Kalim *et al. BMC Plant Biology* (2026) 26:926
https://doi.org/10.1186/s12870-026-09003-w

BMC Plant Biology

RESEARCH Open Access

Restoring soil functionality and improving wheat yield through integrated farmyard manure, compost, crop residues and decomposition enhancers

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Abstract

Background Wheat productivity is frequently constrained by the slow turnover of soil organic matter (OM), which limits nutrient mineralization and reduces their bioavailability to plants. In this context, the present study was conducted to assess the effects of different OM sources on wheat growth, phenological attributes, yield attributes, chlorophyll content and soil physicochemical properties, with a focus on improving sustainable nutrient management strategies for improving wheat productivity and soil health.

Results A field experiment was conducted over two consecutive winter seasons (2022–2023 and 2023–2024) at The University of Agriculture, Peshawar-Pakistan. The experimental design comprised two factors: (i) OM sources supplying 120 kg N/ha, including no residue (control), farmyard manure (FYM), compost, and wheat crop residues; and (ii) decomposition-enhancing materials (DM), namely control, Bio-organic phosphate (100 kg/ha), Bio-aab at the rate of 25 L ha^{-1} (microbial biofertilizer), and humic acid at the rate of 15 kg ha^{-1} was applied as leonardite-derived granular humic acid containing 70% humic substances. OM along with DM were incorporated into the soil 7 days before sowing under optimal field moisture conditions using a field cultivator. Wheat cultivar 'Pirsabak 2015' was sown at a seed rate of 120 kg/ha. Experiment was arranged in a RCB design with three replications. Individual plots measured 3 × 5 m and consisted of 10 rows with 30 cm inter-row spacing. The incorporation of OM delayed phenological development relative to the no-residue control. Among the tested treatments, FYM and compost consistently resulted in greater plant height (86.32 and 86.38 cm), spike density (236 and 239 m^{-2}), grains number (45 and 45), grain weight (41.94 and 41.47 g), biological yield (10385 and 10385 kg ha^{-1}), grain yield (2977 and 2998 kg ha^{-1}), and chlorophyll content (chlorophyll a: 23.37 and 23.07; chlorophyll b 44.74 and 45.59; and total chlorophyll: 68.66 and 68.88). Among DM, humic acid improved wheat growth traits, including plant height (87 cm), spikes m^{-2} (245), grains spike^{-1} (46), grain weight (43 g), biological yield (10452 kg ha^{-1}), grain yield (3013 kg ha^{-1}) and chlorophyll content, compared with other treatments, resulting in better biomass accumulation. Regarding soil fertility, Bio-aab or Bio-organic phosphate combined with FYM or compost increased soil mineral nitrogen, organic matter, total nitrogen

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and organic carbon. The highest net income in economic analysis (279415 ha^{-1}) was recorded in FYM + humic acid treatment. The highest value cost ratio (VCR) was observed in no residue + humic acid, followed by FYM + Bio-aab and FYM + humic acid.

Conclusion Across both seasons, the combination of FYM and compost with humic acid improved crop growth and yield, while untreated plots recorded the lowest values. Integrated application of FYM or compost with humic acid, Bio-aab or Bio-organic phosphate is recommended to enhance wheat productivity and improve soil fertility under semi-arid conditions.

Keywords Farmyard manure, Humic acid, Chlorophyll content, Grain yield, Soil fertility, Sustainable agriculture

Introduction

Wheat (*Triticum aestivum* L.) is the most widely cultivated staple crop worldwide, providing a major source of calories and protein for human population [1, 2]. In Pakistan, it occupies the largest cropped area and plays a central role in national food security [3]. In Pakistan, the total area under wheat cultivation is approximately 8.825 million hectares, with a total production of 24.946 million tones. In Khyber Pakhtunkhwa, wheat is also a key crop, contributing about 1.260 million tones from an area of 0.732 million hectares, reflecting its importance in the regional cropping system [4]. The soils of Khyber Pakhtunkhwa province are characterized by low organic matter (OM) and nutrient deficiencies, leading to reduced crop productivity, especially under dry and semi-arid conditions. Recent soil surveys in northern Pakistan indicate that OM levels are often poorly characterized (typically less than 1%) and nutrient conditions vary widely, highlighting the need for better nutrient management and organic amendments to sustain crop production [5].

Soil quality and crop productivity can be significantly improved through positive soil modifications such as the application of biofertilizers and humic substances, which enhance nutrient and stimulate microbial activity [6, 7]. The decomposition of OM produces humic acid, which improve nutrient availability, enhance soil structure and water retention and stimulates microbial activity in the rhizosphere [8, 9]. Recent study has confirmed that humic substances significantly improve wheat growth, yield and nutrient uptake by enhancing soil fertility and physiological efficiency of plants [10]. Humic acids have been shown to improve crop yield of crops and nitrogen utilization efficiency by improving nutrient mobilization and biological activity within the soil [11]. In addition, the amendment of humic acid with the use of microbial fertilizers, including plant growth-promoting rhizobacteria (PGPR), enhances soil physicochemical properties, microbial networks and crop yields [12]. Furthermore, humic acid combine with organic sources has been found to improve the chemical characteristics of soil and enhance nutrient uptake, soil nutrients content, leading to higher growth and yield in crops [13].

Bio-aab-based formulations act as plant growth-promoting microbial inoculants that enhance nutrient availability through nitrogen fixation, phosphate solubilization, and rhizosphere activity, thereby improving wheat growth and yield [14]. Large scale field experiments in semi-arid wheat systems showed that Bio-aab combined with organic manures significantly improves plant height, dry matter and grain yield, highlighting its role in integrated nutrient management strategies [15]. In contrast, humic acid does not directly participate in decomposition processes; rather, it acts as a non-living organic bio-stimulant derived from humified organic matter. It enhances wheat growth through physiological and biochemical regulation, including improved root development, increased membrane permeability, greater nutrient uptake efficiency, and hormone-like activity (auxin and cytokinin effects), ultimately leading to higher biomass accumulation and grain yield [14]. Therefore, while bio-aab and bio-organic phosphate primarily act through microbially mediated decomposition and nutrient cycling in soil, humic acid operates through direct plant physiological stimulation and improved nitrogen use efficiency (NUE), highlighting fundamentally different mechanistic pathways in wheat-based agroecosystems.

The application of farmyard manure (FYM), has a substantial impact on soil productivity. Organic manure composed of plant and animal remains, provide essential nutrients upon decomposition, improving soil structure [16]. FYM is widely recognized for its role in enhancing soil health and fertility in cereal-based cropping systems by significantly increasing soil organic carbon and nutrient availability [17, 18]. Combining organic amendments with mineral fertilizers offers synergistic advantages, enhancing multiple soil characteristics and improving crop productivity beyond what is achieved with mineral fertilizers alone [19]. In addition to OM, decomposition-enhancer materials like bio-aab, Bio-organic phosphate, and humic acid play an essential role in nutrient cycling. These DM accelerate the breakdown of organic materials, releasing nutrients in forms readily available to plants. The synergy between DM and OM soil fertility, microbial biodiversity, and crop performance. Research suggests that incorporating effective DM not only improves soil structure but also contributes to sustainable agricultural practices by reducing the need for synthetic fertilizers and improving long-term soil health [20, 21]. Despite considerable research on biofertilizers, organic manures, and humic substances, limited information is available on their comparative and mechanistic roles when applied under the same wheat production system. In particular, there is a lack of integrated studies distinguishing the effects of microbial decomposer-based inputs (Bio-aab and bio-organic phosphate) from non-microbial bio-stimulants such as humic acid on soil properties and wheat productivity under agro-climatic conditions of Khyber Pakhtunkhwa. Therefore, this study hypothesizes that bio-aab and Bio-organic phosphate mainly enhance wheat performance through microbial-mediated decomposition and nutrient mineralization, whereas humic acid acts primarily through physiological stimulation and improved nutrient uptake, and that their combined application with organic manures may produce synergistic improvements in soil health and yield. The primary objective of this study is to evaluate the effects of organic-amendments materials (OM sources) and decomposition-enhancing materials (DM) on wheat performance and find out appropriate DM and OM for wheat production.

