment, σ = treatment standard deviation, and $Y_{\max}$ = maximum yield in the experiment from 2010 to 2021 [48].

2.7. System Productivity

System productivity was calculated as wheat grain equivalent yield using the following formula:

$$\text{System productivity} = \frac{\{\text{Maize grain yield (kg ha}^{-1}) \times (\text{Price of maize})\}}{\text{Price of wheat}} + \text{wheat grain yield (kg ha}^{-1}) \quad (2)$$

2.8. Multivariate Analysis and Soil Quality Index

Principal component analysis (PCA) was applied to determine the minimum dataset (MDS) and to construct a statistically derived soil quality index (SQI). Variables

were retained in the MDS when the principal components they loaded onto satisfied three conditions: (i) an eigenvalue exceeding 1, (ii) an explanatory contribution of at least 5% to total variance, and (iii) high factor loadings for the respective soil indicators [49].

Following the selection of MDS variables, each parameter was transformed using linear scoring functions so that all values fell within a standardized range of 0 to 1. These normalized scores were then integrated into a composite soil index through a weighted additive method [50].

The weighting assigned to each principal component was calculated by expressing the variance explained by that component as a proportion of the cumulative variance of all components included in the MDS. Using these weights, the soil quality index was computed according to the formula shown below:

$$SQI = \sum_{i=1}^n (W_i \times S_i) \quad (3)$$

In this equation, W_n is the PCA-derived weight for each soil parameter, and S_n is the corresponding normalized score. Productivity trends for the maize–wheat system from 2010 to 2021 were used to determine system-level output. The validity of the SQI was further tested by correlating it with system productivity and the Sustainable Yield Index (SYI).

2.9. Statistical Analysis

The experimental data were subjected to an analysis of variance (ANOVA) within a randomized block design (RBD) structure [51]. In this model, the factors “year” and “treatment” were considered fixed, while replicates served as random effects. Comparisons among treatment means were performed using Duncan’s Multiple Range Test (DMRT) at the 0.05 significance level, implemented through the OPSTAT statistical software [52].

To investigate relationships among soil quality indicators, system productivity, SQI, and SYI, a stepwise Pearson correlation matrix was generated using R Studio (version 4.2.2; R Core Team, 2019). Graphical outputs were developed using the base plotting functions in R together with the ggplot2 visualization package [53].

3. Results

3.1. Physical Soil Quality Parameters

Across the 2019–2021 observation period, surface soil bulk density (0–0.15 m) varied from 1.16 to 1.43 Mg m^{−3} depending on the nutrient management treatment. Following 48 consecutive cropping cycles, a notable decline in bulk density relative to the initial value of 1.31 Mg m^{−3} was observed in all treatments except 100% NP, 100% N, 100% NPK (−S), and the unfertilized control (Table 2). The greatest improvement occurred under integrated nutrient management, where the combination of FYM with mineral fertilizers (100% NPK + FYM) resulted in approximately a 15% reduction in bulk density compared with the control.

Table 2. Effect of 48 years of integrated nutrient management on physical properties of soil (0–0.15 and 0.15–0.30 m depths) after the harvest of wheat 2020 and 2021.

Treatment	Bulk Density (Mg m ^{−3})				Particle Density (Mg m ^{−3})				Porosity (%)			
	0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
50% NPK + FYM	1.29 ^{def}	1.26 ^e	1.31 ^{cde}	1.29 ^{de}	2.39 ^{ns}	2.39 ^{ns}	2.40 ^{ns}	2.41 ^{ns}	46.58 ^{bc}	47.57 ^c	45.42 ^c	46.81 ^{bc}
100% NPK	1.28 ^{ef}	1.29 ^{cd}	1.30 ^{de}	1.30 ^{cd}	2.40 ^{ns}	2.41 ^{ns}	2.42 ^{ns}	2.41 ^{ns}	46.36 ^{bc}	46.07 ^{de}	45.59 ^c	45.94 ^{cd}

Table 2. Cont.

Treatment	Bulk Density (Mg m ⁻³)				Particle Density (Mg m ⁻³)				Porosity (%)			
	0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
150% NPK	1.30 ^{de}	1.28 ^{de}	1.32 ^{cd}	1.31 ^{bc}	2.43 ^{ns}	2.40 ^{ns}	2.44 ^{ns}	2.42 ^{ns}	46.49 ^{bc}	46.51 ^{cde}	45.11 ^c	45.86 ^{cd}
100% NPK + HW	1.24 ^g	1.22 ^f	1.25 ^{fg}	1.26 ^{ef}	2.39 ^{ns}	2.39 ^{ns}	2.40 ^{ns}	2.41 ^{ns}	48.07 ^b	48.81 ^b	48.09 ^{ab}	47.56 ^{ab}
100% NPK + Zn	1.26 ^{fg}	1.28 ^{de}	1.28 ^{ef}	1.29 ^{de}	2.4 ^{ns}	2.42 ^{ns}	2.42 ^{ns}	2.43 ^{ns}	47.71 ^b	47.09 ^{cd}	47.81 ^{ab}	46.59 ^{bc}
100% NP	1.33 ^c	1.32 ^c	1.35 ^c	1.34 ^b	2.42 ^{ns}	2.42 ^{ns}	2.44 ^{ns}	2.43 ^{ns}	44.99 ^{cd}	45.47 ^e	44.30 ^{cd}	44.91 ^d
100% N	1.42 ^a	1.43 ^a	1.45 ^a	1.43 ^a	2.43 ^{ns}	2.42 ^{ns}	2.44 ^{ns}	2.43 ^{ns}	41.56 ^e	40.89 ^g	41.40 ^e	41.29 ^f
100% NPK + FYM	1.16 ^h	1.18 ^g	1.23 ^g	1.24 ^f	2.38 ^{ns}	2.39 ^{ns}	2.41 ^{ns}	2.41 ^{ns}	51.11 ^a	50.69 ^a	48.60 ^a	48.34 ^a
100% NPK (–S)	1.31 ^{cd}	1.30 ^{cd}	1.33 ^{cd}	1.32 ^{bc}	2.41 ^{ns}	2.40 ^{ns}	2.42 ^{ns}	2.42 ^{ns}	45.46 ^{cd}	46.17 ^{de}	45.44 ^c	45.23 ^d
100% NPK + lime	1.25 ^g	1.23 ^f	1.26 ^{fg}	1.25 ^f	2.39 ^{ns}	2.40 ^{ns}	2.41 ^{ns}	2.42 ^{ns}	47.84 ^b	48.83 ^b	47.05 ^b	48.19 ^a
Control	1.38 ^b	1.37 ^b	1.41 ^b	1.41 ^a	2.43 ^{ns}	2.44 ^{ns}	2.44 ^{ns}	2.45 ^{ns}	43.43 ^{de}	43.98 ^f	43.20 ^d	42.64 ^e
Initial status (1972)	1.31		-		2.44		-		45.36		-	

Values followed by different letter(s) differ significantly at $p < 0.05$ as per Duncan's multiple range test (DMRT); ns = non-significant at $p \leq 0.05$.

Throughout the experiment, particle density in the 0–0.15 m layer remained within the narrow range of 2.38–2.44 Mg m⁻³ (Table 2), and differences among treatments were statistically non-significant in both years. Soil porosity, however, was markedly improved under all nutrient management treatments compared with 100% N and the control plots. In the surface soil, the 100% NPK + FYM treatment enhanced porosity by 17.7% in 2020 and 15.3% in 2021 relative to the control (Table 2).

In the upper soil layer (0–0.15 m), water holding capacity (WHC) varied widely, from a minimum of 50.72% under the 100% N treatment to a maximum of 63.32% with the 100% NPK + FYM treatment (Table 3). Saturated hydraulic conductivity (SHC) in this layer also improved markedly, increasing by 111.7% with 100% NPK + FYM, by 60.5% with 100% NPK + lime, and by 39.4% under the 100% NPK + HW treatment when compared with the control (Table 3). Among all treatments, 100% NPK + FYM produced the highest SHC values, significantly surpassing the others. Mean weight diameter (MWD) of aggregates in the surface soil ranged from 0.96 to 4.65 mm across the two-year assessment period (Table 3). The 100% N treatment, which excluded P and K for nearly five decades, recorded the smallest MWD, while the 100% NPK + FYM treatment achieved the largest aggregate size. At the 0.15–0.30 m depth, bulk density increased and porosity, WHC, SHC, and MWD all declined; however, the overall pattern of treatment effects remained consistent with those observed in the topsoil (Tables 2 and 3).

Table 3. Effect of 48 years of integrated nutrient management on physical properties of soil (0–0.15 and 0.15–0.30 m depths) after the harvest of wheat 2020 and 2021.

Treatment	Water Holding Capacity (%)				Mean Weight Diameter (mm)				Saturated Hydraulic Conductivity (cm h ⁻¹)			
	0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
50% NPK + FYM	58.38 ^c	58.36 ^c	55.12 ^d	55.10 ^{de}	1.67 ^e	1.69 ^e	1.53 ^e	1.56 ^e	3.23 ^e	3.27 ^e	3.15 ^d	2.83 ^{ef}
100% NPK	58.21 ^c	58.14 ^c	56.77 ^c	56.70 ^{cd}	1.92 ^d	1.91 ^d	1.84 ^d	1.81 ^d	3.40 ^{cde}	3.35 ^{de}	3.33 ^{cd}	3.13 ^d
150% NPK	56.90 ^{cd}	56.85 ^{cd}	54.70 ^{de}	54.73 ^{def}	1.55 ^f	1.58 ^{ef}	1.41 ^e	1.43 ^g	3.41 ^{cde}	3.39 ^{cde}	3.27 ^{cd}	3.24 ^{cd}
100% NPK + HW	62.54 ^{ab}	62.44 ^{ab}	59.64 ^b	59.65 ^{ab}	2.25 ^c	2.26 ^c	2.07 ^c	2.09 ^c	3.55 ^c	3.59 ^c	3.41 ^c	3.07 ^{de}
100% NPK + Zn	56.41 ^{de}	56.38 ^{de}	52.32 ^f	52.23 ^f	1.65 ^{ef}	1.62 ^{ef}	1.47 ^e	1.45 ^{efg}	3.34 ^{de}	3.38 ^{cde}	3.24 ^{cd}	3.40 ^c
100% NP	55.10 ^e	55.14 ^e	53.37 ^{ef}	53.34 ^{ef}	1.56 ^{ef}	1.57 ^f	1.52 ^e	1.54 ^{ef}	2.82 ^f	2.80 ^f	2.56 ^e	2.58 ^{gh}
100% N	50.72 ^f	50.75 ^f	46.23 ^g	49.19 ^g	0.98 ^g	0.96 ^h	0.69 ^g	0.66 ⁱ	2.68 ^{fg}	2.65 ^{fg}	2.49 ^e	2.46 ^h
100% NPK + FYM	63.32 ^a	63.28 ^a	61.32 ^a	61.29 ^a	4.65 ^a	4.61 ^a	3.62 ^a	3.65 ^a	5.42 ^a	5.41 ^a	4.36 ^a	4.38 ^a
100% NPK (–S)	56.31 ^{de}	56.35 ^{de}	54.70 ^{de}	54.69 ^{def}	1.62 ^{ef}	1.65 ^{ef}	1.45 ^e	1.44 ^{fg}	3.54 ^{cd}	3.51 ^{cd}	3.11 ^d	3.19 ^{cd}

Table 3. Cont.

Treatment	Water Holding Capacity (%)				Mean Weight Diameter (mm)				Saturated Hydraulic Conductivity (cm h ⁻¹)			
	0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
100% NPK + lime	61.43 ^b	61.40 ^b	58.43 ^b	58.41 ^{bc}	3.67 ^b	3.63 ^b	3.01 ^b	3.07 ^b	4.10 ^b	4.12 ^b	3.84 ^b	3.87 ^b
Control	51.30 ^f	51.12 ^f	47.69 ^g	46.65 ^g	1.02 ^g	1.10 ^g	0.92 ^f	0.95 ^h	2.55 ^g	2.57 ^g	2.50 ^e	2.78 ^{fg}
Initial status (2019)	53.35		48.36		1.84		1.06		2.84		2.72	

Values followed by different letter(s) differ significantly at $p < 0.05$ as per Duncan's multiple range test (DMRT).

3.2. Chemical Soil Quality Parameters

With the exception of the 100% NPK + lime (pH 6.19) and 100% NPK + FYM (pH 5.81) treatments, all other nutrient management practices resulted in a significant decline in soil pH compared with the initial value of 5.80 (Table 4). The most pronounced acidification occurred under the 100% N treatment, where pH dropped to 4.40.

