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BIO-ORGANIC NUTRIENT MANAGEMENT ENHANCES SOIL-PLANT SYSTEM FUNCTIONING AND VARIETAL YIELD RESPONSE OF SHARBATI WHEAT IN VERTISOLS: A PRINCIPAL COMPONENT ANALYSIS APPROACH

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ABSTRACT
Bio-organic nutrient management is increasingly promoted as a sustainable alternative to conventional fertilization; however, its system-level effects on soil health, crop functional traits, and varietal yield realization remain inadequately quantified, particularly in Vertisol-based wheat systems. This study evaluated the integrated response of soil chemical and biological properties, nutrient uptake, grain quality, and yield of sharbati wheat (*Triticum aestivum* L.) under bio-organic management using a multivariate analytical framework. A field experiment was conducted during two consecutive rabi seasons (2015-16 and 2016-17) on Vertisols of central India under a rice-wheat cropping system. Seven bio-organic treatments involving vermicompost, biodynamic preparations (BD-500 and BD-501), and Panchagavya were tested across four wheat varieties. Soil organic carbon, available nutrients, microbial populations, nutrient uptake, grain quality parameters, and grain and straw yield were analyzed. Principal component analysis (PCA) was applied to integrate correlated variables and identify dominant soil-plant system functioning gradients. The soil chemical-biological PCA revealed a dominant integrated fertility-biological axis explaining 78.3% of the total variance, clearly separating integrated bio-organic treatments from the control. A second PCA showed strong coupling between nutrient uptake and grain quality, with the first component explaining 92.9% of the total variability. Grain yield exhibited a strong positive rank-based association with PCA-derived system functioning, while straw yield responded more directly to enhanced system performance. Varietal responses differed significantly, with JW-3020 and C-306 achieving the highest yield gains under high system-functioning conditions.

KEYWORDS: Bio-organic nutrient management; principal component analysis; soil-plant system functioning; nutrient uptake; grain quality; varietal responsiveness; sharbati wheat; Vertisols

1. INTRODUCTION
Wheat (*Triticum aestivum* L.) is one of the most important cereal crops globally and plays a critical role in food and nutritional security, particularly in South Asia. In India, wheat productivity has increased substantially over past decades due to the adoption of high-yielding varieties and intensive nutrient management practices. However, sustained reliance on inorganic fertilizers and input-intensive farming has led to gradual deterioration of soil health, declining nutrient use efficiency, and increasing environmental concerns, especially in cereal-based cropping systems such as rice-wheat rotations (Ladha et al., 2003; Tilman et al., 2011).
Soils under continuous cereal cultivation often exhibit reduced soil organic carbon, nutrient imbalances, and weakened biological activity, which together constrain crop productivity and system sustainability (Lal, 2015; Weil & Brady, 2017). In Vertisol-dominated regions of central India, these challenges are further intensified due to inherent soil characteristics such as high clay content, poor drainage, and limited organic matter replenishment. Improving soil system functioning in such environments requires management strategies that enhance not only nutrient availability but also soil biological processes and organic matter dynamics.
Bio-organic nutrient management practices, including vermicompost, biodynamic preparations, and fermented organic formulations such as Panchagavya, have gained increasing attention as potential alternatives or supplements to

conventional fertilization. These inputs are known to improve soil organic carbon, stimulate microbial activity, and enhance nutrient cycling through biologically mediated pathways (Koepf et al., 1993; Gore & Shreenivasa, 2011; Giannattasio et al., 2013). Unlike synthetic fertilizers, bio-organic inputs act on the soil-plant system holistically, influencing chemical, biological, and physiological processes simultaneously.

Beyond yield enhancement, grain quality has emerged as a critical consideration in wheat production, particularly for premium and specialty wheat types such as sharbati wheat. Grain protein content, gluten strength, and sedimentation value are closely linked to nutrient uptake efficiency and nitrogen metabolism during crop growth (Shewry et al., 2003; Triboi et al., 2006). Management practices that improve nutrient assimilation without compromising soil health are therefore essential for achieving both productivity and quality goals.