Methodology

Experimental site and weather conditions

The experiment was carried out at The University of Agriculture Peshawar's Agronomy Research Farm during winter 2022-23 and 2023–2024 (Altitude: 331 m, latitude: 34.0151ºN and 71.5249ºE). A composite soil sample was taken at a depth of 0–15 cm before incorporation of OM and DM to determine the physicochemical properties of the experimental site (Table 1). Figure 1 illustrates the meteorological conditions at the experimental site over the two wheat cropping seasons (2022–2023 and 2023–2024). The weather data was collected from the local weather station.

Table 1 Physicochemical properties of the experimental soil

Property	Values
pH	7.7
EC (dS m^{-1})	0.2
Sand (%)	8.4
Silt (%)	51.4
Clay (%)	37
Texture class	clay loam
CEC (cmolc kg^{-1})	29.6
Bulk density (mg^{-3})	1.4
Total N (g kg^{-1})	0.6
Total organic C (g kg^{-1})	12.4
Total P (g kg^{-1})	0.22
Total K (g kg^{-1})	13.7
Available N (mg kg^{-1})	13.3
Available P (mg kg^{-1})	3.3
Available K (mg kg^{-1})	74.3

Chemical analysis of nitrogen sources

The nitrogen sources (farmyard manure, wheat residues and compost) were analyzed for total nitrogen by using Kjeldahl method [22]. The FYM, wheat residue and compost contained 0.9%, 0.8% and 0.5% nitrogen content. To apply 120 N ha^{-1}, 13 tones ha^{-1} farmyard manure, 15 tones ha^{-1} wheat residue and 20 tones ha^{-1} compost were incorporated.

Treatments details and setup

The experiment was structured as a two-factor factorial arrangement. Factor A consisted of four organic-amendments matter (OM) sources applied to supply 120 kg N/ha, including no residue, farmyard manure (FYM), compost, and wheat crop residues. The no residue treatments represented the absence of organic amendment input within this factor. Factor B comprised of four decomposition-enhancing materials (DM), namely control (no DM application), Bio-organic phosphate (100 kg ha^{-1}), Bio-aab at the rate of 25 L ha^{-1} (microbial biofertilizer), and humic acid at the rate of 15 kg ha^{-1} was applied as leonardite-derived granular humic acid containing 70% humic substances. This product represents a purified humic fraction obtained from naturally humified organic matter, primarily used as soil bio-stimulant to enhance plant physiological processes and nutrient uptake. Bio-aab is a liquid microbial fertilizer formulated as a decomposer consortium containing beneficial decomposer and nutrient-solubilizing microorganisms (Trichoderma spp) to stimulate microbial activity, promote organic matter decomposition and enhance nutrient mineralization. The no DM treatment represented the absence of microbial or humic based inputs within this factor. The nitrogen content of each OM source was determined prior to application to ensure equivalent nitrogen input across treatments. OM along with DM were incorporated into the soil 7 days before sowing under optimal field moisture conditions using a field cultivator. Subsequently, the wheat cultivar 'Pirsabak 2015' was sown at a seed rate of 120 kg/ha. Experiment was arranged in a RCB design with three replications. Individual plots measured 3 × 5 m and consisted of 10 rows with 30 cm inter-row spacing and a row length of 5 m. Standard agronomic practices, including irrigation and weed management, were uniformly maintained across all treatments to minimize non-treatment variability.

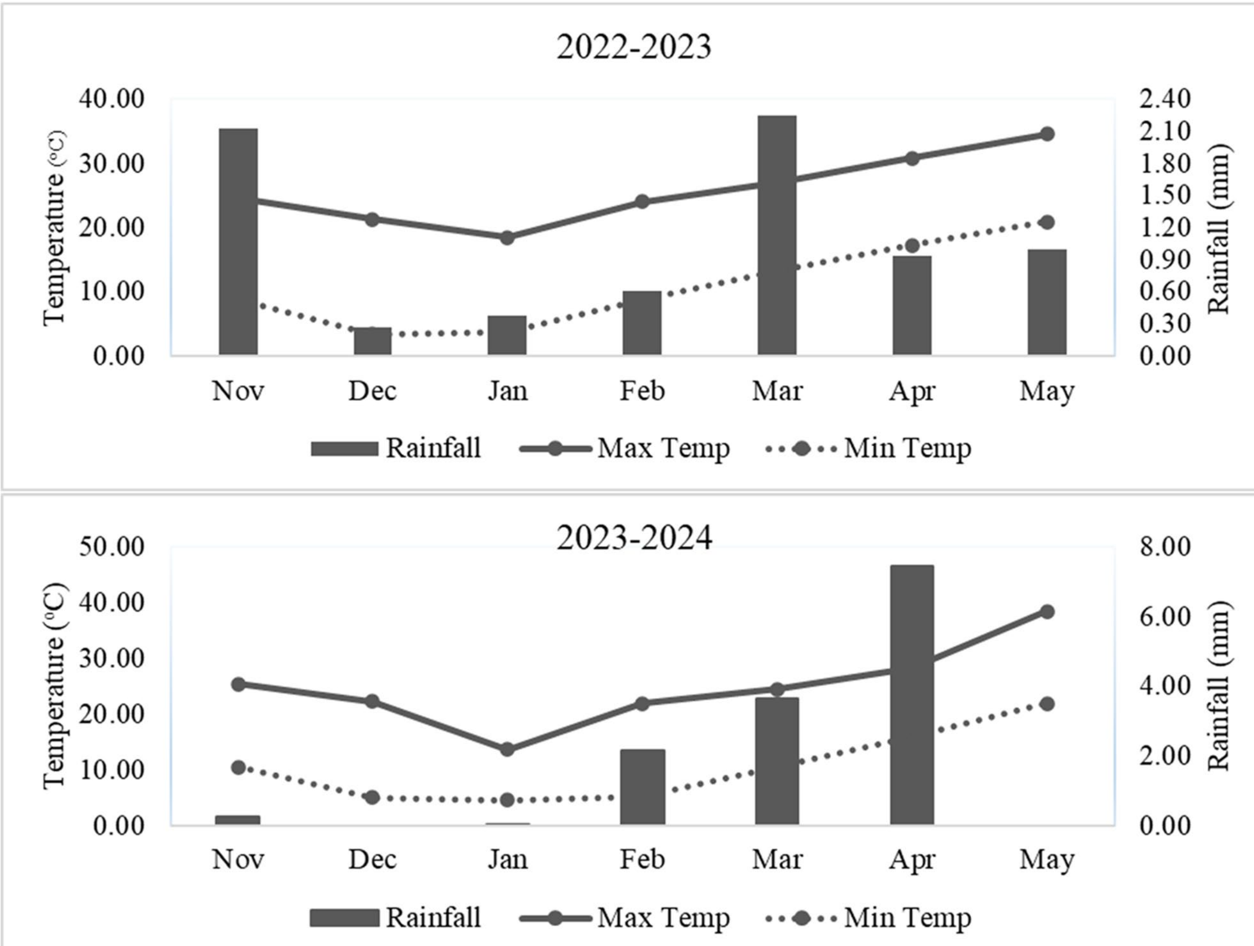

Fig. 1 Weather data of the experimental location across two wheat growing seasons (2022-23 and 2023-24)

Observation and their procedures

Phenological traits and growth parameters

Phenological development was monitored throughout the growing period using standard criteria, with key stages recorded based on the time from sowing until 80% of plants in each plot reached specific growth phases. Days to booting, anthesis, and physiological maturity were defined as the number of days from sowing to when 80% of plants attained the booting stage, fully emerged spikes, and physiological maturity, respectively. Plant height was measured at maturity using ten randomly selected plants from each experimental unit. Measurements were taken from the soil surface to the tip of the spike, excluding awns using a measuring tape, and mean values were calculated. At the anthesis stage, ten representative leaves per plot were selected to determine leaf area. Leaf length and maximum width were measured using a ruler, and average leaf area was subsequently estimated.