Table 4. Effect of 48 years of integrated nutrient management on chemical properties of soil (0–0.15 and 0.15–0.30 m depths) after the harvest of wheat 2020 and 2021.

Treatment	pH				OC (g kg ⁻¹)				CEC {cmol(p ⁺) kg ⁻¹ }			
	0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
50% NPK + FYM	5.26 ^{cd}	5.24 ^{de}	5.36 ^{cd}	5.38 ^{cd}	10.63 ^{cd}	10.68 ^{cd}	7.64 ^c	7.67 ^c	10.43 ^c	10.44 ^c	9.42 ^c	9.46 ^c
100% NPK	5.22 ^{cd}	5.20 ^{ef}	5.28 ^{cd}	5.31 ^{cd}	10.40 ^{de}	10.45 ^{de}	7.47 ^{cd}	7.50 ^c	10.30 ^c	10.28 ^c	9.33 ^c	9.34 ^c
150% NPK	4.84 ^e	4.80 ^g	5.03 ^d	5.10 ^d	9.95 ^{ef}	9.91 ^{ef}	7.51 ^{cd}	7.56 ^c	10.26 ^c	10.22 ^c	9.17 ^c	9.15 ^c
100% NPK + HW	5.35 ^{cd}	5.39 ^c	5.38 ^c	5.40 ^{cd}	11.67 ^b	11.70 ^b	8.32 ^b	8.40 ^b	11.40 ^b	11.43 ^b	10.23 ^b	10.28 ^b
100% NPK + Zn	5.21 ^{cd}	5.21 ^{def}	5.27 ^{cd}	5.34 ^{cd}	9.67 ^f	9.59 ^f	7.24 ^d	7.26 ^c	10.22 ^c	10.18 ^c	8.22 ^d	8.21 ^d
100% NP	5.16 ^d	5.10 ^f	5.24 ^{cd}	5.21 ^{cd}	9.70 ^f	9.68 ^f	6.49 ^e	6.50 ^d	10.09 ^c	9.04 ^e	7.47 ^e	7.44 ^e
100% N	4.44 ^f	4.40 ^h	4.47 ^e	4.45 ^e	8.43 ^g	8.40 ^g	6.11 ^f	6.13 ^d	6.28 ^f	6.26 ^g	5.89 ^f	5.87 ^f
100% NPK + FYM	5.79 ^b	5.81 ^b	5.82 ^b	5.85 ^b	13.90 ^a	13.98 ^a	9.30 ^a	9.37 ^a	12.51 ^a	12.58 ^a	11.13 ^a	11.19 ^a
100% NPK (–S)	5.18 ^d	5.17 ^{ef}	5.20 ^{cd}	5.24 ^{cd}	9.62 ^f	9.71 ^f	6.43 ^e	6.40 ^d	9.50 ^d	9.46 ^d	8.30 ^d	8.25 ^d
100% NPK + lime	6.22 ^a	6.25 ^a	6.26 ^a	6.28 ^a	11.28 ^{bc}	11.30 ^{bc}	7.56 ^c	7.52 ^c	12.39 ^a	12.41 ^a	10.75 ^a	10.79 ^{ab}
Control	5.39 ^c	5.33 ^{cd}	5.49 ^{bc}	5.50 ^c	8.23 ^g	8.19 ^g	6.13 ^f	6.10 ^d	8.52 ^e	8.50 ^f	6.26 ^f	6.23 ^f
Initial status (1972)	5.80		–		7.90		–		12.1		–	

Values followed by different letter(s) differ significantly at $p < 0.05$ as per Duncan's multiple range test (DMRT).

Soil organic carbon (SOC) increased across all treatments relative to the base-line level of 7.90 g kg⁻¹ (Table 4). The integrated application of fertilizers and FYM (100% NPK + FYM) produced the greatest improvement, raising SOC by approximately 34% over the 100% NPK treatment. Manual weed removal (100% NPK + HW) also enhanced SOC significantly—around 12% higher than under chemical weed control (100% NPK).

Cation exchange capacity (CEC) generally declined from the initial value of 12.1 cmol(p⁺) kg⁻¹, except in the 100% NPK + FYM and 100% NPK + lime treatments, both of which showed increases (Table 4). Relative to 100% NPK, CEC improved by 22.37% in the FYM-amended plots and by 20.72% with lime application. In contrast, substantial reductions in CEC were recorded in the control, 100% N, 100% NP, and 100% NPK (–S) treatments, where values decreased by 29.8%, 48.3%, 25.3%, and 21.8%, respectively, compared with the initial measurement.

The available N, P, and K contents were significantly influenced by various nutrient management practices (Table 5). After the 48th cropping cycle of maize–wheat, the available N in soil increased by 34.6% in 100% NPK, 40.5% in 150% NPK, 38.7% in 100% NPK + HW, and 47.6% in 100% NPK + FYM treatments compared to the control. After 48 cycles of maize–wheat, the available N content in control plots declined by 63.4% compared to its initial value (736 kg ha⁻¹). Long term application of P fertilizers increased the available

P content in soil well above its initial value (12 kg ha^{-1}). The build-up in available P increased with increasing doses of P. After the completion of 48th cropping cycle of maize–wheat, the available P content in soil increased by 567.6% in 100% NPK, 1214.4% in 100% NPK + FYM and 1299.0% in 150% NPK treatment, in comparison to the control. Except 100% NPK + FYM treatment, there was a significant reduction in the available K content in soil under all the treatments from its initial level (194 kg ha^{-1}). In comparison to its initial value, the available K content in soil decreased by 40.7, 35.6 and 38.1% in control, 100% NP and 100% N plots, respectively. Compared to the control, the 150% NPK and 100% NPK + FYM treatments recorded 56.5 and 77.4% higher available K content.

Table 5. Effect of 48 years of integrated nutrient management on chemical properties of soil (0–0.15 and 0.15–0.30 m depths) after the harvest of wheat 2020 and 2021.

Treatment	Available N (kg ha^{-1})				Available P (kg ha^{-1})				Available K (kg ha^{-1})			
	0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
50% NPK + FYM	358 ^{cde}	356 ^{cd}	249 ^{def}	243 ^{fg}	57.6 ^h	58.4 ^g	42.6 ^h	43.8 ^g	151 ^e	147 ^d	138 ^d	135 ^f
100% NPK	367 ^{bcd}	362 ^{bcd}	256 ^{cde}	250 ^{ef}	73.0 ^g	74.1 ^f	64.1 ^g	67.1 ^f	163 ^d	161 ^c	148 ^c	144 ^{ef}
150% NPK	375 ^{bc}	373 ^{bc}	271 ^b	279 ^b	157.0 ^a	155.3 ^a	136.5 ^a	138.8 ^a	182 ^b	180 ^b	164 ^b	158 ^{bc}
100% NPK + HW	371 ^{ab}	378 ^{ab}	268 ^{bc}	275 ^{bc}	88.6 ^e	86.7 ^e	73.8 ^e	77.3 ^e	164 ^{cd}	161 ^c	145 ^{cd}	147 ^{de}
100% NPK + Zn	362 ^{bcd}	355 ^{cd}	260 ^{bcd}	252 ^{def}	81.4 ^f	79.8 ^{ef}	70.9 ^{ef}	73.2 ^e	173 ^{bcd}	176 ^b	141 ^{cd}	144 ^{ef}
100% NP	351 ^e	352 ^{de}	235 ^f	232 ^g	103.4 ^d	104.4 ^d	91.8 ^d	94.1 ^d	127 ^f	125 ^e	109 ^e	105 ^g
100% N	333 ^f	335 ^e	245 ^{ef}	256 ^{de}	14.4 ⁱ	13.6 ^h	6.9 ⁱ	7.1 ^h	126 ^f	120 ^e	108 ^e	100 ^g
100% NPK + FYM	390 ^a	397 ^a	308 ^a	315 ^a	146.8 ^b	145.9 ^b	122.3 ^b	124.3 ^b	202 ^a	204 ^a	174 ^a	179 ^a
100% NPK (–S)	352 ^{de}	356 ^{cd}	265 ^{bc}	263 ^{cd}	130.5 ^c	133.1 ^c	99.4 ^c	104.2 ^c	173 ^{bc}	178 ^b	158 ^b	154 ^{cd}
100% NPK + lime	359 ^{bcd}	358 ^{cd}	270 ^{bc}	272 ^{bc}	79.0 ^f	75.4 ^f	67.6 ^{fg}	65.7 ^f	168 ^{cd}	164 ^c	162 ^b	167 ^b
Control	272 ^g	269 ^f	179 ^g	177 ^h	11.9 ⁱ	11.1 ^h	6.7 ⁱ	7.0 ^h	119 ^f	115 ^e	101 ^e	97 ^g
Initial status (1972)	736		–		12.0		–		194		–	

Values followed by different letter(s) differ significantly at $p < 0.05$ as per Duncan's multiple range test (DMRT).

A clear sulfur deficiency appeared in the control, 100% N, and 100% NPK (–S) treatments, as neither crop received any supplemental S in these plots (Table 6). Conversely, treatments that supplied sulfur-containing inputs showed marked increases in available S, with the 150% NPK and 100% NPK + FYM treatments exhibiting increases of 167.8% and 149.6%, respectively, compared with the control.

Table 6. Effect of 48 years of integrated nutrient management on chemical properties of soil (0–0.15 and 0.15–0.30 m depths) after the harvest of wheat 2020 and 2021.

Treatment	Available S (kg ha^{-1})				Exchangeable Ca ($\text{cmol(p}^+) \text{ kg}^{-1}$)				Exchangeable Mg ($\text{cmol(p}^+) \text{ kg}^{-1}$)			
	0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
50% NPK + FYM	27.8 ^{cd}	28.1 ^{cde}	22.7 ^e	23.0 ^e	3.08 ^{cd}	3.09 ^{cd}	2.55 ^d	2.59 ^d	0.44 ^c	0.45 ^c	0.29 ^c	0.30 ^c
100% NPK	28.5 ^c	28.9 ^{cd}	25.9 ^c	26.1 ^c	3.06 ^{cd}	3.04 ^{cd}	2.71 ^c	2.69 ^{cd}	0.33 ^d	0.30 ^d	0.25 ^c	0.23 ^{de}
150% NPK	37.9 ^a	38.3 ^a	31.3 ^a	31.5 ^a	3.21 ^c	3.17 ^c	2.76 ^c	2.73 ^{cd}	0.24 ^{ef}	0.22 ^{ef}	0.20 ^d	0.19 ^{def}
100% NPK + HW	28.8 ^c	29.5 ^c	24.2 ^d	24.5 ^d	3.11 ^{cd}	3.15 ^c	2.78 ^c	2.80 ^c	0.43 ^c	0.46 ^c	0.37 ^b	0.39 ^b
100% NPK + Zn	27.6 ^{cd}	27.9 ^{de}	23.7 ^{de}	23.8 ^{de}	2.79 ^{de}	2.82 ^{de}	2.40 ^{de}	2.39 ^e	0.32 ^d	0.30 ^d	0.27 ^c	0.24 ^{cd}
100% NP	26.8 ^d	26.9 ^e	24.5 ^d	24.8 ^d	2.56 ^e	2.59 ^e	2.30 ^e	2.28 ^e	0.28 ^{de}	0.25 ^{de}	0.19 ^d	0.17 ^{efg}
100% N	16.2 ^e	16.0 ^f	13.2 ^{fg}	13.0 ^{fg}	1.47 ^g	1.45 ^g	1.26 ^g	1.22 ^g	0.16 ^g	0.17 ^f	0.10 ^e	0.11 ^g
100% NPK + FYM	35.2 ^b	35.7 ^b	29.4 ^b	29.7 ^b	4.08 ^b	4.12 ^b	3.24 ^b	3.28 ^b	0.73 ^a	0.75 ^a	0.49 ^a	0.52 ^a
100% NPK (–S)	16.4 ^e	16.2 ^f	13.8 ^f	13.5 ^f	2.13 ^f	2.16 ^f	1.61 ^f	1.59 ^f	0.25 ^{ef}	0.24 ^{def}	0.11 ^e	0.12 ^g
100% NPK + lime	27.8 ^{cd}	27.2 ^e	24.5 ^d	24.2 ^{de}	4.94 ^a	4.97 ^a	3.87 ^a	3.90 ^a	0.62 ^b	0.65 ^b	0.38 ^b	0.41 ^b

Table 6. Cont.