Despite growing interest in bio-organic management, most studies continue to evaluate treatment effects using univariate approaches, focusing on individual soil properties, nutrient uptake parameters, or yield components in isolation. Such approaches often fail to capture the integrated and interdependent nature of soil chemical, biological, and crop functional processes. Multivariate techniques, particularly principal component analysis (PCA), offer a powerful framework for synthesizing complex datasets and identifying dominant system-level gradients that govern agroecosystem functioning (Jolliffe & Cadima, 2016).

PCA is especially valuable in agroecological studies where multiple correlated variables interact simultaneously. By reducing dimensionality and minimizing multicollinearity, PCA enables objective identification of integrated soil-plant system responses and facilitates classification of management practices based on overall system performance rather than individual indicators. However, the application of PCA to link soil health, nutrient uptake, grain quality, and varietal yield response under bio-organic management remains limited, particularly in Vertisol-based wheat systems.

Another important but underexplored aspect is varietal responsiveness to improved system functioning. Wheat varieties differ in their ability to exploit enhanced soil fertility and nutrient availability due to inherent differences in root architecture, nutrient use efficiency, biomass partitioning, and sink strength (Foulkes et al., 2011). Understanding how different varieties respond to bio-organic system enhancement is essential for optimizing management strategies and maximizing yield gains under sustainable production systems.

In this context, the present study was undertaken to evaluate the integrated effects of bio-organic nutrient management on soil chemical and biological properties, nutrient uptake, grain quality, and yield of sharbati wheat grown on Vertisols of central India. A multivariate framework was adopted to move beyond conventional single-variable analyses and to capture system-level responses and varietal exploitation efficiency.

2. MATERIALS AND METHODS

2.1 Experimental Site, Soil Characteristics, and Cropping History

The field experiment was conducted during two consecutive rabi seasons (2015-16 and 2016-17) at the Adhartal Research Farm of Jawaharlal Nehru Krishi Vishwavidyalaya (JNKVV), Jabalpur, Madhya Pradesh, India (23°90′ N, 79°90′ E; 411.78 m above mean sea level). The experimental site represents a semi-arid agro-ecological region of central India, characterized by a subtropical climate with hot summers and cool winters. The experimental soil was classified as Vertisol according to USDA Soil Taxonomy, locally known as black cotton soil, developed from basaltic parent material. Vertisols are characterized by high clay content (>30%), pronounced shrink-swell behavior, deep cracking during dry periods, and moderate to poor internal drainage (Soil Survey Staff, 2014). Prior to initiation of the experiment, composite soil samples were collected from the 0-15 cm soil depth across the experimental field using a soil auger to assess baseline soil fertility status. The initial soil was neutral in reaction, normal in electrical conductivity, low in available nitrogen, and medium in available phosphorus, potassium, and organic carbon content. These characteristics are typical of Vertisols under continuous cereal-based cropping systems in the region (Jackson, 2005; Weil & Brady, 2017). The field had a uniform cropping history of rice during the kharif season followed by wheat during the rabi season, with recommended fertilizer application prior to the study period, ensuring relatively homogeneous initial soil conditions.

Table 1. Cropping history and fertilizer application of the experimental field prior to the study

Year	Kharif crop	Rabi crop	Fertility level applied (N : P_2O_5 : K_2O, kg ha^{-1})
2010-11	Rice	Wheat	60 : 30 : 20
2011-12	Rice	Wheat	60 : 30 : 20
2012-13	Rice	Wheat	60 : 30 : 20
2013-14	Rice	Wheat	60 : 30 : 20
2014-15	Rice	Wheat	60 : 30 : 20

2.2 Experimental Design and Treatment Details

The experiment was laid out in a split-plot design with three replications. Bio-organic nutrient management treatments were assigned to main plots, while wheat varieties were allocated to sub-plots. Seven bio-organic treatments were evaluated to represent increasing levels of bio-organic input complexity. The treatments comprised vermicompost (VC) applied at 4 t ha^{-1} either alone or in combination with biodynamic preparations BD-500 (75 g ha^{-1}) and BD-501 (2.5 g ha^{-1}), and Panchagavya applied as a 3% foliar spray. The complete set of treatments included: VC + BD-500, VC + BD-501, VC + Panchagavya, VC + BD-500 + BD-501, VC + BD-500 + BD-501 + Panchagavya, VC alone (control), and an absolute control without any organic input. Four sharbati wheat (*Triticum aestivum* L.) varieties-C-306, Sujata, HW-2004, and JW-3020-were used as sub-plot treatments to evaluate varietal response under different bio-organic nutrient management regimes.