Yield and yield components

Spike density was determined by counting spikes number within a one-meter row segment at three arbitrarily selected locations in each plot unit. The recorded values were averaged and subsequently converted to spikes per square meter. From each plot, ten representative spikes were randomly collected, and the number of grains per spike was counted and averaged to determine grains number spike^{-1}. Thousand-grain weight was measured by counting 1000 grains from each sample and weighing them using a digital balance, with results expressed in grams. For yield estimation, four central rows from each plot were harvested to avoid border effects, sun-dried to a constant moisture level, and weighed. The recorded yield was then converted to kg ha^{-1}. The harvest index was calculated as the ratio of grain yield to total aboveground biological yield and expressed as a percentage.

Determination of chlorophyll content

Leaf pigment concentrations were quantified spectrophotometrically following solvent extraction. For each plot, 200 mg of fresh flag leaf tissue was immersed in 5 mL of 80% (v/v) acetone and incubated in the dark at 4 °C for 48 h in the dark in the refrigerator to ensure complete pigment extraction. The resulting extract was then analyzed using a spectrophotometer, and absorbance was recorded at 663.2 and 646.8 nm. Chlorophyll a, chlorophyll b and total chlorophyll contents were subsequently calculated based on the recorded absorbance values. The pigment concentration was computed using Lichtenthaler's technique [23] and given in mg g^{-1} of leaf FW.

$$\text{Chl a } (\mu g/\text{ ml}) = 12.25A_{663.2} - 2.79A_{646.8}$$

$$\text{Chl b } (\mu g/\text{ ml}) = 21.50A_{646.8} - 5.10A_{663.2}$$

$$\text{Total chl } (\mu g/\text{ ml}) = 7.15A_{663.2} + 18.71A_{646.8}$$

Whereas A represents absorbance reading.

Soil parameters

Soil physicochemical properties were determined by taking soil sample at a depth of 0–15 cm after the wheat harvest following standard procedures. Soil pH and electrical conductivity (EC) were measured in a 1:5 soil-water suspension using a calibrated pH and EC meter as described by Thomas [24] and Rhoades [25], respectively. Soil organic matter was quantified using the wet oxidation (Walkley-Black) method, as outlined by Nelson and Sommers [26]. Soil mineral nitrogen was extracted using potassium chloride (KCl) and analyzed by steam distillation with the Kjeldahl method, according to Keeney and Nelson [27]. Soil organic carbon was determined using a modified dichromate oxidation method, as described by Nelson and Sommers [26], while total soil nitrogen was measured using the Kjeldahl digestion procedure outlined by Bremmer and Mulvaney [28]. Soil moisture content was determined gravimetrically by oven-drying fresh soil samples at 105 °C until a constant weight was achieved.

Statistical analysis

The data were analyzed using the RCB design, with inter-treatment comparisons performed via the LSD test at a 5% significance level ($P < 0.05$) as per Jan et al. [29]. Graphs, principal component analysis, and Pearson correlation were performed using Origin Pro 2025 and R-Program. The Shapiro-Wilk test showed that some variables were normally distributed ($p > 0.05$), while others exhibited minor but statistically significant deviations from normality ($p < 0.05$). Q-Q plots confirmed that these deviations were small and the data were deemed appropriate for parametric analysis.

Results

Phenological traits

Organic-amendments matter significantly influenced the phenological development of wheat across both growing seasons but not significant for DM however DM significantly affected days to anthesis in the first season (Fig. 2A-C). Days to booting was delayed in plots where wheat residue (115 days) and FYM (115 days) was applied, while early days to booting was noted in no residue plots (113 days) (Fig. 2A). Year-wise comparison show in the second year early booting was observed. All the interactions were non-significant for days to booting. In OM treatment, the application of FYM (126 days) and compost (125 days) delayed days to anthesis, while no residue plots showed the earliest anthesis (124 days) (Fig. 2B). In the first year, the application of Bio-aab (127 days) and humic acid (127 days) delayed the anthesis stage, while control plots recorded the earliest anthesis (125 days). The interaction between OM x DM and Year x OM x DM were significant, while Year x OM and Year x DM were non-significant. In OM treatment, FYM (157 days) and compost (157 days) resulted in delayed maturity, while no residue plots matured earlier (156 days) (Fig. 2C). The interaction between OM x DM was significant, while Year x OM, Year x DM and Year x OM x DM were non-significant.

Morphological traits

The application of different OM sources and DM significantly affected average leaf area and spikes m^{-2}. The plant height was significantly affected by OM in both years, while DM had a significant effect in first year but non-significant effect in second year (Fig. 3A-C). Among Om treatments, compost (86.38 cm) and FYM (86.32 cm) producing the tallest plants, while no residue plots recorded the lowest plant height (80.09 cm) (Fig. 3A). In DM treatments, humic acid (73.47 cm) produced the highest plant height in the second year, while control plots produced the lowest plant height (66.15 cm). In OM treatments, FYM (26.44 cm^2) and compost (25.01 cm^2) had the largest leaf area, while no residue plots had the smallest leaf area (21.81 cm^2) (Fig. 3B). Among DM treatments, humic acid recorded the highest leaf area (29.56 cm^2), while the lowest values were recorded in control plots (20.44 cm^2). The highest spikes m^{-2} was produced in compost (239) and FYM (236) plots, while lowest spikes m^{-2} was recorded in the no residue plots (205) (Fig. 3C). Among DM treatments, the plots receiving humic acid had highest number of spikes m^{-2} (245), while control treatment produced the lowest values (212). Year-wise comparison indicated that an increase was noted in 2023–2024 than 2022–2023. All the interactions were found to be non-significant for plant height,