Treatment	Available S (kg ha ⁻¹)				Exchangeable Ca (cmol(p ⁺) kg ⁻¹)				Exchangeable Mg (cmol(p ⁺) kg ⁻¹)			
	0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
Control	14.2 ^f	14.3 ^g	12.2 ^g	12.0 ^g	1.96 ^f	1.92 ^f	1.37 ^g	1.34 ^g	0.21 ^{fg}	0.20 ^{ef}	0.16 ^d	0.14 ^{fg}
Initial status (1972)	23.6		-		5.30		-		1.30		-	

Values followed by different letter(s) differ significantly at $p < 0.05$ as per Duncan's multiple range test (DMRT).

Exchangeable calcium levels declined across all treatments relative to the initial baseline of 5.30 cmol(p⁺) kg⁻¹ (Table 6). Nevertheless, in comparison with the 100% NPK treatment, the incorporation of FYM elevated exchangeable Ca by 35.5%, while lime addition produced an even greater increase of 63.5%. Exchangeable magnesium displayed its lowest value under the 100% N treatment and its highest under 100% NPK + FYM (Table 6). Although Mg levels dropped below the initial 1.30 cmol(p⁺) kg⁻¹ across all treatments, the reductions were notably smaller where FYM or lime had been applied.

At the subsurface layer (0.15–0.30 m), soil pH rose slightly, whereas SOC, CEC, available N, P, K, S, and exchangeable Ca and Mg all declined. Nevertheless, the overall pattern of treatment responses at this depth closely mirrored those observed in the topsoil (Tables 4–6).

3.3. Biological Soil Quality Parameters

After 48 continuous crop cycles, microbial biomass carbon (MBC) values ranged between 180 and 685 mg kg⁻¹, microbial biomass nitrogen (MBN) ranged from 10.61 to 24.94 mg kg⁻¹, and dehydrogenase activity (DHA) varied from 13.90 to 44.20 µg TPF g⁻¹ 24 h⁻¹ across all treatments (Table 7). The most pronounced enhancements in these biological indicators occurred under the integrated nutrient management treatments—specifically 100% NPK + HW, 100% NPK + FYM, and 100% NPK + lime. When compared with the control, these three treatments boosted MBC by 99.3%, 141.2%, and 124.6%; increased MBN by 87.4%, 135.1%, and 115.6%; and raised DHA by 104.4%, 119.7%, and 101.8%, respectively.

Table 7. Effect of 48 years of integrated nutrient management on biological properties of soil (0–0.15 and 0.15–0.30 m depths) after the harvest of wheat 2020 and 2021.

Treatment	Microbial Biomass Carbon (mg kg ⁻¹)				Microbial Biomass Nitrogen (mg kg ⁻¹)				Dehydrogenase Activity (µg TPF g ⁻¹ Soil Per 24 h)			
	0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m		0–0.15 m		0.15–0.30 m	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
50% NPK + FYM	383 ^f	381 ^g	273 ^f	277 ^f	14.87 ^f	14.60 ^f	12.07 ^{fg}	12.10 ^f	29.86 ^e	28.96 ^e	25.16 ^e	25.22 ^d
100% NPK	494 ^d	497 ^d	448 ^d	449 ^d	18.81 ^d	18.75 ^d	15.06 ^{de}	15.11 ^{de}	38.71 ^{cd}	38.80 ^{cd}	33.78 ^d	33.84 ^c
150% NPK	455 ^e	454 ^e	402 ^e	401 ^e	20.17 ^c	20.21 ^c	16.86 ^{bc}	16.81 ^{bc}	26.78 ^f	26.84 ^f	21.59 ^f	21.61 ^{ef}
100% NPK + HW	563 ^c	566 ^c	527 ^c	529 ^c	19.87 ^c	19.88 ^{cd}	15.98 ^{cd}	16.00 ^{cd}	40.93 ^b	41.12 ^b	35.47 ^c	35.55 ^b
100% NPK + Zn	431 ^e	433 ^f	391 ^e	395 ^e	17.16 ^e	17.27 ^e	14.82 ^e	14.89 ^e	37.89 ^d	37.92 ^d	32.60 ^d	32.65 ^c
100% NP	291 ^g	290 ^h	248 ^g	248 ^g	14.09 ^f	14.16 ^f	12.78 ^f	12.72 ^f	29.85 ^e	29.90 ^e	22.77 ^f	22.79 ^e
100% N	179 ^h	180 ⁱ	151 ^h	150 ^h	12.18 ^g	12.15 ^g	11.61 ^g	11.70 ^f	13.94 ⁱ	13.90 ⁱ	9.73 ^h	9.78 ^h
100% NPK + FYM	687 ^a	685 ^a	630 ^a	631 ^a	24.99 ^a	24.94 ^a	18.27 ^a	18.32 ^a	44.17 ^a	44.20 ^a	39.62 ^a	39.68 ^a
100% NPK (–S)	453 ^e	450 ^{ef}	380 ^e	376 ^e	14.93 ^f	14.98 ^f	14.10 ^e	14.17 ^e	24.57 ^g	24.52 ^g	20.10 ^g	20.16 ^{fg}
100% NPK + lime	637 ^b	638 ^b	587 ^b	589 ^b	22.82 ^b	22.88 ^b	17.08 ^b	17.16 ^b	40.55 ^{bc}	40.61 ^{bc}	37.09 ^b	37.18 ^b
Control	278 ^g	284 ^h	234 ^g	233 ^g	10.48 ^h	10.61 ^h	9.52 ^h	9.60 ^g	19.78 ^h	20.12 ^h	19.78 ^g	19.88 ^g
Initial status (2019)	366		278		13.8		11.7		28.3		24.6	

Values followed by different letter(s) differ significantly at $p < 0.05$ as per Duncan's multiple range test (DMRT).

The sole fertilizer treatment (100% NPK) also enhanced microbial activity, raising MBC, MBN, and DHA by 75.0%, 76.7%, and 92.8%, respectively, when compared with the

control (Table 7). Similar trends were observed at the 0.15–0.30 m depth, where increases in MBC, MBN, and DHA were recorded, although the relative treatment effects closely mirrored those in the surface layer (Table 7).

3.4. Crop Yield, Sustainable Yield Index and System Productivity

With the exception of the 100% N treatment, combined maize and wheat grain yields during 2010–2021 ranged from 764 to 5577 kg ha^{−1} for maize and from 450 to 2995 kg ha^{−1} for wheat (Table 8). The control plot produced the lowest yields for both crops (764 kg ha^{−1} for maize and 450 kg ha^{−1} for wheat), whereas the 100% NPK + FYM treatment recorded the highest productivity (5577 and 2995 kg ha^{−1}, respectively). Relative to the 100% NPK treatment, the addition of FYM increased maize grain yield by 41.8%, wheat grain yield by 56.7%, and system productivity by 47.4%; the 100% NPK + lime treatment improved these metrics by 33.7%, 47.6%, and 38.9%, respectively (Table 8).

Table 8. Average yield of maize & wheat (2010–2021) and system productivity.

Treatments	Maize Yield	Wheat Yield	System Productivity
	(kg ha ^{−1})		
50% NPK+ FYM	3416 ^e	1641 ^e	4406 ^e
100% NPK	3932 ^d	1911 ^d	5094 ^d
150% NPK	3665 ^{de}	1641 ^e	4608 ^e
100% NPK + HW	4254 ^c	2181 ^c	5624 ^c
100% NPK + Zn	3870 ^d	1873 ^d	5006 ^d
100% NP	1968 ^f	1030 ^f	2624 ^f
100% N	0 ^h	0 ^h	0 ^h
100% NPK + FYM	5577 ^a	2995 ^a	7509 ^a
100% NPK (−S)	1770 ^f	993 ^f	2426 ^f
100% NPK + lime	5258 ^b	2820 ^b	7076 ^b
Control	764 ^g	450 ^g	1068 ^g

Values followed by different letter(s) differ significantly at $p < 0.05$ as per Duncan's multiple range test (DMRT).

Maize Sustainable Yield Index (SYI) values were greatest under 100% NPK + FYM (0.85) and 100% NPK + lime (0.79), followed by 100% NPK + HW (0.66) and 100% NPK (0.60) (Table 9). A similar pattern was observed for wheat, where the SYI peaked under 100% NPK + FYM (0.75), next under 100% NPK + lime (0.71), and then under 100% NPK + HW (0.55). Apart from the 100% N treatment, the control plot consistently registered the lowest SYI values for both crops.

Table 9. Sustainable yield index of maize and wheat (2010–2021).

Treatments	Maize	Wheat
50% NPK+ FYM	0.49 ^g	0.43 ^e
100% NPK	0.60 ^d	0.49 ^d
150% NPK	0.54 ^f	0.41 ^f
100% NPK + HW	0.66 ^c	0.55 ^c
100% NPK + Zn	0.58 ^e	0.46 ^e
100% NP	0.28 ^h	0.23 ^g

Table 9. *Cont.*

Treatments	Maize	Wheat
100% N	0.00 ^k	0.00 ^j
100% NPK + FYM	0.85 ^a	0.75 ^a
100% NPK (–S)	0.24 ⁱ	0.22 ^h
100% NPK + lime	0.79 ^b	0.71 ^b
Control	0.10 ^j	0.08 ⁱ

Values followed by different letter(s) differ significantly at $p < 0.05$ as per Duncan's multiple range test (DMRT).

3.5. Key Indicators and Soil Quality Index (SQI)

Principal component analysis (PCA) was used to analyze the long-term effects of inorganic fertilizers, FYM and lime on soil quality and crop productivity. The analysis revealed that ten principal components accounted for over 99% of the variability in the dataset. However, only two principal components with eigenvalues exceeding 1, which collectively accounted for 84% of the total variability in the dataset, were selected for further analysis (Table 10). The PC1 explained 74% variability, with MBC, CEC, WHC, porosity, MBN, SOC, SHC, MWD, and DHA contributing the most. The 9% variability was explained by the PC2, with the maximum contribution of available P, available N, available S and available K (Table 10). With the exception of bulk density and particle density, all other assessed variables exhibited a positive correlation with the PC1 (Figure 2). This indicates a negative correlation of bulk density and particle density with all other variables.

Table 10. Loading values and percent contribution of soil variables on the axis identified by the principal component analysis.

	PC1		PC2	
Eigen value	14.337		1.648	
Variability (%)	75.461		8.675	
Cumulative %	75.461		84.137	
Variables	Loading Values	Contribution (%)	Loading Values	Contribution (%)
System productivity	0.969	6.555	−0.040	0.100
Bulk density	−0.961	6.446	−0.005	0.002
Particle density	−0.522	1.906	−0.135	1.107
Porosity	0.951	6.318	−0.025	0.040
Water holding capacity	0.952	6.332	−0.020	0.026
Saturated hydraulic conductivity	0.911	5.794	−0.004	0.001
Mean weight diameter	0.902	5.681	−0.239	3.488
pH	0.723	3.653	−0.625	23.735
Soil organic carbon	0.932	6.067	−0.020	0.026
Cation exchange capacity	0.953	6.346	−0.136	1.129
Available N	0.757	3.997	0.526	16.842
Available P	0.640	2.858	0.609	22.530
Available K	0.823	4.732	0.371	8.381
Available S	0.752	3.945	0.413	10.387
Exchangeable Ca	0.895	5.595	−0.227	3.140

Table 10. Cont.

	PC1		PC2	
Exchangeable Mg	0.884	5.450	−0.350	7.444
Microbial biomass carbon	0.959	6.425	−0.070	0.304
Microbial biomass nitrogen	0.944	6.226	0.104	0.6597
Dehydrogenase activity	0.901	5.665	−0.103	0.650

PC: Principal component.