2.3 Crop Management Practices

The wheat crop was grown during the rabi seasons of 2015-16 and 2016-17 following recommended agronomic practices for the region. Certified seeds of the selected wheat varieties were sown within the optimum sowing window using uniform seed rate and spacing across all treatments to maintain comparable plant populations. Field preparation was carried out using conventional tillage practices suitable for Vertisol conditions, followed by land leveling to facilitate uniform irrigation. Vermicompost was incorporated into the soil prior to sowing according to the respective treatment combinations. Biodynamic preparations and Panchagavya were applied as per the treatment schedule, with Panchagavya (3%) administered as foliar sprays at crown root initiation, tillering, and jointing stages. The crop was grown under assured irrigation, and irrigation scheduling was maintained uniformly across all plots to avoid moisture stress. Weed management was carried out manually at critical growth stages, and no chemical herbicides or synthetic inputs were used during the experimental period.

2.4 Soil, Nutrient Uptake, and Grain Quality Analysis

Soil chemical properties, including soil organic carbon and available nitrogen, phosphorus, and potassium, were analysed using standard laboratory procedures. Soil biological properties, including bacterial, fungal, and actinomycetes populations, were estimated using serial dilution and culture-based methods with appropriate selective media. Nutrient uptake by wheat was calculated by multiplying nutrient concentrations in grain and straw by the corresponding yields and expressed on a per-hectare basis. Grain quality parameters, including protein content, gluten content, and sedimentation value, were determined using standard analytical methods commonly employed for wheat quality assessment. All measurements were summarized as treatment-wise and variety-wise mean values across replications and years, forming the basis for subsequent multivariate and statistical analyses. Grain protein content was calculated from grain nitrogen concentration using a standard conversion factor.

Table 2. Procedure for analysis of soil biological properties

S. No.	Biological property	Dilution used	Culture medium / methodology
1	Total bacteria	10^5	Thornton's medium (Thornton, 1930)
2	Total fungi	10^3	Rose Bengal streptomycin agar medium (Rao, 1988)
3	Actinomycetes	10^5	Casein agar medium (Rao, 1988)

2.5 Principal Component Analysis (PCA)

Principal component analysis (PCA) was employed as an exploratory multivariate technique to evaluate integrated responses of soil properties and crop functional traits to bio-organic treatments. Two separate PCA models were developed. The first PCA was performed using soil chemical and biological variables, including soil organic carbon, available nitrogen, phosphorus, potassium, and microbial populations (bacteria, fungi, and actinomycetes), to identify dominant gradients representing soil system functioning. The second PCA was conducted using nutrient uptake variables (nitrogen, phosphorus, and potassium uptake) together with grain quality parameters (protein content, gluten content, and sedimentation value) to assess functional coupling between nutrient assimilation and grain quality formation. Prior to PCA, all variables were standardized to zero mean and unit variance. Eigenvalues, percentage variance explained, and variable loadings were examined to interpret the principal components, and PCA biplots were used to visualize treatment separation.

2.6 Association Between PCA-Derived System Functioning and Yield

To examine the relationship between PCA-derived system functioning and crop productivity, PCA scores were evaluated in relation to grain and straw yield. Linear regression models were initially fitted to assess overall associations; however, given the treatment-level and pooled nature of PCA scores relative to year- and variety-level yield variation, emphasis was placed on rank-based association rather than strict prediction. Spearman's rank correlation analysis was therefore employed to assess the directional association between mean grain yield and the dominant nutrient assimilation-grain quality PCA axis. This non-parametric approach was chosen for its robustness to non-normality and its suitability for evaluating monotonic relationships.