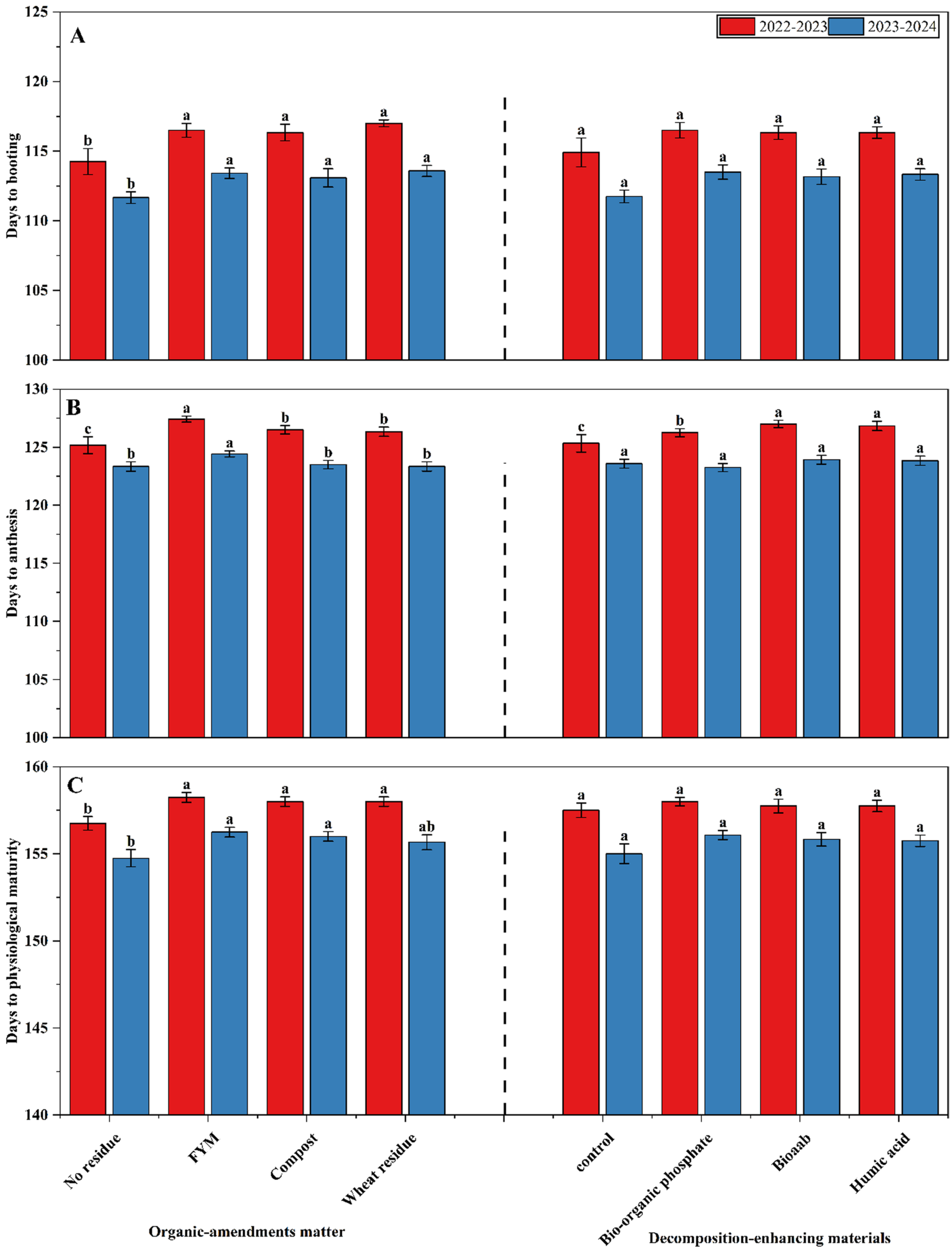

Fig. 2 Mean effect OM sources and DM on days to (**A**) booting, (**B**) anthesis and (**C**) physiological maturity of wheat during the 2022–2023 and 2023–2024 growing seasons

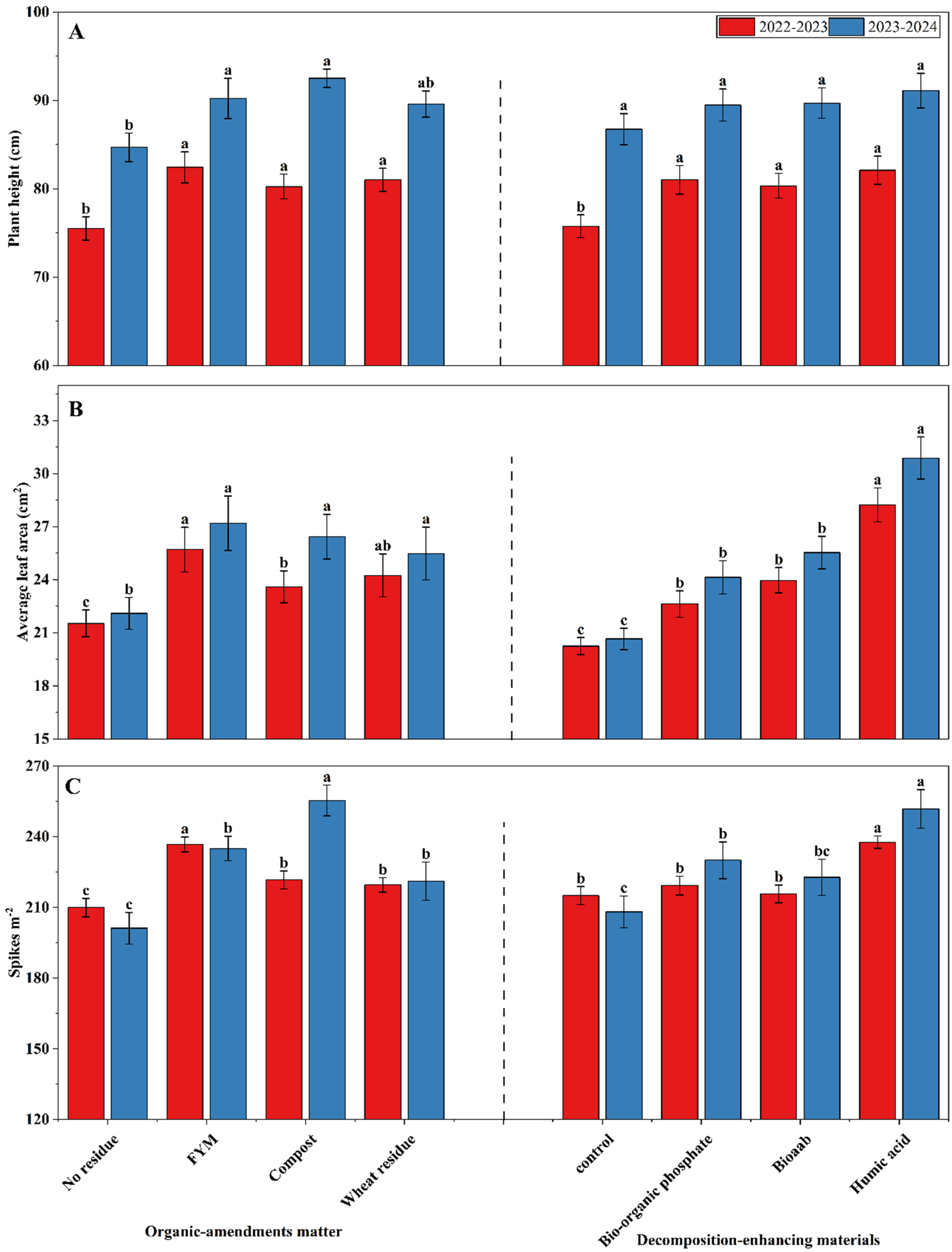

Fig. 3 Mean effect of OM and DM on (**A**) plant height (**B**) average leaf area and (**C**) spikes m^{-2} of wheat during the 2022–2023 and 2023–2024 growing seasons

average leaf area and spikes m^{-2} but only Year x OM was significant for spikes m^{-2}.

Yield components

Across both growing seasons, OM sources and DM significantly influenced key yield components of wheat, including grains per spike, thousand-grain weight, and biological yield, with consistent treatment effects observed across both seasons (Fig. 4A-C). In grains $spik^{-1}$, the highest values were recorded in FYM (45) and compost (45) followed by wheat residue (41), while no residue produced the lowest grains $spike^{-1}$ (37). Among DM treatments, humic acid showed the highest grains $spike^{-1}$ (46) followed by Bio-aab (43) and Bio-organic phosphate (42), whereas the control treatment recorded the lowest grains $spike^{-1}$ (36). Thousand grain weight also followed a similar trend. The highest thousand grain weight was observed in FYM (41.94 g) and compost (41.47 g), while the lowest values were recorded in no residue treatment (35.97 g). Among DM treatments, humic acid resulted in the highest thousand grain weight (43.40 g), while the control showed the lowest values (34.52 g). The highest biological yield was recorded by FYM (10385 kg ha^{-1}), while no residue treatment produced the lowest biological yield (8415 kg ha^{-1}). Among the DM treatments, humic acid produced the highest biological yield (10452 kg ha^{-1}), followed by Bio-aab (9679 kg ha^{-1}) and Bio-organic phosphate (9669 kg ha^{-1}), whereas the control recorded the lowest biological yield (8484 kg ha^{-1}). Year-wise comparison showed an overall improvement in 2023–2024 compared to 2022–2023 for all three traits. Interaction showed that OM x DM was non-significant for all three parameters. However, Year x OM showed significant effects for all traits, while Year x DM was significant for grain $spike^{-1}$ thousand grain weight and biological yield. The three-way interaction (Year x OM x DM) remained non-significant across all parameters.