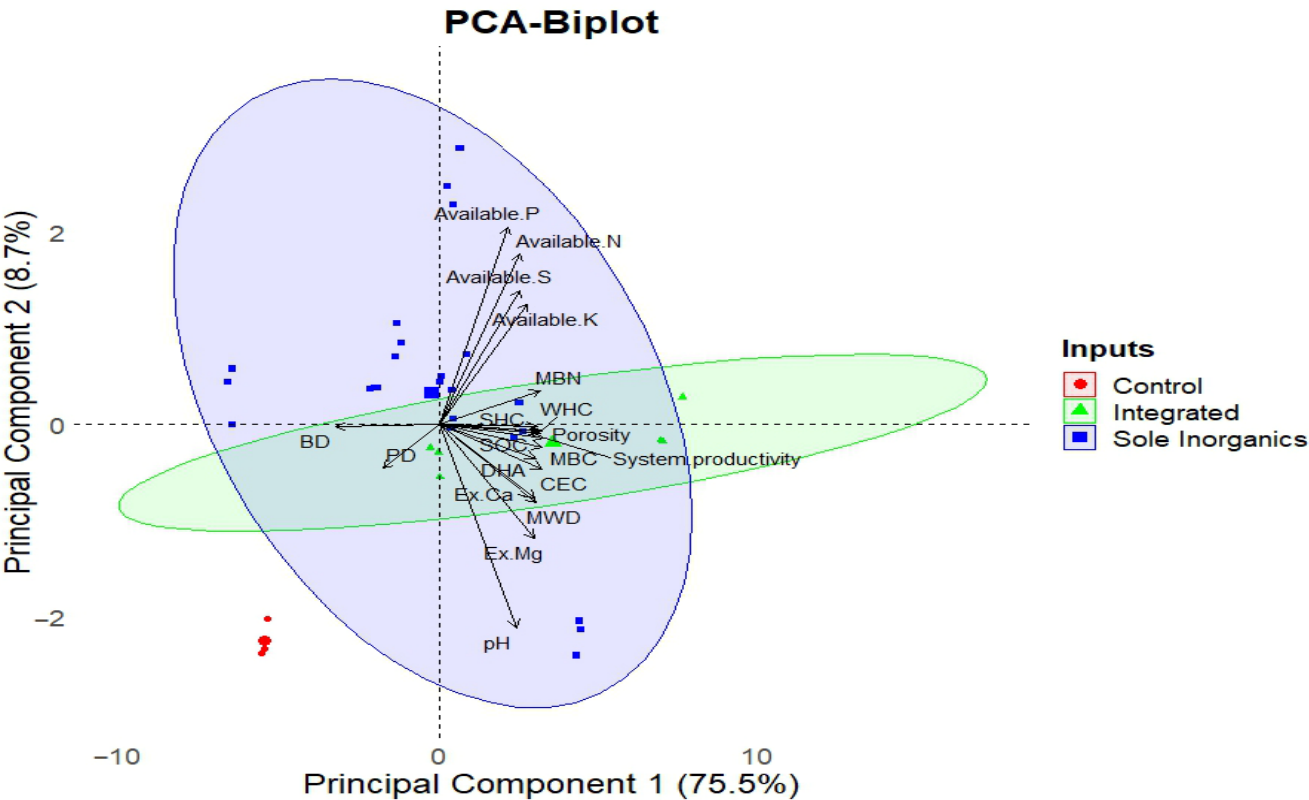


Figure 2. Principal component analysis (PCA) illustrating soil quality indicators and the ellipse-based grouping of the full dataset according to treatments. The ellipse represents the 84% confidence interval for the treatment clusters. Larger symbols denote the centroid positions of the respective treatment groups. The angles formed between the black arrows indicate the strength and direction of correlations among the soil variables.

Principal component analysis (PCA) clearly differentiated the nutrient management practices and the soil attributes associated with them (Figure 2). Treatments involving integrated nutrient management—specifically 50% NPK + FYM, 100% NPK + FYM, 100% NPK + HW, 100% NPK + Zn, and 100% NPK + lime—formed a separate cluster distinct from the treatments relying solely on inorganic fertilizers (100% NPK, 150% NPK, 100% N, 100% NP, and 100% NPK (−S)). The close positioning of soil variables and treatment centroids within the PCA axes indicates strong positive linkages between soil properties and system productivity. The grouping pattern implies that INM strategies exerted a substantial influence on both soil indicators and crop responses. The alignment of vectors representing MBC, MBN, DHA, CEC, SOC, WHC, and system productivity toward the INM cluster points to positive correlations between these soil parameters and integrated nutrient approaches. This pattern reinforces the critical role of INM in enhancing soil quality and improving productivity in maize–wheat systems cultivated on Alfisols under sub-humid climatic conditions (Figure 2). Principal component analysis was further applied to gen-

erate a statistically derived soil quality index (SQI). Because multiple variables loaded strongly on PC1 and PC2, the selection of the minimum dataset (MDS) was guided by both inter-variable correlations and expert judgment. For example, bulk density, microbial biomass carbon (MBC), cation exchange capacity (CEC), and water holding capacity (WHC) showed the greatest influence on PC1, whereas soil pH, available phosphorus (P), available nitrogen (N), and available sulfur (S) were the dominant contributors to PC2. From these, only bulk density and MBC (PC1), and pH and available P (PC2) were initially shortlisted as candidates for the MDS (Figure 2). However, because available P levels are naturally high in the soils of the study region, relying on this parameter is not meaningful for SQI development. Therefore, the final MDS used for SQI calculation consisted of bulk density, MBC, pH, and available N.

As indicated by the SQI values, the soil properties were significantly affected by the long-term nutrient management practices (Figure 3). The SQI ranged from 1.29 (100% N) to 1.83 (100% NPK + FYM). The INM treatments showed significantly higher SQI values. Furthermore, the scores for each indicator in the minimum dataset indicated that, among the four chosen datasets, bulk density and MBC were the primary contributors to the SQI, accounting for 88.5%, followed by available N (5.9%) and pH (5.6%) (Figure 4). The contribution of variables towards SQI was ranked as follows: bulk density (51.8%) > MBC (36.7%) > Available N (5.9%) > pH (5.6%). Bulk density and MBC, with their higher weights, accounted for the greatest variance in the dataset and had a significant impact on soil quality under the INM treatments (Figure 3).

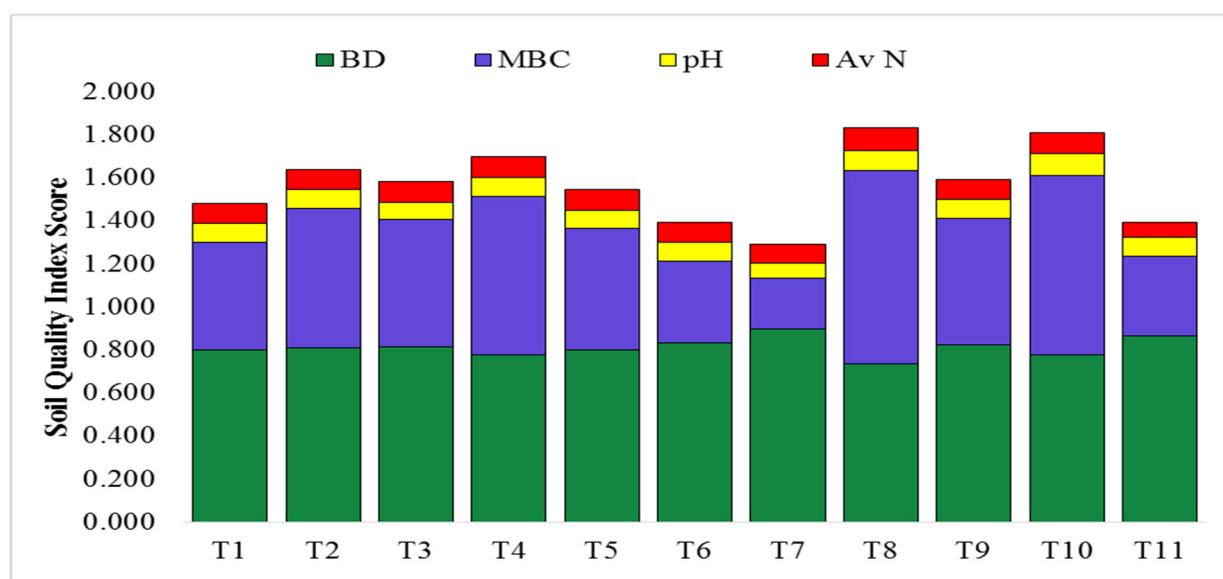


Figure 3. Influence of long-term nutrient management strategies on the soil quality index (SQI) within the maize–wheat cropping system, along with the proportional contribution of major soil indicators to the overall index. Treatment codes: T1 = 50% NPK + FYM; T2 = 100% NPK; T3 = 150% NPK; T4 = 100% NPK + Hand Weeding (HW); T5 = 100% NPK + Zinc (Zn); T6 = 100% NP; T7 = 100% N; T8 = 100% NPK + FYM; T9 = 100% NPK (–S); T10 = 100% NPK + lime; T11 = Control.

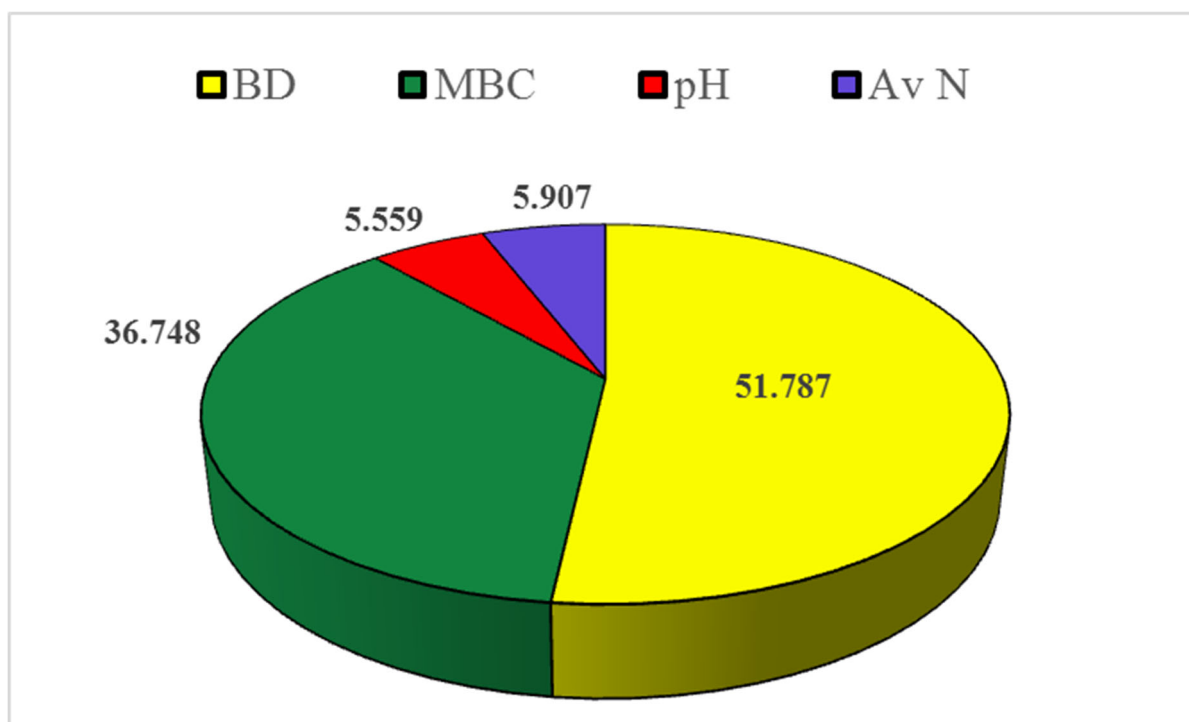


Figure 4. Overall contribution (%) of the selected soil quality indicators to the soil quality index.

4. Discussion

4.1. Soil Quality Indicators

The prolonged combined application of chemical fertilizers with FYM or lime had a pronounced influence on soil physical properties. After nearly five decades of FYM incorporation, the rise in SOC likely promoted the formation of soil aggregates and the development of both macro- and micropores, ultimately resulting in reduced bulk density in FYM-amended plots [29,54,55]. Lime additions may have improved soil structure through enhanced flocculation and stabilization of soil aggregates [56,57].

The rise in saturated hydraulic conductivity (SHC) observed in plots receiving FYM appears to result from enhanced soil aggregation, reductions in bulk density, and increased pore space driven by higher SOC levels. The addition of FYM also provides direct organic inputs, which further promote SHC improvements. In line with this, SHC was consistently greater in the upper soil layer compared with the sub-surface layer, where higher compaction likely restricts water movement [58].

Enhanced soil aggregation in FYM-treated plots may stem from the binding capability of organic compounds introduced with manure, which help cement soil particles together [59]. Improvements in soil structural attributes under balanced fertilization could also be linked to greater root biomass production and residue return from crops [60]. Moreover, the incorporation of organic materials promotes aggregate stability, particularly as decomposition progresses and microorganisms generate polysaccharides, mycelial networks, and other binding agents [61]. The addition of FYM also stimulated root growth, thereby fostering microbial activity and contributing to increased mean weight diameter (MWD) of soil aggregates [62].