2.7 Classification of System Functioning, Variety Response Analysis, and Statistical Software

Based on the nutrient assimilation-grain quality PCA scores, bio-organic treatments were classified into three system functioning categories, namely low, medium, and high, representing increasing levels of integrated soil-crop functional performance. This PCA-based classification enabled structured comparison of crop yield responses across different degrees of system enhancement. Variety-specific grain yield responses were evaluated across these PCA-derived system functioning classes. Mean grain yield for each wheat variety within each class was calculated to examine trends in yield realization under progressively improved system conditions. To assess statistical differences in grain yield across system functioning classes for individual varieties, non-parametric Kruskal-Wallis tests were employed. This approach was selected due to its robustness to non-normal data distributions and its suitability for comparing yield responses across ordinal system classes without assuming homogeneity of variance. In addition, yield gains between high and low system functioning classes were computed to quantify the magnitude of varietal responsiveness to improved soil and crop functional conditions. All data compilation, statistical analyses, and graphical visualizations were performed using the R statistical computing environment. Principal component analyses were conducted using the *FactoMineR* package, while PCA visualization was carried out using *factoextra*. Data handling, classification, and summary statistics were implemented using packages from the *tidyverse* ecosystem. All analyses were based on datasets compiled directly from treatment-wise and variety-wise experimental tables.

3. RESULTS

3.1 Multivariate Response of Soil Chemical and Biological Properties

The combined response of soil chemical and biological properties to different bio-organic treatments was examined using principal component analysis (PCA). The first two principal components together explained 94.68% of the total variance, indicating a strong and interpretable multivariate structure of the soil system (Table 3).

Table 3. Eigenvalues and variance explained by soil chemical biological PCA

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	5.48	78.27	78.27
PC2	1.15	16.41	94.68
PC3	0.25	3.62	98.30

The first principal component (PC1) alone accounted for 78.3% of the variance and was positively associated with soil organic carbon, available nitrogen, phosphorus and potassium, as well as bacterial and fungal populations. PC1 therefore represents an integrated soil fertility-biological axis, reflecting the cumulative improvement of soil nutrient status and microbial activity under bio-organic management.

The second principal component (PC2), explaining 16.4% of the variance, was dominated by actinomycetes, indicating a microbial functional differentiation axis largely independent of bulk nutrient availability (Table 4). PC1 represents an integrated soil fertility-biological axis, while PC2 represents actinomycetes-dominated functional differentiation.

Table 4. PCA loadings of soil chemical and biological variables

Variable	PC1	PC2
Soil organic carbon	0.879	-0.418
Available nitrogen	0.983	0.141
Available phosphorus	0.939	-0.194
Available potassium	0.987	-0.040
Bacteria	0.983	-0.112
Fungi	0.887	0.260
Actinomycetes	0.362	0.913

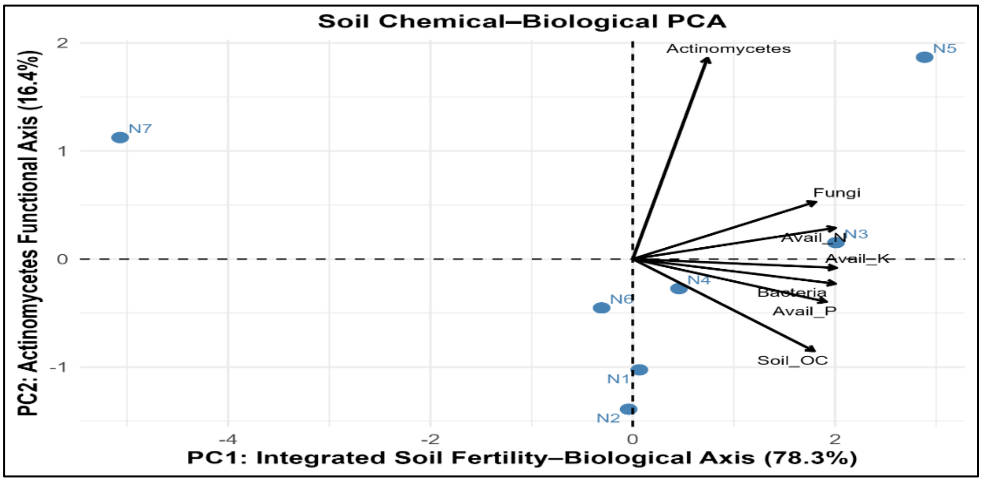

Figure 1. Soil chemical biological PCA biplot

The PCA biplot (Figure 1) clearly illustrates the separation of treatments along these axes. Treatments receiving combined bio-organic inputs, particularly N5 and N3, were positioned on the positive side of PC1, indicating enhanced soil system functioning. In contrast, the absolute control (N7) was located at the negative extreme of PC1, reflecting poor soil fertility and biological activity. Intermediate treatments occupied central positions, suggesting a graded soil response to increasing bio-organic complexity.