Grain yield, harvest index and Soil pH

The OM and DM significantly influenced grain yield and soil pH across both years, while OM and DM significantly affected harvest index in the first year, while in the second year the effect was found non-significant (Fig. 5A-C). Grain yield was significantly higher in compost (2998 kg ha^{-1}) and FYM (2977 kg ha^{-1}), while no residue produced lowest grain yield (2375 kg ha^{-1}). Among DM treatments, humic acid resulted in the highest grain yield (3013 kg ha^{-1}) followed by Bio-aab (2789 kg ha^{-1}) and Bio-organic phosphate (2763 kg ha^{-1}), whereas control treatment recorded the lowest grain yield (2409 kg ha^{-1}) (Fig. 5A). Year-wise comparison recorded that an increase in grain yield was noted in 2023–2024 than 2022–2023. All the interactions for grain yield were non-significant. In the first year, the highest harvest index was recorded with compost (29.06%), while no residue recorded the lowest harvest index (26.65%). Among DM application, the highest harvest index was recorded in humic acid (28.95%), while the lowest was recorded at control treatment (26.81%) (Fig. 5B). Year-wise means increased slightly from 2022 to 2023 to 2023–2024. Interaction between Year x OM and Year x DM were significant, while the interaction between OM x DM and three-way interaction remained non-significant. Among OM sources, compost (7.74) and FYM (7.77) resulted in relatively lower soil pH, while wheat residue showed the higher soil pH (7.93) (Fig. 5C). Among the DM treatment, humic acid produced the lowest soil pH (7.65), while control recorded the highest soil pH (7.88). Interaction between OM x DM and Year x OM were significant, while Year x DM and Year x OM x DM were non-significant.

Chlorophyll contents

The analyzed data showed that OM sources and DM exhibited a significant effect on chlorophyll contents of wheat across both experimental seasons (Fig. 6. A-C). Among OM treatments, the highest chlorophyll a was recorded in FYM (22.37) and compost (23.07), while no residue plots showed the lowest value (20.35) (Fig. 6A). Among DM treatments, humic acid produced the highest chlorophyll a (23.34), whereas control recorded the lowest values (21.06). Chlorophyll b followed the similar trend as compost (45.59) and FYM (44.74) produced the highest chlorophyll b, while no-residue plots showed the lowest values (41.32) (Fig. 6A). Among DM treatment, humic acid resulted in the highest chlorophyll b (45.46), whereas control showed the lowest value (41.68). The highest chlorophyll a + b was recorded in compost (68.88) and FYM (68.66), while no residue plots recorded the lowest value (62.72) (Fig. 6C). Among the DM treatments, humic acid resulted in the highest chlorophyll a + b (69.61), whereas the lowest values were recorded in control treatments (63.10). All the interactions were found to be non-significant for chlorophyll contents (a, b and a + b).

Soil electrical conductivity, organic matter and organic carbon

Across both growing season, OM and DM significantly impacted soil electrical conductivity, organic matter content and organic carbon (Fig. 7A-C). The highest electrical conductivity was recorded in no residue (0.75 dS m^{-1}), while lowest values were recorded in compost (0.58 dS m^{-1}) (Fig. 7A). Among DM treatment, control showed the highest electrical conductivity (0.68 dS m^{-1}), followed by Bio-aab and Bio-organic phosphate (0.66 dS m^{-1} each), whereas humic acid produced the lowest

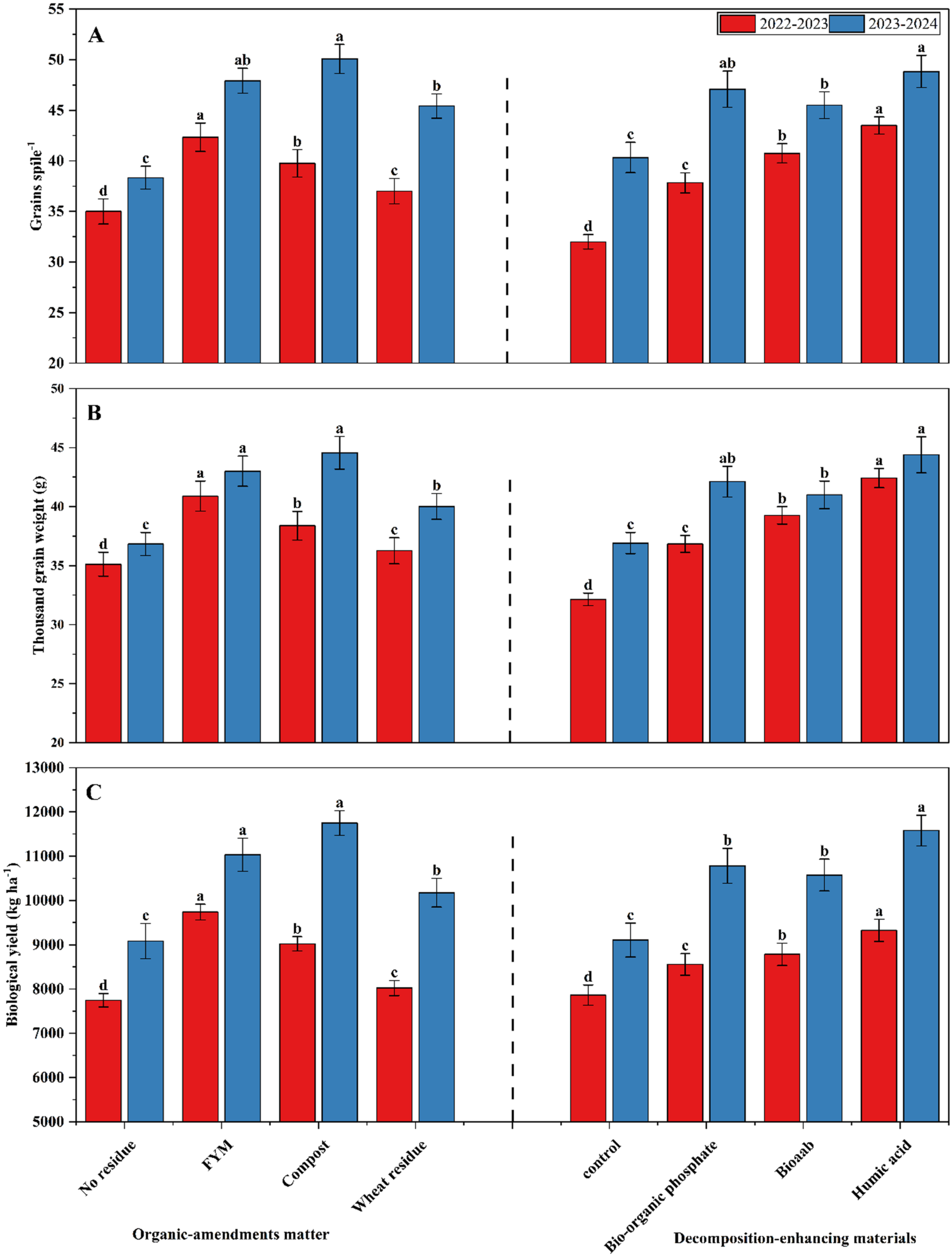

Fig. 4 Mean effect of OM and DM on (**A**) grains spike-1, **B** grain weight and (**C**) biological yield of wheat during the 2022-2023 and 2023-2024 growing seasons