The 100% NPK + lime treatment produced notably higher mean weight diameter (MWD) values. This improvement may be linked to the role of calcium ions in promoting aggregate stability, as Ca acts as an effective flocculating agent. When calcium interacts with clay particles, it enhances their binding, resulting in larger and more stable aggregates. Additionally, the application of lime contributes indirectly to better soil structure by sup-

porting increases in organic matter and stimulating microbial activity. Liming raises the soil pH, which enhances microbial activity in soil. Microorganisms produce a variety of organic compounds, some of which contribute to binding soil aggregates together. Comparable improvements in physical properties of the soil under long-term INM practices have also been reported by many researchers [62–65]. In the sub-surface horizon, bulk density increased, whereas porosity, water holding capacity (WHC), saturated hydraulic conductivity (SHC), and mean weight diameter (MWD) were all lower than in the surface layer. These changes are likely associated with greater compaction, reduced organic carbon levels, and diminished root penetration at deeper soil depths [66].

The addition of lime helped counter soil acidity, raising the pH to a level approaching neutrality (around 6.25) [67]. Farmyard manure (FYM) also contributed to moderating soil acidity, most likely because organic compounds in the manure form complexes with Al^{3+} ions, thereby lowering their activity in the soil solution [68]. In contrast, the substantial drop in soil pH under the 100% N treatment can be attributed to the hydrogen ions released during the nitrification process, following the conversion of urea-derived ammonium to nitrate [69].

Among all treatments, the greatest accumulation of soil organic carbon (SOC) occurred under 100% NPK + FYM, with values significantly exceeding those of other nutrient management practices. This enrichment is attributed to the direct incorporation of organic matter from FYM, along with contributions from crop residues and root biomass, which upon decomposition promote humus formation [70–73]. Additionally, the wet temperate conditions of the study region likely slow organic matter mineralization, thereby enhancing SOC buildup [74,75]. Elevated SOC levels in the 100% NPK + HW plots, compared with chemically weeded plots, reflect continuous input and recycling of carbon through weed biomass. As expected, SOC was higher in the surface horizon than at depth, likely due to greater root proliferation in the upper soil layer [66].

The improvement in cation exchange capacity (CEC) with the combined application of FYM and fertilizers (100% NPK + FYM) is attributed to the formation of humified organic colloids that increase the soil's exchange sites [76]. Increasing fertilizer levels similarly enhanced CEC because of their positive effect on soil organic matter accumulation. Lime application also increased CEC, possibly through Ca addition and the accompanying rise in soil pH. Regardless of treatment, CEC values declined with depth, reflecting the lower SOC content in sub-surface layers. In contrast, the long-term application of urea in the 100% N treatment resulted in reduced CEC, likely due to sustained acidification and consistently lower pH in those plots [14,22,77].

The concentrations of available N, P, and K were markedly higher in the 100% NPK + FYM treatment compared with the plots receiving only 100% NPK. This enhancement can be attributed to the long-term, balanced supplementation of nutrients through both FYM and mineral fertilizers (urea, SSP, and MOP). In contrast, the reduced availability of N, P, and K observed in the control, 100% N, and 100% NPK treatments likely reflects the continual depletion of soil nutrients caused by nearly five decades of intensive cropping without replenishing NPK, PK, or K inputs, respectively [76,78,79].

The rise in available sulfur observed in the 100% NPK + FYM and 150% NPK treatments is likely attributable to the S supplied through single superphosphate (SSP) and FYM. Similar increases in available S have been reported when FYM is applied jointly with NPK fertilizers [80]. Conversely, the decline in available S in treatments that received no sulfur inputs is consistent with expectations [14,62,81].

Higher concentrations of exchangeable Ca in the lime-treated plots can be explained by the dissociation and subsequent release of Ca^{2+} ions from the applied lime [67]. FYM additions also contributed to elevated Ca levels, potentially due to its strong adsorp-

tion capacity—which may retain Ca that would otherwise leach [82]—as well as nutrient release during manure mineralization [81,83]. Furthermore, treatments involving P fertilization exhibited increased Ca levels because SSP, the phosphorus source, contains Ca as a constituent [84].

The incorporation of lime or FYM, together with balanced NPK fertilization, enhanced exchangeable Mg availability. This improvement likely stems from Mg release during manure decomposition and the amelioration of soil acidity [85–87]. The continued depletion of Mg under sole chemical fertilizer application highlights the importance of supplementing NPK fertilizers with Mg to sustain soil fertility and support long-term crop productivity.

The markedly elevated levels of MBC, MBN, and DHA in the 100% NPK + FYM treatment are primarily linked to the steady input of organic matter derived from FYM. Combining FYM or lime with a balanced NPK supply enhances soil biological processes by increasing root-derived inputs and crop residues, in addition to supplying easily decomposable carbon and nitrogen sources [62,65,88]. These amendments foster more favorable conditions for microbial growth. Incorporating weed biomass, as in the 100% NPK + HW treatment, also stimulated microbial activity, resulting in significantly greater MBC, MBN, and DHA than those recorded under the 100% NPK treatment alone. While chemical fertilizers provide microbes with mineral nutrients, they lack the organic carbon necessary for microbial cell formation and metabolic function [89,90]. The carbon supplied through decomposing weed residues therefore served as an essential energy and nutrient source, promoting microbial proliferation and activity. Conversely, prolonged application of urea as the sole nitrogen source in the 100% N treatment led to strong soil acidification, which can suppress beneficial microbial communities and ultimately degrade the biological functioning of the soil [66].

4.2. Crop Yield, SYI, and System Productivity

Significantly higher crop yields and Sustainable Yield Index (SYI) values were recorded under the INM treatments—especially where 100% NPK was supplemented with FYM or lime—compared with treatments relying solely on mineral fertilizers. As discussed earlier, prolonged FYM application improved soil physical properties (Tables 2 and 3) and enriched the soil nutrient pool (Tables 5 and 6), which in turn stimulated soil biological activity (Table 7). Collectively, these improvements created a more conducive soil environment for plant growth and nutrient uptake [57,90]. While recommended NPK fertilizers contribute mainly macronutrients, their continued use without organic inputs can lead to nutrient imbalances and subsequent declines in crop performance. The incorporation of FYM enhanced soil fertility by improving structure, supplying multiple nutrients, and fostering conditions that supported greater root development. Increased root biomass enhances the plant's ability to capture water and nutrients from deeper soil layers [33]. Comparable benefits of substituting part of the inorganic fertilizer requirement with FYM have been documented in earlier studies, where improvements in yield and SYI were consistently observed [79,91–93]. Conversely, treatments such as 100% NP, 100% N, 100% NPK (–S), and the unfertilized control failed to maintain crop yields over time. The reduced productivity in these treatments is likely linked to deficiencies in secondary and micronutrients, which are more adequately supplied in FYM-based nutrient management systems [94]. An increased yield and SYI observed with the lime application can be attributed to its ability to ameliorate soil acidity by raising pH from its initial value of 5.80 to 6.24. This increase in pH facilitates enhanced microbial activity, increased the availability of nutrients such as Ca and Mg, and improved the physical properties of the soil [95,96]. Hand-weeded plots produced significantly higher maize and wheat grain yields than those receiving chemical weed control; however, the yields were still lower than those obtained under the

100% NPK + FYM treatment. This indicates that recycling only the above-ground weed biomass does not supply sufficient nutrients to meet the higher crop demand required for maximum productivity. The very low yields and lack of long-term sustainability observed in the control plots further demonstrate that inherent soil nutrient reserves alone cannot support continuous crop production. Interestingly, the control treatment still outperformed the 100% N plots, where prolonged urea application caused severe soil acidification and elevated exchangeable Al to toxic concentrations [97], ultimately resulting in complete yield failure. Numerous studies have similarly reported that long-term use of nitrogen fertilizers contributes substantially to soil acidification [57,66,73,98]. The enhancement in soil quality under the 100% NPK + FYM treatment translated directly into higher system productivity, indicating that a consistent nutrient supply together with the improved soil environment created by FYM is vital for maintaining long-term crop performance. Collectively, the results underscore the value of integrating organic amendments with mineral fertilizers, as this approach promotes more efficient nutrient cycling, maintains soil fertility, improves crop growth attributes, and ultimately increases overall yield sustainability.

4.3. Key Indicators and Soil Quality Index

The 100% NPK + FYM treatment produced the highest soil quality index (SQI), with the 100% NPK + lime treatment ranking next. Incorporating FYM alongside balanced NPK fertilization enhanced soil organic matter, promoted microbial activity, and increased residual nutrient availability, all of which contributed to the elevated SQI values [66,99]. Across diverse agro-ecological environments, SOC has consistently been recognized as one of the most influential determinants of soil quality [33,90,100–103]. The improvement in SQI under lime-amended plots may be attributed to the reduction in exchangeable Al^{3+} toxicity, improvements in soil structural properties, and increased availability of phosphorus, calcium, and magnesium [9]. This indicates that using either lime or FYM is effective in enhancing the quality of continuously cultivated acid soils in sub-humid region. In contrast, applying imbalanced fertilizers, such as 100% N, 100% NP and 100% NPK (–S) led to significant decrease in the SQI. This decline is attributed to the omission of PK, K and S in the respective fertilization schedule of the treatments.

Bulk density reflects compactness of the soil, which affects its air-water dynamics. A higher MBC indicates an increased rate of C mineralization, suggesting a higher C availability to plants. Therefore, MBC is considered as a vital indicator of biological soil quality. It might have contributed positively to yield improvements because it directly influences nutrient availability, transformations and microbial activity in the soil [99].

Soil pH is one of the most influential soil attributes, as it governs nutrient solubility, availability, and chemical transformations, and shapes numerous physicochemical reactions within the soil environment [104]. For this reason, pH plays a substantial role in determining the soil quality index (SQI). Nitrogen, on the other hand, is a fundamental nutrient in agricultural systems and frequently represents the most limiting factor for plant growth, especially in terms of its plant-available form [105]. The supply of available nitrogen is directly tied to vegetative development and yield formation, making it an essential chemical indicator of soil quality that must be incorporated into soil quality evaluation frameworks [31,106]. The indicators selected for the minimum dataset displayed strong positive relationships with both maize–wheat system productivity and other soil health parameters (Figure 5). Our results also showed that integrated nutrient management (INM), especially treatments combining FYM or lime with 100% NPK, enhanced all soil quality indicators more effectively than mineral fertilizers alone. Consequently, these INM treatments achieved significantly higher SQI values compared with either sole chemical fertilizer applications or unfertilized control plots (Figure 2).

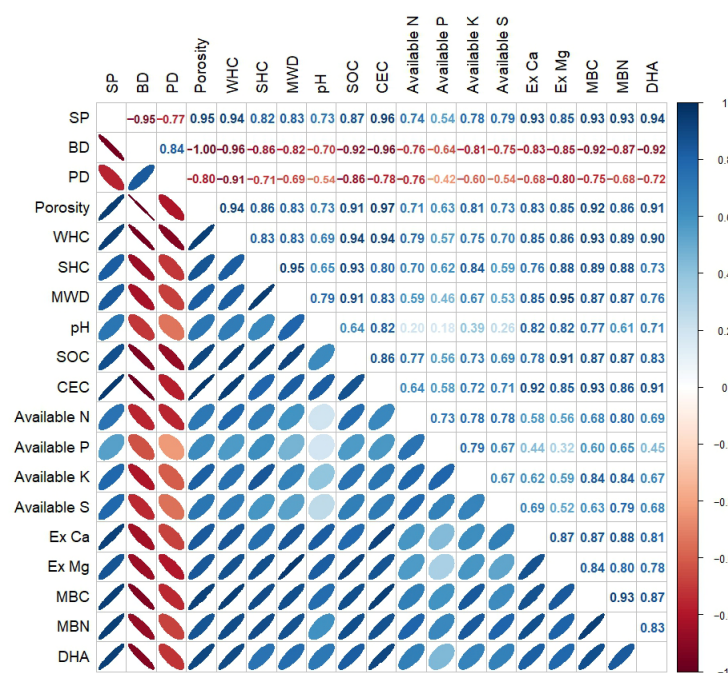


Figure 5. Pearson correlation matrix illustrating relationships among soil properties and productivity of the maize–wheat cropping system. Blue shades indicate positive correlations, while red shades denote negative correlations. The shape of the ellipses reflects the strength of the association: narrower ellipses represent stronger correlations, whereas broader ones indicate weaker relationships.