3.2 Nutrient Uptake and Grain Quality Relationships

A second PCA was conducted to examine the relationship between nutrient uptake (N, P and K uptake) and grain quality attributes (protein content, gluten content and sedimentation value). This analysis revealed a highly consolidated functional structure, with PC1 alone explaining 92.9% of the total variance and the first two components together accounting for 99.1% (Table 5).

Table 5. Eigenvalues and variance explained by nutrient uptake-grain quality PCA

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	5.57	92.91	92.91
PC2	0.37	6.23	99.14
PC3	0.04	0.72	99.86

All nutrient uptake and grain quality variables loaded strongly and positively on PC1 (Table 6), indicating a tight coupling between nutrient assimilation efficiency and grain quality formation. Accordingly, PC1 was interpreted as a nutrient assimilation-grain quality axis, while PC2 (6.2% variance) captured minor differentiation among quality traits at similar uptake levels.

Table 6. PCA loadings of nutrient uptake and grain quality variables

Variable	PC1	PC2
Nitrogen uptake	0.988	0.117
Phosphorus uptake	0.903	0.413
Potassium uptake	0.991	0.121
Protein content	0.991	−0.061
Gluten content	0.939	−0.337
Sedimentation value	0.968	−0.239

The PCA biplot (Figure 2) shows that treatments receiving integrated bio-organic inputs (notably N5 and N3) clustered at higher PC1 scores, corresponding to superior nutrient uptake and improved grain quality. Treatments with minimal or no bio-organic inputs were positioned at lower PC1 scores, indicating reduced functional performance.

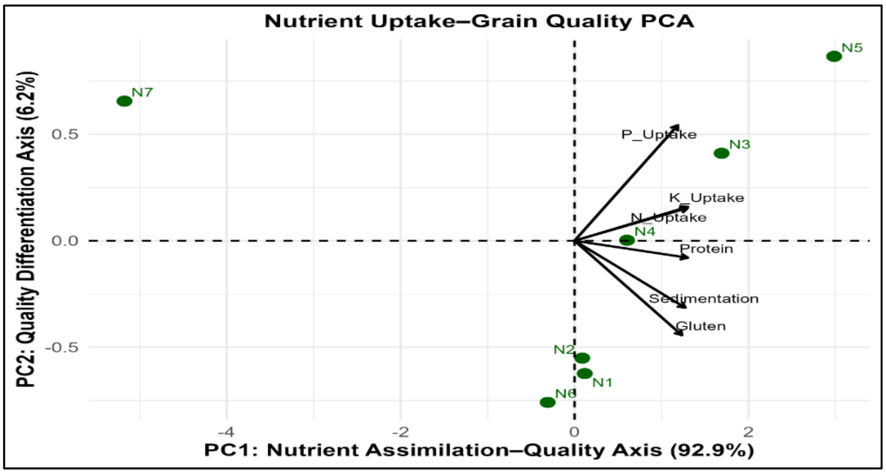

Figure 2. Nutrient uptake-grain quality PCA biplot

3.3 Association Between PCA-Derived System Functioning and Grain Yield

To evaluate how PCA-derived system functioning was associated with grain yield, PCA scores were examined in relation to mean grain yield across treatments. Linear regression models showed significant overall fits but non-significant individual coefficients, reflecting the pooled, treatment-level nature of PCA scores relative to year- and variety-level yield variability. To assess directional consistency, a Spearman rank correlation was performed between mean grain yield and the nutrient assimilation-grain quality PCA axis (PC1). The analysis revealed a strong and statistically significant positive association ($\rho = 0.597$, $p = 0.0008$), indicating that treatments with higher PCA scores consistently achieved higher grain yield ranks (Table 7). This result confirms that PCA captures yield potential and ranking, rather than exact plot-level yield prediction. In addition to grain yield, straw yield also exhibited a positive response to PCA-derived system functioning. Treatments positioned at higher scores along the nutrient assimilation-grain quality PCA axis consistently produced greater straw yield compared to treatments with lower PCA scores. Although individual PCA regression coefficients for straw yield were not statistically significant, the overall trend indicated enhanced biomass production under higher system functioning, reflecting improved resource availability and vegetative growth. This pattern suggests that straw yield responded more directly to integrated soil and nutrient system improvements, whereas grain yield was additionally influenced by varietal partitioning efficiency and inter-annual variability.