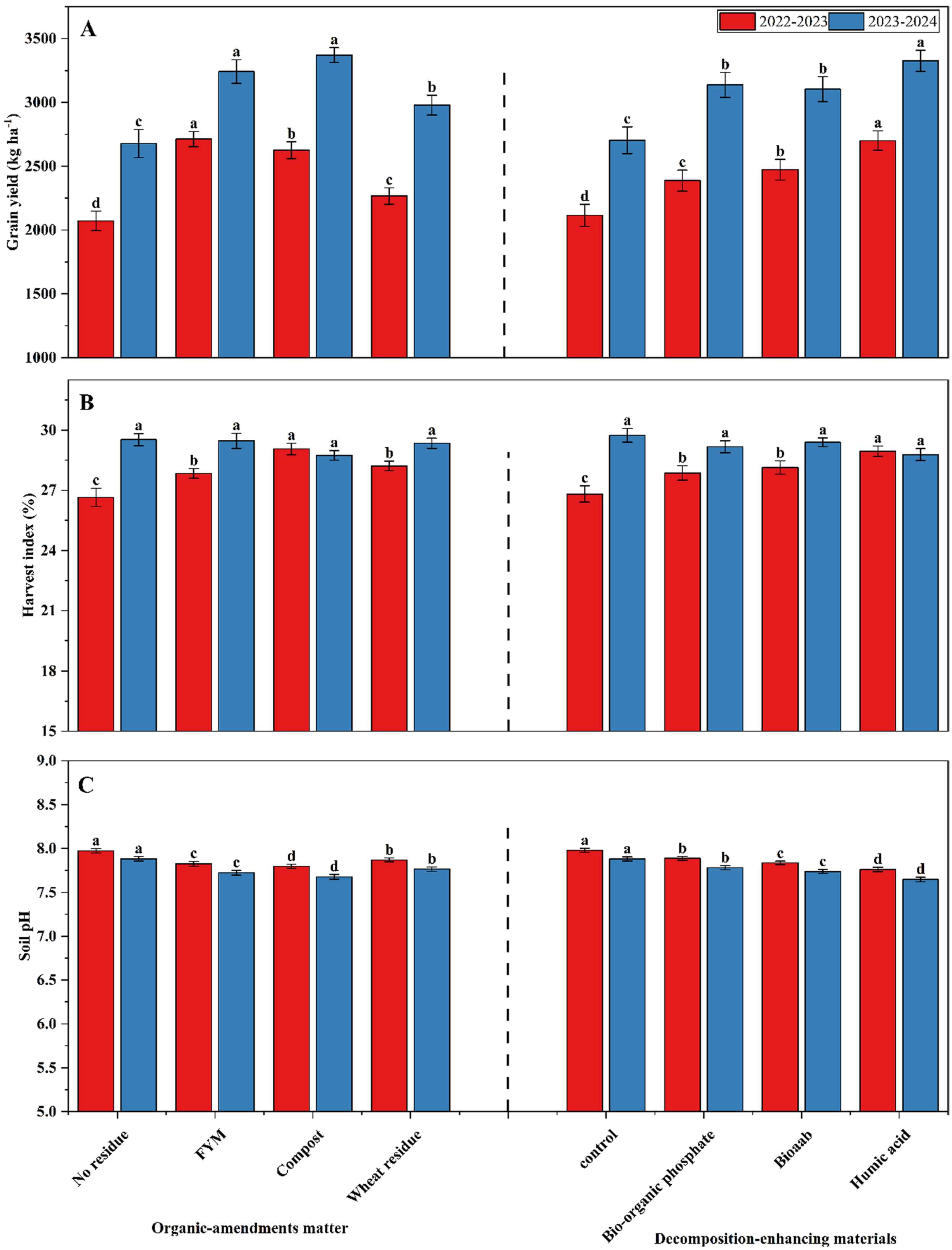

Fig. 5 Mean effect OM and DM on (**A**) grain yield, (**B**) harvest index (%) and (**C**) Soil pH of wheat during the 2022–2023 and 2023–2024 growing seasons

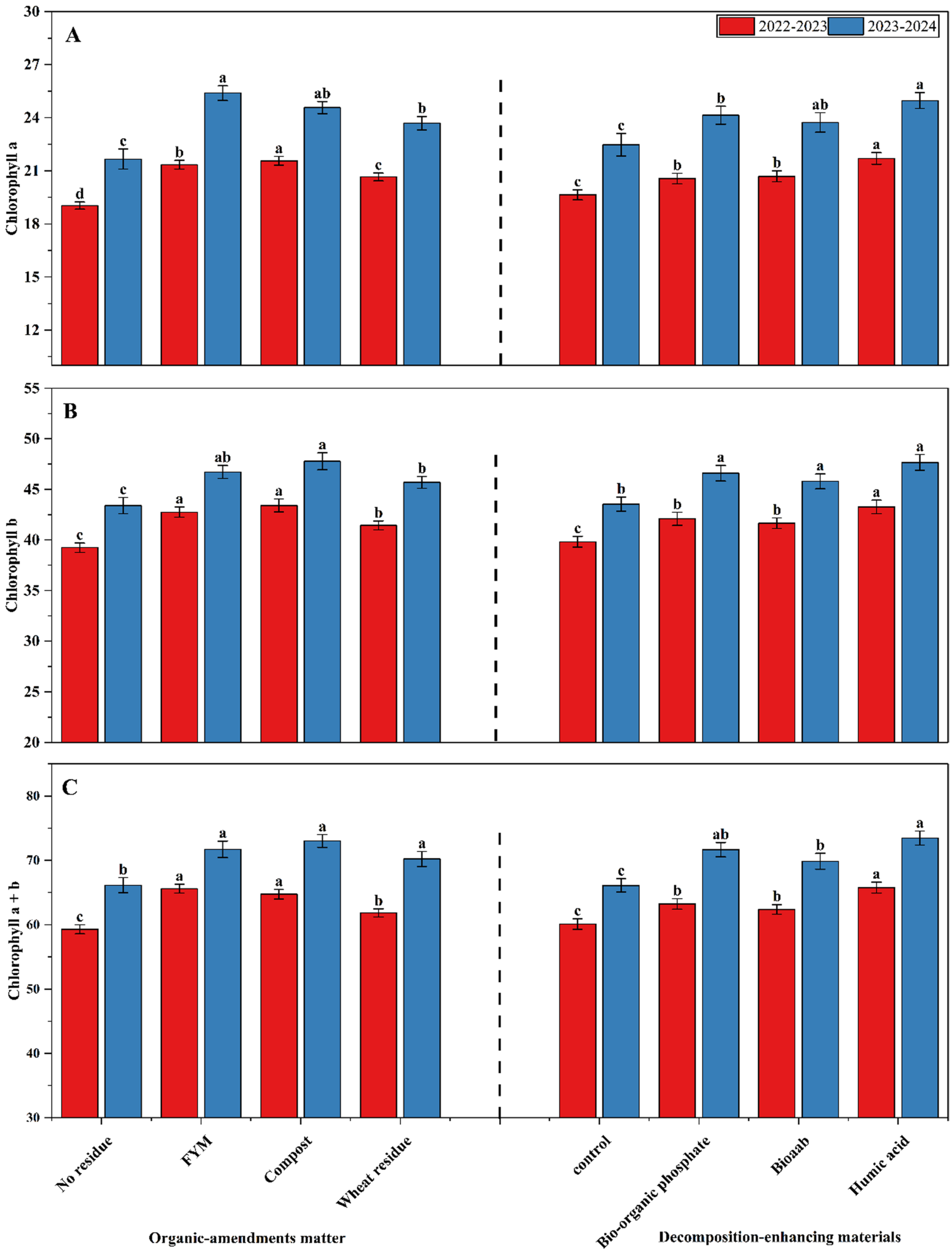

Fig. 6 Mean effect of OM and DM on (**A**) chlorophyll a, **B** chlorophyll b and (**C**) chlorophyll a + b of wheat during the 2022–2023 and 2023–2024 growing seasons