4.4. Quantitative Relationships Between System Productivity and SQI

Our results demonstrated a strong linear relationship between the soil quality index (SQI) and overall system productivity, showing that crop yields rose consistently with improvements in SQI (Figure 6). This positive association highlights the pivotal role that soil quality plays in determining crop performance. Therefore, SQI emerges as a dependable indicator for forecasting agricultural productivity in Alfisols of the Northwestern Himalayan region. Furthermore, the strength of this relationship suggests that the approach can be applied to other agro-ecosystems with comparable soil types, cropping systems, and climatic conditions, offering a valuable framework for guiding nutrient management decisions and promoting sustainable farming strategies.

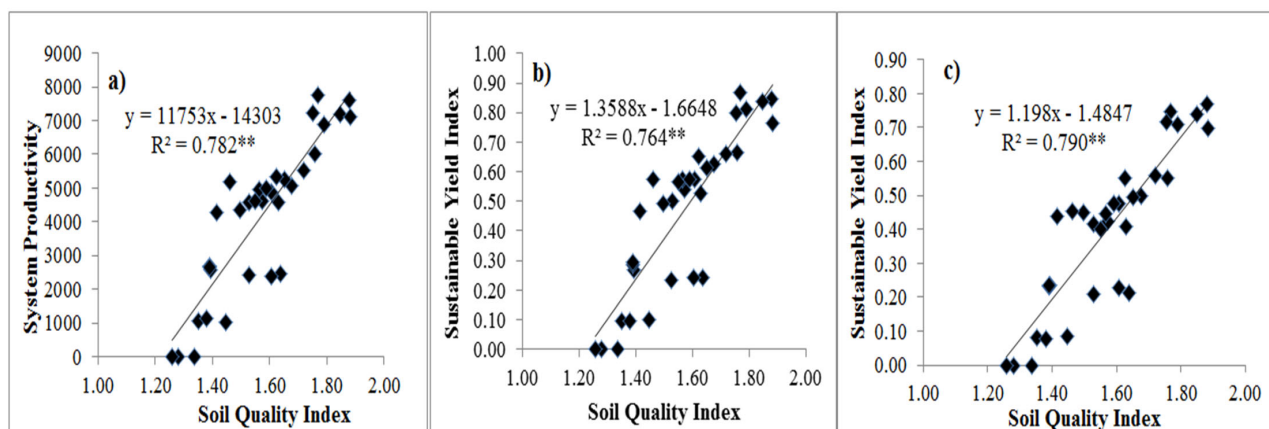


Figure 6. The linear relationship of soil quality indices with system productivity (a) and sustainable yield indices of maize (b) and wheat (c); ** indicates significance at $p \leq 0.01$ in the figure caption.

5. Conclusions

The 48-year field experiment revealed that the soil quality was significantly improved with the application of 100% NPK with FYM/lime compared to sole inorganic fertilization. The key soil quality indicators identified for the experimental Alfisols in the sub-humid region included bulk density, MBC, pH, and available N. The calculated SQI showed a positive correlation with system productivity and SYI of both maize and wheat. Furthermore, the highest grain yields, system productivity, and sustainability were recorded with the 100% NPK + FYM and 100% NPK + lime treatments, indicating that these two practices are superior options for the nutrient management in maize–wheat cropping system. Therefore, INM strategies in sub-humid climates should incorporate FYM or lime as part of the nutrient application package to promote balanced fertilization.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land15010183/s1>, Table S1: Treatments details; Table S2: Doses of chemical fertilizers and FYM applied in different treatments (N:P:K, kg ha^{−1}); Table S3: Average yield of maize & wheat (2010–2021) and system productivity; Table S4: Sustainable yield index of maize and wheat (2010–2021); Table S5: Soil quality index.

Author Contributions: D.S.: Data curation, Investigation, Methodology, Visualization, Writing—original draft, Writing—review and editing. R.P.S.: Conceptualization, Methodology, Resources, Supervision, Writing review and editing; S.G.: Data curation, Formal Analysis, Methodology, Visualization, Writing—original draft, Supervision, Writing—review and editing. N.K.S.: Conceptualization, Methodology, Supervision, Writing—review and editing; S.M.: Writing—review and editing; J.S.: Data curation, Writing—review and editing; T.S.: Formal Analysis, Writing—original draft, Writing review and editing, Software, Visualization. N.A.-A.: Methodology, Writing—review and editing. M.A.M.: Methodology, Writing—original draft, Writing—review and editing. A.S.: Methodology, Writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ongoing Research Funding program, (ORF-2026-958), King Saud University, Riyadh, Saudi Arabia.

Data Availability Statement: The primary data will be made available subjected to a valid and reasonable request.

Acknowledgments: The authors extend their appreciation to Ongoing Research Funding program, (ORF-2026-958), King Saud University, Riyadh, Saudi Arabia. The authors are highly thankful to the Indian Council of Agricultural Research for funding the study under the All India Coordinated Research Project on Long-Term Fertilizer Experiments and CSK Himachal Pradesh Agricultural University, Palampur for providing essential facilities.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Karlen, D.L.; Mausbach, M.J.; Doran, J.W.; Clive, R.G.; Harris, R.F.; Schuman, G.E. Soil quality: A concept, definition and framework for evaluation. *Soil Sci. Soc. Am. J.* **1997**, *61*, 4–10. [\[CrossRef\]](#)
2. Cavalcante, D.M.; Silva, A.P.F.; de Almeida, B.G.; Freire, F.J.; dos Santos Silva, T.H.; Cavalcante, F.M.S. Physical soil quality indicators for environmental assessment and agricultural potential of oxisols under different land uses in the Araripe Plateau. *Brazil Soil Till Res.* **2021**, *209*, 104951. [\[CrossRef\]](#)
3. Biswas, S.; Hazra, G.; Purakayastha, T.; Saha, N.; Mitran, T.; Roy, S.S. Establishment of critical limits of indicators and indices of soil quality in rice-rice cropping systems under different soil orders. *Geoderma* **2017**, *292*, 34–48. [\[CrossRef\]](#)
4. Qi, Y.; Darilek, J.L.; Huang, B.; Zhao, Y.; Sun, W.; Gu, Z. Evaluating soil quality indices in an agricultural region of Jiangsu province. China. *Geoderma* **2009**, *149*, 325–334. [\[CrossRef\]](#)
5. Govaerts, B.; Sayre, K.D.; Deckers, J. A minimum data set for soil quality assessment of wheat and maize cropping in the highlands of Mexico. *Soil Till Res.* **2006**, *87*, 163–174. [\[CrossRef\]](#)

6. Juhos, K.; Szabó, S.; Ladányi, M. Explore the influence of soil quality on crop yield using statistically-derived pedological indicators. *Ecol. Indic.* **2016**, *63*, 366–373. [CrossRef]
7. Gong, L.; Ran, Q.; He, G.; Tiyp, T. A soil quality assessment under different land use types in keriya river basin, southern xinjiang, China. *Soil Till Res.* **2015**, *146*, 223–229. Correction in *Soil Tillage Res.* **2015**, *148*, 142. <https://doi.org/10.1016/j.still.2014.12.010>. [CrossRef]
8. Khaki, B.D.; Honarjoo, N.; Davatgar, N.; Jalalian, A.; Golsefidi, H.T. Assessment of two soil fertility indexes to evaluate paddy fields for rice cultivation. *Sustainability* **2017**, *9*, 1299. [CrossRef]
9. Suri, D.; Sharma, R.P.; Sankhyan, N.K.; Manuja, S.; Singh, J. Micronutrient availability in soil–plant system as influenced by 47 years long application of chemical fertilizers, organics and lime under maize–wheat cropping in an acid Alfisol. *Cereal Res. Commun.* **2024**, *52*, 1187–1199. [CrossRef]
10. Jain, N.K.; Singh, H.; Dashora, L.N.; Mundra, S.L. Maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system: Intensification through introduction of pulses. *Ind. J. Agron.* **2015**, *60*, 347–351. [CrossRef]
11. Ram, S.; Singh, V.; Sirari, P. Effects of 41 years of application of inorganic fertilizers and farm yard manure on crop yields, soil quality, and sustainable yield index under a rice–wheat cropping system on Mollisols of north India. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 179–193. [CrossRef]
12. Vasu, D.; Singh, S.K.; Ray, S.K.; Duraisami, P.V.; Tiwary, P.; Chandran, P.; Nimkar, A.M.; Anantwar, S.G. Soil quality index (SQI) as a tool to evaluate crop productivity in semi-arid Deccan plateau, India. *Geoderma* **2016**, *282*, 70–79. [CrossRef]
13. Gourav, N.; Sankhyan, N.K.; Sharma, R.P.; Sharma, G.D. Vertical distribution of sulfur fractions in a continuously fertilized acid Alfisol under maize–wheat cropping system. *Commun. Soil Sci. Plant Anal.* **2018**, *49*, 923–933.
14. Dhiman, D.; Sharma, R.P.; Sankhyan, N.K.; Sepehya, S.; Sharma, S.K.; Kumar, R. Effect of regular application of fertilizers, manure and lime on soil health and productivity of wheat in an acid Alfisol. *J. Plant Nutr.* **2019**, *42*, 2507–2521. [CrossRef]
15. Majhi, P.; Rout, K.K.; Nanda, G.; Singh, M. Soil quality for rice productivity and yield sustainability under long-term fertilizer and manure application. *Commun. Soil Sci. Plant Anal.* **2019**, *50*, 1330–1343. [CrossRef]
16. Zuber, S.M.; Behnke, G.D.; Nafziger, E.D.; Villamil, M.B. Multivariate assessment of soil quality indicators for crop rotation and tillage in Illinois. *Soil Tillage Res.* **2017**, *174*, 147–155. [CrossRef]
17. Brar, S.K.; Dhaliwal, S.S.; Sharma, V. Soil Quality Assessment in Diversified Long-Term Experimentation Under Different Agriculturally Based Cropping Systems. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 1727–1739. [CrossRef]
18. Yang, Z.C.; Zhao, N.; Huang, F.; Lv, Y.Z. Long-term effects of different organic and inorganic fertilizer treatments on soil organic carbon sequestration and crop yields on the North China Plain. *Soil Tillage Res.* **2015**, *146*, 47–52. [CrossRef]
19. Xie, H.T.; Li, J.W.; Zhu, P.; Peng, C.; Wang, J.K.; He, H.B.; Zhang, X.D. Long-term manure amendments enhance neutral sugar accumulation in bulk soil and particulate organic matter in a Mollisol. *Soil Biol. Biochem.* **2014**, *78*, 45–53. [CrossRef]
20. Zhou, M.; Xiao, Y.; Li, Y.; Zhang, X.; Wang, G.; Jin, J.; Ding, G.; Liu, X. Soil quality index evaluation model in responses to six-year fertilization practices in Mollisols. *Arch. Agron. Soil Sci.* **2020**, *68*, 180–194. [CrossRef]
21. Singh, R.P.; Das, S.K.; Rao, U.M.B.; Reddy, M.N. *Sustainability Index under Different Management: Annual Report*; CRIDA: Hyderabad, India, 1990.
22. Majhi, P.; Rout, K.K.; Nanda, G.; Singh, M. Long term effects of fertilizer and manure application on productivity, sustainability and soil properties in a rice–rice system on Inceptisols of Eastern India. *Commun. Soil Sci. Plant Anal.* **2021**, *52*, 1631–1644. [CrossRef]
23. Li, P.; Zhang, T.; Wang, X.; Yu, D. Development of biological soil quality indicator system for sub-tropical China. *Soil Tillage Res.* **2013**, *126*, 112–118. [CrossRef]
24. Saha, S.; Saha, B.; Mohanty, S.; Ray, M.; Hazra, G.C.; Chatterjee, S.; Mukhopadhyay, S.K. Identifying suitable soil quality indicators in an Indian rice–wheat system as influenced by long-term (30 years) inorganic–organic fertilization. *Arch. Agron. Soil Sci.* **2022**, *68*, 704–718. [CrossRef]
25. Choudhary, M.; Panday, S.C.; Meena, V.S.; Singh, V.; Yadav, R.P.; Mahanta, D.; Mondal, T.; Mishra, P.K.; Bisht, J.K.; Pattanayak, A. Long-term effects of organic manure and inorganic fertilization on sustainability and chemical soil quality indicators of soybean–wheat cropping system in the Indian mid-Himalayas. *Agric. Ecosyst. Environ.* **2018**, *257*, 38–46. [CrossRef]
26. Kour, B.; Sharma, P.; Ramya, S.; Gawdiya, S.; Sudheer, K.; Ramakrishnan, B. Cyanobacterial biofertilizer inoculation has a distinctive effect on the key genes of carbon and nitrogen cycling in paddy rice. *J. Appl. Phycol.* **2024**, *36*, 1859–1874. [CrossRef]
27. Mbuthia, L.W.; Acosta-Martínez, V.; DeBryun, J.; Schaeffer, S.; Tyler, D.; Odoi, E.; Mpheshea, M.; Walker, F.; Eash, N. Long-term tillage, cover crop, and fertilization effects on microbial community structure, activity: Implications for soil quality. *Soil Biol. Biochem.* **2015**, *89*, 24–34. [CrossRef]
28. Sharma, K.L.; Ramachandrapa, B.K.; Chandrika, D.S.; Sathish, A.; Dhanpal, G.N.; Rao, C.h.S.; Shankar, M.A.; Grace, J.K.; Sankar, G.R.M.; Chary, G.R.; et al. Effect of organic manure and crop residue-based long-term nutrient management systems on soil quality changes under sole finger millet (*Eleusine coracana* (L.) Gaertn.) and groundnut (*Arachis hypogaea* L.)–finger millet rotation in rainfed Alfisol. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 899–914. [CrossRef]