Table 7. Association between nutrient assimilation-quality PCA axis and mean grain yield

Test	Statistic	Value	Significance
Spearman rank correlation	ρ	0.597	p = 0.0008

3.4 Variety-Specific Grain Yield Response Across PCA-Based System Functioning Classes

Based on the nutrient assimilation-grain quality PCA axis (PC1), bio-organic treatments were classified into Low, Medium and High system functioning classes (Table 8). This classification enabled evaluation of genotype-specific yield responses across increasing levels of system enhancement.

Table 8. Classification of bio-organic treatments based on PCA scores

Treatment	Quality_PC1 Score	PCA-Based System Class
N1	0.117	Medium
N2	0.088	Low
N3	1.691	High
N4	0.603	Medium
N5	2.984	High
N6	-0.309	Low
N7	-5.175	Low

Across all varieties, grain yield increased monotonically from low to high system functioning classes (Figure 3; Table 9). However, the magnitude of yield response differed substantially among varieties.

Table 9. Variety-wise grain yield across PCA-based system functioning classes

Variety	Low (kg ha⁻¹)	Medium (kg ha⁻¹)	High (kg ha⁻¹)	Yield Gain (High-Low)
C-306	1681	2122	2535	854
HW-2004	1347	1692	1887	540
JW-3020	2672	3323	3595	923
Sujata	1256	1641	1868	611

Among the tested varieties, JW-3020 exhibited the highest absolute yield and the greatest yield gain between low and high system functioning classes (+923 kg ha⁻¹), indicating superior capacity to exploit biologically and nutritionally enriched soil systems. C-306 also showed strong responsiveness (+854 kg ha⁻¹), while Sujata (+611 kg ha⁻¹) and HW-2004 (+540 kg ha⁻¹) displayed consistent but comparatively lower yield gains.

Non-parametric Kruskal-Wallis tests confirmed that yield differences across PCA-based system functioning classes were statistically significant for all varieties ($p < 0.05$), demonstrating that varietal yield responses were systematically linked to changes in system functioning rather than random variation.

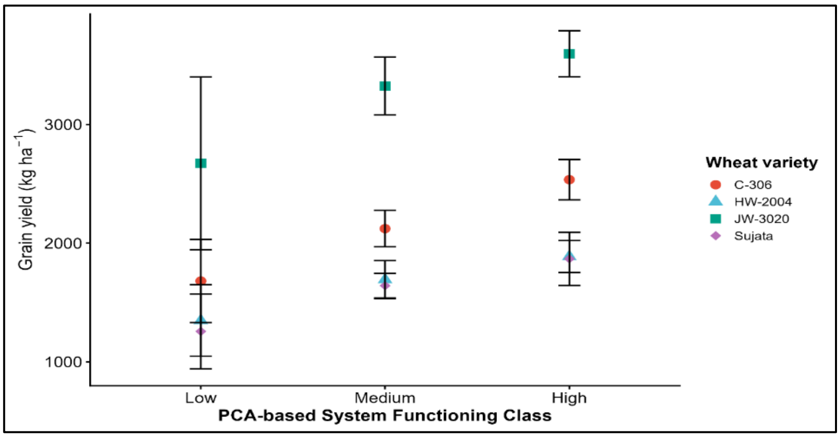

Figure 3. Variety-wise grain yield response across PCA-based system functioning classes

The point–error bar visualization (Figure 3) further illustrates that yield variability was higher under low system functioning and progressively declined under medium and high functioning classes, indicating improved yield stability with enhanced soil–nutrient integration. Among the tested genotypes, JW-3020 exhibited the strongest yield response across system classes, whereas Sujata showed comparatively lower but consistent gains.