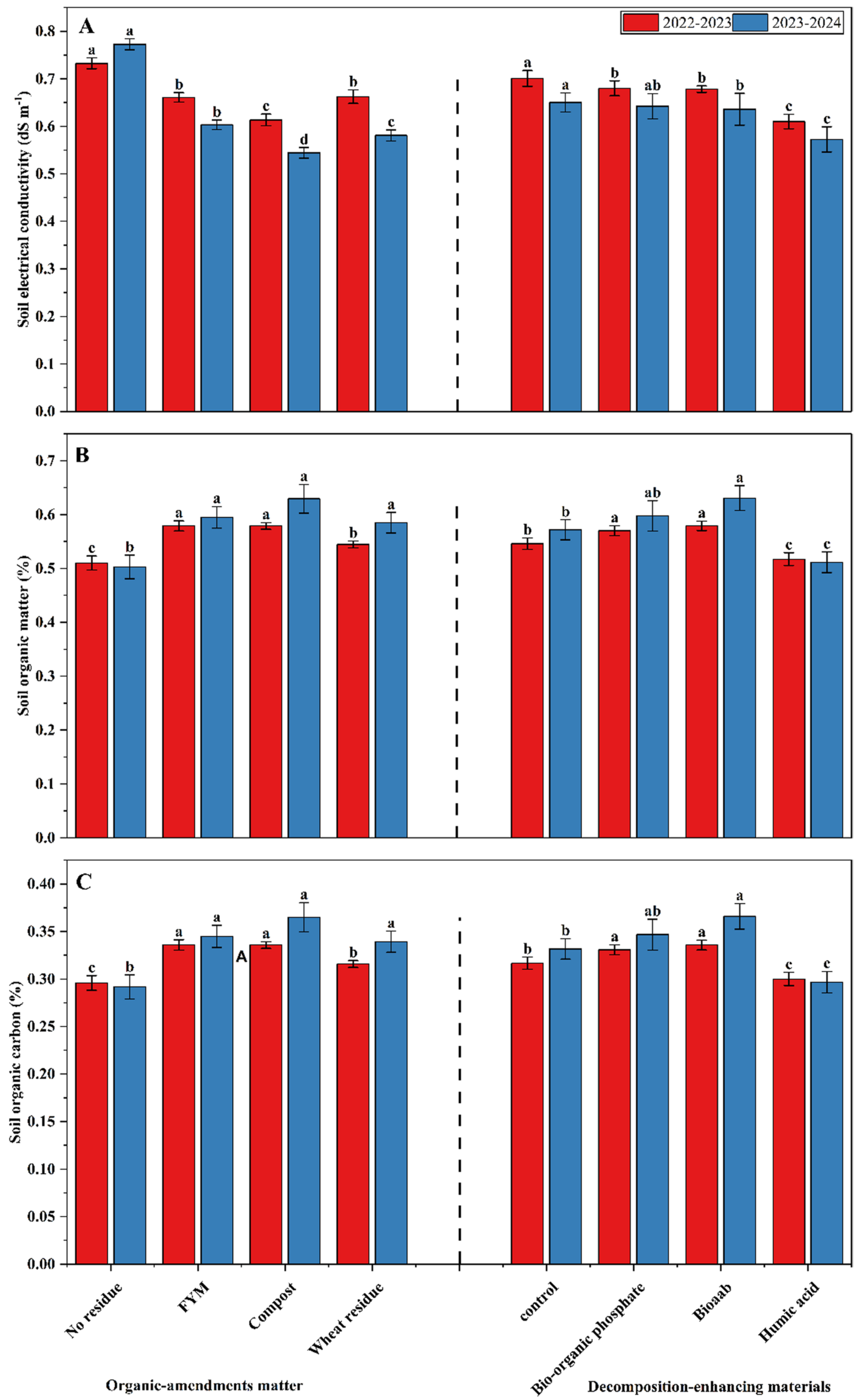

Fig. 7 Mean effect of OM and DM on (**A**) soil electrical conductivity (**B**) soil organic matter and (**C**) soil organic carbon of wheat during the 2022–2023 and 2023–2024 growing seasons

electrical conductivity (0.59 dS m^{-1}). Year-wise comparison showed that a slight decrease in 2023–2024 than 2022–2024. The interaction between OM x DM, Year x OM and Year x OM x DM were significant, while Year x DM was non-significant. Soil organic matter had a similar trend as soil electrical conductivity (Fig. 7B). The highest organic matter was recorded in compost (0.60%) and FYM (0.59%), while no residue plots showed the lowest organic matter (0.51%). Among DM treatment, Bio-aab (0.61%) and Bio-organic phosphate (0.58%) produced the highest organic matter, whereas humic acid recorded the lowest organic matter (0.51%). All the interactions were non-significant for organic matter. Soil organic carbon followed a similar trend (Fig. 7C). Among OM treatments, compost (0.35%) and FYM (0.34%) recorded the highest soil organic carbon, while no residue plots showed the lowest soil organic carbon (0.29%). Among DM treatments, Bio-aab (0.35%) and Bio-organic phosphate (0.34%) produced the highest soil organic carbon, whereas humic acid recorded the lowest soil organic carbon (0.30%). Year-wise comparison showed an increase in 2023–2024 from 2022 to 2023. All the interactions were found non-significant for soil organic carbon.

Soil mineral nitrogen, total nitrogen and moisture content

Across both experimental seasons, OM and DM influenced soil mineral nitrogen, total nitrogen but moisture content was not significant for OM (Fig. 8A-C). Among OM application, the highest soil mineral nitrogen was recorded in compost (80.38 mg kg^{-1}) and FYM (77.63 mg kg^{-1}), while the lowest soil mineral nitrogen was observed in no residue (74.88 mg kg^{-1}) (Fig. 8A). Among DM application, Bio-aab (82.25 mg kg^{-1}) and Bio-organic phosphate (79.25 mg kg^{-1}) produced the highest soil mineral nitrogen, whereas humic acid resulted in the lowest mineral nitrogen (71.88 mg kg^{-1}). The interaction between OM x DM and Year x DM were significant, while Year x OM and Year x OM x DM were non-significant. Soil total nitrogen followed the similar trend as among OM, the compost (0.16%) and FYM (0.15%) recorded the highest soil total nitrogen, while no residue plots showed the lowest soil total nitrogen (0.13%) (Fig. 8B) Among DM treatment, Bio-abb (0.16%) and Bio-phosphate (0.15%) resulted in the highest soil total nitrogen, whereas humic acid recorded the lowest soil total nitrogen (0.14%). Year-wise comparison showed an increased from 2022 to 2023 to 2023–2024. The interaction between OM x DM, Year x OM and Year x OM x DM were non-significant, while Year x DM was found significant for soil total nitrogen. OM and DM had a non-significant effect soil moisture in both growing years (Fig. 8C).

Economic analysis

Economic analysis of OM and DM for wheat production is presented in Table 2. The results revealed significant variation in gross income, net income and value cost ratio (VCR) among treatments. The highest net income (Rs. 279415 ha^{-1}) was recorded in FYM combined with humic acid, followed by compost + humic acid (Rs. 270645 ha^{-1}) and compost + Bio-aab (Rs. 254906 ha^{-1}). In contrast, the lowest net income (Rs. 172931 ha^{-1}) was recorded in no residue with control treatments. Similarly, VCR ranged from 3.29 to 4.15. the highest VCR (4.15) was obtained under no residue + humic acid closely followed by FYM + Bio-aab (4) and FYM + humic acid (3.99), while lowest VCR (3.29) was recorded in compost + control treatment. Overall, FYM and compost based systems exhibited higher economic returns compared to wheat residue and no residue treatments. Among decomposers, humic acid and Bio-aab consistently enhanced profitability and VCR.