29. Rakshit, R.; Das, A.; Padbhushan, R.; Sharma, R.P.; Sushant Kumar, S. Assessment of soil quality and identification of parameters influencing system yield under long-term fertilizer trial. *J. Indian. Soc. Soil Sci.* **2018**, *66*, 166–171. [\[CrossRef\]](#)
30. Chandra, M.S.; Naresh, R.K.; Bhatt, R.; Manisha; Gourkhede, P.H.; Kumar, R.; Gawdiya, S. Impact of tillage-cum crop establishment methods and nutrient management strategies on wet rice (*Oryza sativa* L.): Crop productivity, water footprint, soil health, and profitability in Typic Ustochrept soils under a semi-arid sub-tropical environment. *Paddy Water Environ.* **2023**, *21*, 165–179. [\[CrossRef\]](#)
31. Biswas, S.; Singh, P.; Rahaman, R.; Patil, K.V.; De, N. Soil quality and crop productivity under 34 years old long-term rainfed rice based cropping system in an Inceptisol of sub-tropical India. *Front. Soil Sci.* **2023**, *3*, 1155712. [\[CrossRef\]](#)
32. Reddy, D.D.; Subba Rao, A.; Sammi Reddy, K.; Takkar, P.N. Yield sustainability and phosphorus utilization in soybean-wheat system on Vertisols in response to integrated use of manure and fertilizer phosphorus. *Field Crops Res.* **1999**, *62*, 181–190. [\[CrossRef\]](#)
33. Gabhane, V.V.; Ramteke, P.; Ravindra Chary, G.; Patode, R.S.; Ganvir, M.M.; Chorey, A.; Tupe, A.R. Effects of long-term nutrient management in semi-arid Vertisols on soil quality and crop productivity in a cotton-greengram intercropping system. *Field Crops Res.* **2023**, *303*, 109115. [\[CrossRef\]](#)
34. Singh, R.A. *Soil Physical Analysis*; Kalyani Publishers: Ludhiana, India, 1980.
35. Gupta, R.P.; Dhakshinamoorthy, C. *Procedures for Physical Analysis of Soils and Collection of Agrometeorological Data*; Division of Agricultural Physics, Indian Agricultural Research Institute: New Delhi, India, 1980.
36. Piper, C.S. *Soil and Plant Analysis (Asia Edition)*; Hans Publishers: Bombay, India, 1966.
37. Yoder, R.E. A direct method of aggregate analysis and study of the physical nature of erosion losses. *J. Am. Soc. Agron.* **1936**, *28*, 337–351. [\[CrossRef\]](#)
38. Klute, A. *Method of Soil Analysis Part-I*; American Society of Agronomy: Madison, WI, USA, 1965; pp. 210–220.
39. Walkley, A.; Black, I.A. An examination of the Degtjareff (wet acid) method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* **1934**, *37*, 29–38. [\[CrossRef\]](#)
40. Subbiah, B.V.; Asija, G.L. A rapid procedure for the determination of available nitrogen in soils. *Curr. Sci.* **1956**, *25*, 259–260.
41. Olsen, S.R.; Cole, C.V.; Watanabe, F.S.; Dean, L.A. *Estimation of Available Phosphorus by Extraction with Sodium Carbonate*; USDA Circular No. 939; US Government Printing Office: Washington, DC, USA, 1954; pp. 19–33.
42. Chesnin, L.; Yien, C.H. Turbidimetric determination of available sulphate. *Soil Sci. Soc. Am. Proc.* **1950**, *15*, 149–151. [\[CrossRef\]](#)
43. Jackson, M.L. *Soil Chemical Analysis*; Prentice Hall Inc.: Englewood Cliffs, NJ, USA, 1973.
44. Jenkinson, D.S.; Powlson, D.S. The effect of biological treatments on metabolism in Soil V.A. method for measuring soil biomass. *Soil Biol. Biochem.* **1976**, *8*, 209–213. [\[CrossRef\]](#)
45. Vance, E.D.; Brookes, P.C.; Jenkinson, D.S. An extraction method for measuring soil microbial biomass carbon. *Soil Biol. Biochem.* **1987**, *19*, 703–707. [\[CrossRef\]](#)
46. Brookes, P.C.; Landman, A.; Pruden, G.; Jenkinson, D.S. Chloroform fumigation and release of soil nitrogen. A rapid direct extraction method to measure microbial biomass nitrogen in Soil. *Soil Biol. Biochem.* **1985**, *19*, 837–842. [\[CrossRef\]](#)
47. Casida, L.E.; Klein, D.A.; Santoro, T. Soil dehydrogenase activity. *Soil Sci.* **1964**, *98*, 371–376. [\[CrossRef\]](#)
48. Sharma, K.L.; Mandal, U.K.; Srinivas, K.; Vittal, K.P.R.; Mandal, B.; Grace, J.K.; Ramesh, V. Long-term soil management effects on crop yields and soil quality in a dryland Alfisol. *Soil Res.* **2005**, *83*, 246–259. [\[CrossRef\]](#)
49. Brejda, J.J.; Moorman, T.B.; Karlen, D.L.; Dao, T.H. Identification of regional soil quality factors and indicators, I: Central and southern high plains. *Soil Sci. Soc. Am. J.* **2000**, *64*, 2115–2124. [\[CrossRef\]](#)
50. Andrews, S.S.; Karlen, D.L.; Mitchell, J.P. A comparison of soil quality indexing methods for vegetable production systems in northern California. *Agric. Ecosyst. Environ.* **2002**, *90*, 25–45. [\[CrossRef\]](#)
51. Gomez, K.A.; Gomez, A.A. *Statistical Procedure for Agricultural Research*, 2nd ed.; John Wiley and Sons: New York, NY, USA, 1984.
52. Sheoran, O.P.; Tonk, D.S.; Kaushik, L.S.; Hasija, R.C.; Pannu, R.S. Statistical software package for agricultural research workers. In *Recent Advances in Information Theory, Statistics and Computer Applications*; Hooda, D.S., Hasija, R.C., Eds.; Department of Mathematics Statistics, CCS HAU: Hisar, India, 1998.
53. Wickham, H. *ggplot2: Elegant Graphics for Data Analysis*; Springer-Verlag: New York, NY, USA, 2016; ISBN 978-3-319-24277-4.
54. Zhai, L.; Wang, Z.; Zhai, Y.; Zhang, L.; Zheng, M.; Yao, H.; Jia, X. Partial substitution of chemical fertilizer by organic fertilizer benefits grain yield, water use efficiency, and economic return of summer maize. *Soil Till. Res.* **2022**, *217*, 105287. [\[CrossRef\]](#)
55. Chander, S.; Tripathi, S.C.; Venkatesh, K.; Meena, R.P.; Kumar, N.; Chhokar, R.S.; Kumar, N.; Samota, S.R.; Sharma, D.; Singh, G. Sustaining rice-wheat system through integrated nutrient management via FYM or Sesbania Aculeata in India on long term basis. *Int. J. Plant Prod.* **2023**, *17*, 775–793. [\[CrossRef\]](#)
56. Sadhukhan, R.; Kumar, D.; Sepat, S.; Ghosh, A.; Banerjee, K.; Shivay, Y.S.; Bhupenchandra, I. Precision nutrient management influences the productivity, nutrient use efficiency, N₂O fluxes, and soil enzymatic activity in zero-till wheat (*Triticum aestivum* L.). *Field Crops Res.* **2024**, *317*, 109526. [\[CrossRef\]](#)