3.5 Integrated Interpretation of Bio-Organic Management Effects

The combined findings from soil chemical-biological PCA, nutrient uptake grain quality PCA, yield association analysis and variety-specific response are summarized conceptually in Figure 4. The framework illustrates how bio-organic inputs enhance soil chemical and biological properties, leading to improved nutrient uptake efficiency and grain quality, which collectively increase yield potential. Final yield realization is modulated by genotype responsiveness and inter-annual climatic variability, explaining observed differences among varieties under similar system conditions.

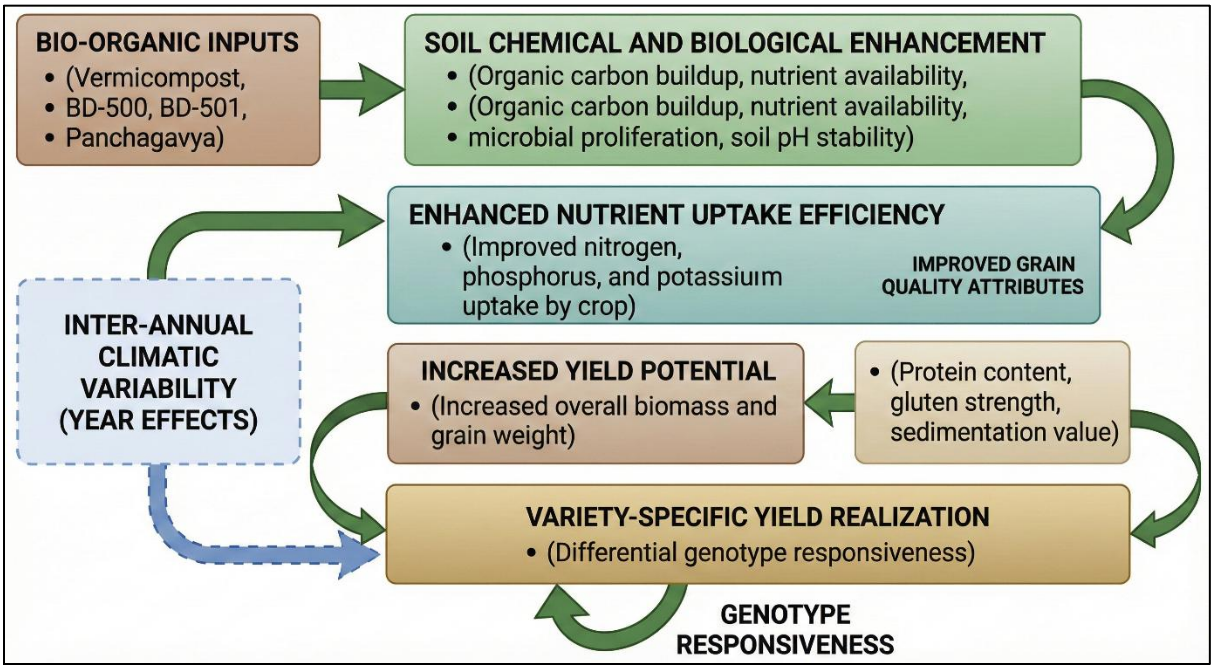

Figure 4. Conceptual framework of bio-organic management effects on soil-plant-yield systems

4. DISCUSSION

4.1 Bio-Organic Management Restructures Soil and Crop Functional Systems

The results clearly demonstrate that bio-organic inputs act as system-level drivers, inducing coordinated changes in soil chemical and biological properties rather than isolated effects on individual variables. The soil chemical-biological PCA showed that a dominant principal component explained most of the variance, reflecting a tightly coupled improvement in soil organic carbon, nutrient availability, and microbial abundance under bio-organic management. This indicates that bio-organic amendments enhance soil functioning through synergistic interactions among chemical fertility and biological activity, rather than through simple nutrient supplementation. The strong association of bacterial and fungal populations with available nutrients along the primary PCA axis highlights the role of microbial mediation in nutrient cycling under bio-organic inputs. The distinct positioning of actinomycetes along the secondary axis suggests functional differentiation among microbial groups, likely reflecting their role in decomposing complex organic substrates. Together, these patterns confirm that bio-organic management enhances both soil fertility and biological complexity, creating a more functionally resilient soil system.