57. Chauhan, N.; Sankhyan, N.K.; Sharma, R.P.; Singh, J.; Gourav. Effect of long-term application of inorganic fertilizers, farm yard manure and lime on wheat (*Triticum aestivum* L.) productivity, quality and nutrient content in an acid alfisol. *J. Plant Nutr.* **2020**, *43*, 2569–2578. [\[CrossRef\]](#)
58. Kumari, M.; Sheoran, S.; Prakash, D.; Yadav, D.B.; Yadav, P.K.; Jat, M.K. Long-term application of organic manures and chemical fertilizers improve the organic carbon and microbiological properties of soil under pearl millet–wheat cropping system in north-western India. *Heliyon* **2024**, *10*, e25333. [\[CrossRef\]](#)
59. Bandyopadhyay, K.K.; Misra, A.K.; Ghosh, P.K.; Hati, K.M. Effect of integrated use of farmyard manure and chemical fertilizers on soil physical properties and productivity of soybean. *Soil Till. Res.* **2010**, *110*, 115–125. [\[CrossRef\]](#)
60. Latif, M.A.; Mehuys, G.R.; Mackenzie, A.F.; Alli, I.; Faris, M.A. Effects of legumes on soil physical quality in a maize crop. *Plant Soil* **1992**, *140*, 15–23. [\[CrossRef\]](#)
61. Chaudhury, J.; Mandal, U.K.; Sharma, K.L.; Ghosh, H.; Mandal, B. Assessing soil quality under long-term rice-based cropping system. *Commun. Soil Sci. Plant Anal.* **2005**, *36*, 1141–1161. [\[CrossRef\]](#)
62. Tripathy, S.; Biswas, S.; Singh, P. Soil Quality, Resilience, and Crop Productivity Under 32-Year-Old Long-term Rice-Rice System in Acidic Alfisol of Assam. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 5333–5344. [\[CrossRef\]](#)
63. Sharma, M.; Mishra, B.; Singh, R. Long-term effects of fertilizers and manure on physical and chemical properties of a Mollisol. *J. Ind. Soc. Soil Sci.* **2007**, *55*, 523–524.
64. Zhao, J.; Ni, T.; Li, J.; Lu, Q.; Fang, Z.; Huang, Q.; Shen, Q. Effects of organic-inorganic compound fertilizer with reduced chemical fertilizer application on crop yield, soil biological activity and bacterial community structure in a rice-wheat cropping system. *Appl. Soil Ecol.* **2016**, *99*, 1–12. [\[CrossRef\]](#)
65. Dhaliwal, S.S.; Sharma, V.; Kaur, J.; Shukla, A.K.; Hossain, A.; AbdelHafez, S.H.; Gaber, A.; Sayed, S.; Singh, V.K. The pedospheric variation of DTPA-extractable Zn, Fe, Mn, Cu and other physicochemical characteristics in major soil orders in existing land use systems of Punjab, India. *Sustainability* **2021**, *14*, 29. [\[CrossRef\]](#)
66. Sankhyan, N.K.; Sharma, N.; Sharma, R.P.; Anjali Sharma, G.D.; Thakur, A. Sustainable soil management: Insights from a 47-year maize-wheat cropping system study. *Appl. Soil Ecol.* **2023**, *195*, 105230. [\[CrossRef\]](#)
67. Chimdi, A.; Gebrekidan, V.; Kibret, K.; Tadesse, A. Effects of liming on acidity-related chemical properties of soils of different land use systems in Western Oromia, Ethiopia. *World J. Agric. Sci.* **2012**, *8*, 560–567.
68. Hue, N.V. Correcting soil acidity of a highly weathered ultisols with chicken manure and sewage sludge. *Commun. Soil Sci. Plant Anal.* **1992**, *23*, 241–264. [\[CrossRef\]](#)
69. Liu, X.; Zhou, J.; Li, W.; Xu, J.; Brookes, P.C. The combined effects of urea application and simulated acid rain on soil acidification and microbial community structure. *Environ. Sci. Poll. Res.* **2014**, *21*, 6623–6631. [\[CrossRef\]](#)
70. Bhattacharyya, R.; Prakash, V.; Kundu, S.; Ghosh, B.N.; Srivastva, A.K.; Gupta, H.S. Soil properties and their relationships with crop productivity after 30 years of different fertilization in the Indian Himalayas. *Arch. Agron. Soil Sci.* **2009**, *55*, 641–661. [\[CrossRef\]](#)
71. Liang, Q.; Chen, H.; Gong, Y.; Fan, M.; Yang, H.; Lal, R.; Kuzyakov, Y. Effects of 15 years of manure and inorganic fertilizers on soil organic carbon fractions in a maize-wheat system in the North China Plain. *Nutr. T Cycl. Agroecosyst.* **2012**, *92*, 21–33. [\[CrossRef\]](#)
72. Hemalatha, S.; Chellamuthu, S. Impacts of long term fertilization on Soil Nutritional quality under finger Millet: Maize cropping sequence. *J. Environ. Res. Dev.* **2013**, *7*, 15–71.
73. Brar, B.S.; Singh, J.; Singh, G.; Kaur, G. Effects of long-term application of inorganic and organic fertilizers on soil organic carbon and physical properties in maize–wheat rotation. *Agronomy* **2015**, *5*, 220–238. [\[CrossRef\]](#)
74. Sharma, S.P.; Subehia, S.K.; Sharma, P.K. Long-Term Effects of Chemical Fertilizers on Soil Quality, Crop productivity, and Sustainability (Research Bulletin No. 1); CSK Himachal Pradesh Krishi Vishvavidyalaya: Palampur, HP, India, 2002.
75. Verma, G.; Sharma, R.P.; Sharma, S.P.; Subehia, S.K.; Shambhavi, S. Changes in soil fertility status in maize–wheat system due to longterm use of chemical fertilizers and amendments in an Alfisol. *Plant Soil Environ.* **2012**, *58*, 529–533. [\[CrossRef\]](#)
76. Gourav Sankhyan, N.K.; Sharma, R.P.; Sharma, G.D. Long term effect of fertilizers and amendments on the properties of an acid Alfisol and uptake of primary nutrients and sulfur in maize-wheat rotation in north western Himalayas. *J. Plant Nutr.* **2019**, *42*, 1770–1788. [\[CrossRef\]](#)
77. Meena, H.M.; Sharma, R.P. Long-term effect of fertilizers and amendments on different fractions of organic matter in an acid Alfisol. *Commun. Soil Sci. Plant Anal.* **2016**, *47*, 1430–1440. [\[CrossRef\]](#)
78. Jadhao, S.D.; Bajpai, R.K.; Tiwari, A.; Bachkaiya, V.; Singh, M.; Kharche, V.K.; Mali, D.V.; Sonune, B.A. Nitrogen dynamics in soil as influenced by long-term manuring and fertilization under rice grown on Vertisol of Chhattisgarh. *J. Ind. Soc. Soil Sci.* **2019**, *67*, 65–72. [\[CrossRef\]](#)
79. Meena, A.L.; Pandey, R.N.; Kumar, D.; Dotaniya, M.L.; Sharma, V.K.; Singh, G.; Meena, B.P.; Kumar, A.; Bhanu, C. 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. *Commun. Soil Sci. Plant Anal.* **2020**, *51*, 2331–2348. [\[CrossRef\]](#)

80. Moharana, P.C.; Sharma, B.M.; Biswas, D.R.; Dwivedi, B.S.; Singh, R.V. Long-term effect of nutrient management on soil fertility and soil organic carbon pools under a 6-year-old pearl millet–wheat cropping system in an Inceptisol of subtropical India. *Field Crops Res.* **2012**, *136*, 32–41. [\[CrossRef\]](#)
81. Parven, H.; Kumar, S.; Shambhavi, S.; Kumar, S.; Kumar, R.; Kumari, D. Long term effect of integrated nutrient management on secondary and micronutrient of alluvial soils. *Int. J. Curr. Microbiol. Appl. Sci.* **2020**, *9*, 1990–1999. [\[CrossRef\]](#)
82. Bellaki, M.A.; Badanur, V.P.; Setty, R.A. Effect of long-term nutrient management on some important properties of a vertisol. *J. Ind. Soc. Soil Sci.* **1998**, *46*, 176–180.
83. Shen, Q.R.; Shen, Z.G. Effects of pig manure and wheat straw on growth of mung bean seedlings grown in aluminium toxicity. *Soil Bioresour. Tech.* **2001**, *76*, 235–240. [\[CrossRef\]](#) [\[PubMed\]](#)
84. Sharma, U.; Paliyal, S.S.; Sharma, S.P.; Sharma, G.D. Effects of continuous use of chemical fertilizers and manure on soil fertility and productivity of maize-wheat under rainfed conditions of the western Himalayas. *Commun. Soil Sci. Plant Anal.* **2014**, *45*, 2647–2659. [\[CrossRef\]](#)
85. Rahman, M.A.; Meisner, C.A.; Duxbury, J.M.; Lauren, J.; Hossain, A.B.S. Yield response and change in soil nutrient availability by application of lime, fertilizer and micronutrients in an acidic soil in a rice-wheat cropping system. In Proceedings of the 17th WCSS, Bangkok, Thailand, 14–21 August 2002.
86. Gawde, N.; Singh, A.K.; Agrawal, S.K.; Kumar, R. Long term effect of integrated nutrient management on soil nutrient status under rice-wheat cropping system in Inceptisols. *Int. J. Chem. Stud.* **2017**, *5*, 1050–1057.
87. Shambhavi, S.; Kumar, R.; Sharma, S.P.; Sharma, S.K.; Sharma, R.P. Effect of 36 years of continuous cropping and fertilization on productivity, micro and secondary nutrient status and uptake by maize-wheat cropping system in western Himalayas. *Int. J. Bio.-Res. Stress. Manag.* **2018**, *9*, 197–202. [\[CrossRef\]](#)
88. Basak, B.B.; Biswas, D.R.; Rattan, R.K. Comparative effectiveness of value-added manures on crop productivity, soil mineral nitrogen and soil carbon pools under maize-wheat cropping system in an Inceptisol. *J. Ind. Soc. Soil Sci.* **2012**, *60*, 288–298.
89. Chang, E.H.; Wang, C.H.; Chen, C.L.; Chung, R.S. Effects of long-term treatments of different organic fertilizers complemented with chemical N fertilizer on the chemical and biological properties of soils. *Soil Sci. Plant Nutr.* **2014**, *60*, 449–451. [\[CrossRef\]](#)
90. Singh, G.P.; Singh, P.L.; Panwar, A.S. Response of groundnut (*Arachishypogaea*) to biofertilizer, organic and inorganic sources of nutrient in North East India. *Legume Res.* **2015**, *34*, 196–201.
91. Kumawat, A.; Kumar, D.; Shivay, Y.S.; Yadav, D.; Sadhukhan, R.; Gawdiya, S.; Jat, R.A. Sustainable basmati rice yield and quality enhancement through long-term organic nutrient management in the Indo-Gangetic Plains. *Field Crops Res.* **2024**, *310*, 109356. [\[CrossRef\]](#)
92. Han, X.; Hu, C.; Chen, Y.; Qiao, Y.; Liu, D.; Fan, J.; Zhang, Z. Crop yield stability and sustainability in a rice-wheat cropping system based on 34-year field experiment. *Eur. J. Agron.* **2020**, *113*, 125965. [\[CrossRef\]](#)
93. Shivashankar, K.; Potdar, M.P.; Gawdiya, S.; Golshetti, A.; Kanade, A.K.; Balol, G.; Salem, A. SPAD dynamics in maize crop with precision nitrogen management under rain-fed and irrigated conditions. *Sci. Rep.* **2025**, *15*, 22842. [\[CrossRef\]](#) [\[PubMed\]](#)
94. Bhattacharyya, R.; Pandey, A.K.; Gopinath, K.A.; Mina, B.L.; Bisht, J.K.; Bhatt, J.C. Fertilization and crop residue addition impacts on yield sustainability under a rainfed maize–wheat system in the Himalayas. *Proc. Natl. Acad. Sci. India Sect. B Biol. Sci.* **2016**, *86*, 21–32. [\[CrossRef\]](#)
95. Bharti, A.; Sharma, R.P.; Sankhyan, N.K.; Kumar, R. Productivity and NPK uptake by maize as influenced by conjunctive use of FYM, lime and fertilizers in an acid Alfisol. *J. Soil Water Cons.* **2021**, *20*, 100–106. [\[CrossRef\]](#)
96. Patial, D.; Sankhyan, N.K.; Sharma, R.P.; Dev, P.; Anjali. Assessing soil physical and chemical properties under long term fertilization after forty-eight years in North-Western Himalayas. *Commun. Soil Sci. Plant Anal.* **2022**, *53*, 2257–2270. [\[CrossRef\]](#)
97. Kumari, G.; Thakur, S.K.; Kumar, N.; Mishra, B. Long-term effect of fertilizer, manure and lime on yield sustainability and soil organic carbon status under maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system in Alfisols. *Ind. J. Agron.* **2013**, *58*, 152–158.
98. Majhi, S.; Thakur, R.; Pal, S.K.; Upasani, R.R.; Puran, A.N.; Kujur, A.N. Long-term influence of nutrient management on productivity and profitability of maize (*Zea mays*)–wheat (*Triticum aestivum*) cropping system. *Ind. J. Agron.* **2018**, *63*, 14–20.
99. Dutta, J.; Sharma, S.P.; Sharma, S.K.; Sharma, G.D.; Sankhyan, N.K. Indexing Soil Quality under Long-Term Maize-Wheat Cropping System in an Acidic Alfisol. *Commun. Soil Sci. Plant Anal.* **2015**, *46*, 1841–1862. [\[CrossRef\]](#)
100. Sharma, K.; Grace, J.K.; Mandal, U.K.; Gajbhiye, P.N.; Srinivas, K.; Korwar, G.; Bindu, V.H.; Ramesh, V.; Ramachandran, K.; Yadav, S. Evaluation of long-term soil management practices using key indicators and soil quality indices in a semi-arid tropical Alfisol. *Soil Res.* **2008**, *46*, 368–377. [\[CrossRef\]](#)
101. Nabiollahi, K.; Heshmat, E.; Mosavi, A.; Kerry, R.; Zeraatpisheh, M.; Taghizadeh-Mehrjardi, R. Assessing the Influence of Soil Quality on Rainfed Wheat Yield. *Agriculture* **2020**, *10*, 469. [\[CrossRef\]](#)
102. Parihar, C.M.; Singh, A.K.; Jat, S.L.; Dey, A.; Nayak, H.S.; Mandal, B.N.; Yadav, O.P. Soil quality and carbon sequestration under conservation agriculture with balanced nutrition in intensive cereal-based system. *Soil Res.* **2020**, *202*, 104653. [\[CrossRef\]](#)

103. Ramteke, P.R.; Vashisht, B.B.; Sharma, S.; Jalota, S.K. Assessing and ranking influence of rates of rice (*Oryza sativa* L.) straw incorporation and N fertilizer on Soil Physicochemical Properties and Wheat (*Triticum aestivum* L.) yield in rice- wheat system. *J. Soil Sci. Plant Nutr.* **2022**, *22*, 515–526. [[CrossRef](#)]
104. Neina, D. The role of soil pH in plant nutrition and soil remediation. *Appl. Environ. Soil Sci.* **2019**, *2019*, 1–9. [[CrossRef](#)]
105. Brady, N.C.; Weil, R.R.; Weil, R.R. *The Nature and Properties of Soils Upper Saddle River*; Prentice Hall: Hoboken, NJ, USA, 2008; Volume 13, pp. 662–710.
106. Das, S.; Bhattacharyya, R.; Das, T.K.; Sharma, A.R.; Dwivedi, B.S.; Meena, M.C.; Chaudhari, S.K. Soil quality indices in a conservation agriculture based rice-mustard cropping system in North-western Indo-Gangetic Plains. *Soil Till. Res.* **2021**, *208*, 104914. [[CrossRef](#)]

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