Similarly, the nutrient uptake grain quality PCA revealed an exceptionally strong coupling between nutrient assimilation and grain quality traits. The dominance of a single PCA axis indicates that improved uptake of nitrogen, phosphorus, and potassium directly translates into enhanced protein content, gluten strength, and sedimentation value. This finding emphasizes that bio-organic management improves not only yield-related processes but also the functional quality of wheat grain, reinforcing its relevance for sustainable and quality-oriented production systems.

4.2 Linking System Functioning to Yield Potential

The relationship between PCA-derived system functioning and grain yield provides important insight into how soil and crop processes translate into productivity. While linear regression models did not show significant individual PCA coefficients, the strong and significant Spearman correlation between grain yield and the nutrient assimilation quality PCA axis indicates that improved system functioning consistently corresponds to higher yield ranks across treatments. This demonstrates that PCA effectively captures yield potential and relative performance, even though it does not predict exact plot-level yields. This distinction is critical for interpretation. PCA scores represent treatment-level, pooled indicators of system state, whereas grain yield is influenced by additional layers of variability, including varietal traits and inter-annual climatic conditions. Consequently, PCA-derived indices should be viewed as indicators of the capacity of the system to support yield, rather than deterministic predictors. The stronger explanatory power observed for straw yield compared to grain yield further supports this interpretation, as biomass production is more directly linked to soil resource availability, while grain yield is more tightly regulated by physiological partitioning and environmental modulation.

Overall, these results highlight that yield enhancement under bio-organic management emerges from improved system functioning, but final yield expression depends on how effectively crops convert this potential into harvestable grain.

4.3 Variety-Specific Exploitation of Enhanced System Functioning

A key contribution of this study is the demonstration that wheat varieties differ substantially in their responsiveness to improved system functioning. Classification of treatments into low, medium, and high PCA-based system functioning classes revealed a consistent, monotonic increase in grain yield for all varieties, confirming that bio-organic management benefits wheat productivity across genotypes. However, the magnitude of yield gain varied markedly among varieties, indicating strong genotype-dependent exploitation efficiency. Among the tested varieties, JW-3020 exhibited the highest absolute yield and the largest yield gain between low and high system functioning classes, suggesting superior capacity to capitalize on enhanced soil fertility, nutrient uptake, and grain quality. C-306 also showed strong responsiveness, while Sujata and HW-2004 displayed more moderate yield gains despite clear improvements in system conditions. These differences likely reflect inherent varietal traits related to nutrient use efficiency, biomass allocation, and sink strength.
The integrated conceptual framework developed in this study underscores that bio-organic management enhances soil and crop functional processes, but genotype selection ultimately determines the extent to which this enhanced potential is realized. Therefore, sustainable yield improvement in wheat requires a combined strategy that integrates soil system enhancement through bio-organic inputs with the selection of varieties capable of efficiently exploiting improved system conditions.

5. CONCLUSION

The present study demonstrates that bio-organic management induces a coordinated improvement in soil chemical and biological properties, leading to enhanced nutrient uptake efficiency, improved grain quality, and increased yield potential in wheat. Multivariate analysis revealed that soil organic carbon, nutrient availability, and microbial populations respond synergistically to bio-organic inputs, confirming that such practices act as system-level interventions rather than isolated amendments. The strong coupling observed between nutrient uptake and grain quality highlights that bio-organic inputs improve not only crop productivity but also functional grain attributes critical for end-use quality. Treatments combining multiple bio-organic components consistently occupied favourable positions along the principal component axes, indicating superior system functioning compared to single-input or control treatments. Importantly, yield response to improved system functioning was found to be genotype-dependent. While all tested wheat varieties benefited from enhanced soil and crop functional conditions, the magnitude of yield gain varied substantially among varieties. The superior responsiveness of JW-3020 and C-306 underscores the importance of aligning soil management strategies with varieties capable of efficiently exploiting improved system conditions. Overall, the findings emphasize that sustainable wheat production under bio-organic management requires an integrated approach that combines soil system enhancement with informed varietal selection. Such integration can maximize yield potential, improve grain quality, and contribute to environmentally sustainable intensification of wheat-based cropping systems.

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