Correlation analysis

The correlation analysis revealed strong relationships among phenological traits, physiological parameters, yield components and soil properties of wheat (Fig. 9). Phenological traits including days to booting, days to anthesis and days to physiological maturity showed a significant correlation with each other ($r = 0.50–0.64$), indicating synchronized development. Growth and yield attributes such as leaf area, spikes m^{-2}, grains $spike^{-1}$, thousand grain weight, biological yield and grain yield exhibited positive associations ($r = 0.55–0.97$). Grain yield was particularly significantly correlated with biological yield ($r = 0.97$), grains $spike^{-1}$ ($r = 0.87$) and chlorophyll traits (Chl a, Chl b and Chl a + b; $r = 0.84–0.90$), suggesting that improved photosynthetic activity contributed to higher productivity. In contrast, soil pH and electrical conductivity showed negative correlations with most growth and yield traits. Soil pH exhibited strong negative associations with LA (r = -0.70), spikes m^{-2} (r = -0.66), GPS (r = -0.87), TWG (r = -0.84) and GY (r = -0.86), while similar trends were observed for SEC. Conversely, soil fertility indicators such as soil organic matter, soil organic carbon, soil mineral nitrogen and soil total nitrogen were positively correlated with yield and physiological traits. Grain yield showed moderate positive relationships with SOC ($r = 0.36$), SMN ($r = 0.18$) and STN ($r = 0.59$). STN showed a positive relationship with yield components and overall productivity. It was positively correlated with GY ($r \approx 0.59$), BY ($r \approx 0.51$), grains $spike^{-1}$ ($r \approx 0.48$) and thousand grain weight ($r \approx 0.36$), indicating that improved nitrogen availability enhances both vegetative growth and reproductive development, ultimately contributing to higher yield formation. In contrast, soil physical condition such as Soil pH exhibited strong

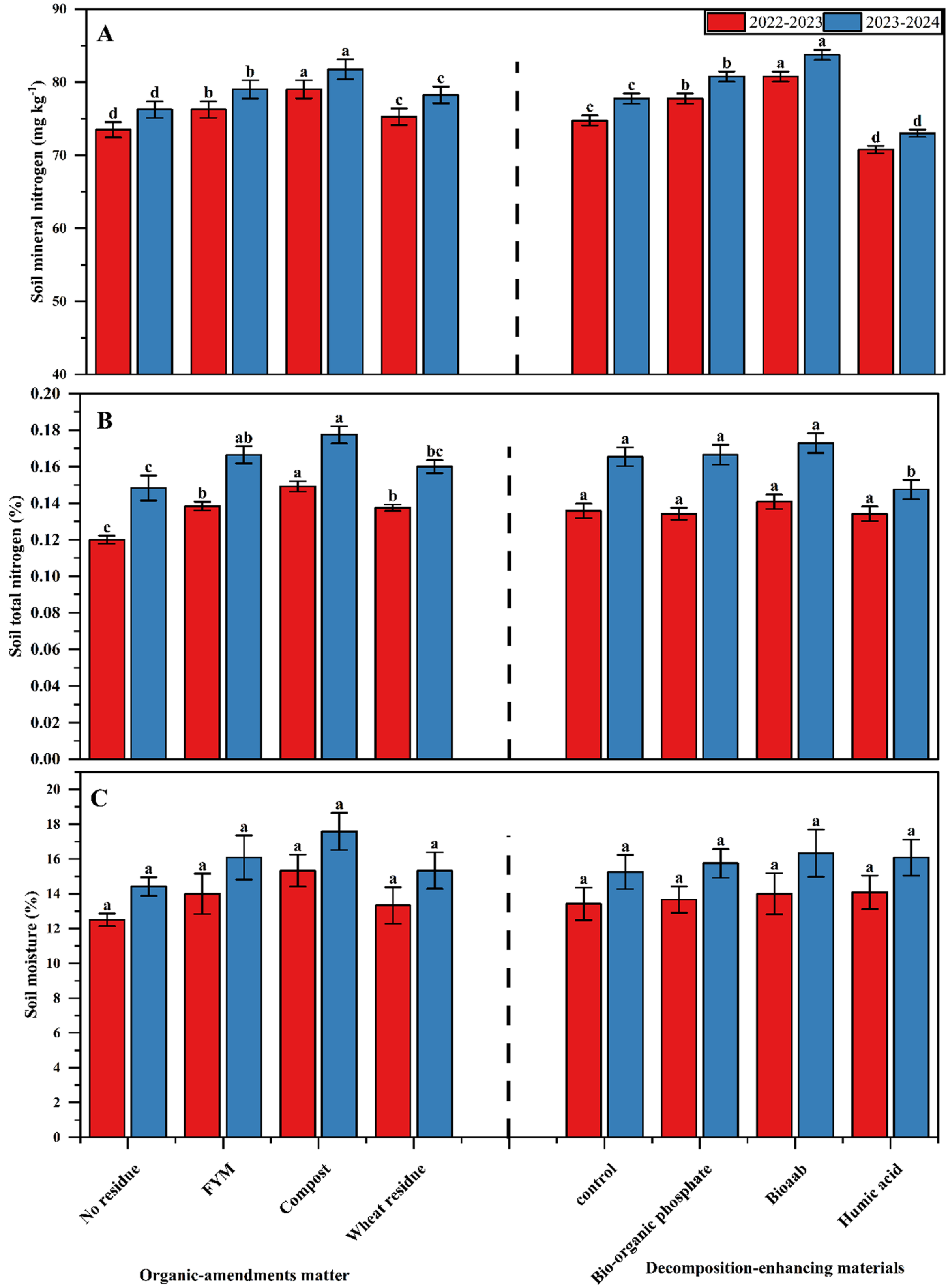

Fig. 8 Mean effect of OM and DM on (**A**) soil mineral nitrogen (mg kg^{-1}), **B** soil total nitrogen (%) and (**C**) soil moisture content (%) of wheat during the 2022–2023 and 2023–2024 growing seasons

Table 2 Economic analysis of wheat as affected by various organic matter sources and decomposition enhancing materials

OM	DM	GY (kg ha^{-1})	SY (kg ha^{-1})	Grain value (Rs)	Straw value (Rs)	Gross income (Rs)	SSP cost (Rs)	K (Rs)	OM cost (Rs)	DM cost (Rs)	Seed cost (Rs)	Cultivation cost (RS)	Labour charges (Rs)	Total expenditure (Rs)	Net income (Rs)	VCR
No residue	control	2003	7409	140,233	81,497	221,731	5400	8400	0	0	12,000	15,000	8000	48,800	172,931	3.54
No residue	BOP	2383	8487	166,833	93,353	260,187	5400	8400	0	7200	12,000	15,000	8000	56,000	204,187	3.65
No residue	Bi-oaab	2388	8407	167,183	92,472	259,655	5400	8400	0	4200	12,000	15,000	8000	53,000	206,655	3.90
No residue	HA	2725	9357	190,750	102,922	293,672	5400	8400	0	8250	12,000	15,000	8000	57,050	236,622	4.15
FYM	control	2642	9181	184,917	100,986	285,902	5400	8400	13,000	0	12,000	15,000	8000	61,800	224,102	3.63
FYM	BOP	3008	10,420	210,583	114,616	325,200	5400	8400	13,000	7200	12,000	15,000	8000	69,000	256,200	3.71
FYM	Bio-aab	3050	10,587	213,500	116,455	329,955	5400	8400	13,000	4200	12,000	15,000	8000	66,000	263,955	4.00
FYM	HA	3208	11,353	224,583	124,881	349,465	5400	8400	13,000	8250	12,000	15,000	8000	70,050	279,415	3.99
compost	control	2708	9422	189,583	103,644	293,227	5400	8400	19,500	0	12,000	15,000	8000	68,300	224,927	3.29
compost	BOP	3033	10,565	212,333	116,211	328,545	5400	8400	19,500	7200	12,000	15,000	8000	75,500	253,045	3.35
compost	Bio-aab	3033	10,461	212,333	115,073	327,406	5400	8400	19,500	4200	12,000	15,000	8000	72,500	254,906	3.52
compost	HA	3217	11,094	225,167	122,029	347,195	5400	8400	19,500	8250	12,000	15,000	8000	76,550	270,645	3.54
Wheat residue	Control	2283	7923	159,833	87,153	246,986	5400	8400	8100	0	12,000	15,000	8000	56,900	190,086	3.34
Wheat residue	BOP	2625	9206	183,750	101,261	285,011	5400	8400	8100	7200	12,000	15,000	8000	64,100	220,911	3.45
Wheat residue	Bio-aab	2683	9260	187,833	101,862	289,695	5400	8400	8100	4200	12,000	15,000	8000	61,100	228,595	3.74
Wheat residue	HA	2900	10,005	203,000	110,051	313,051	5400	8400	8100	8250	12,000	15,000	8000	65,150	247,901	3.81

Grain value: 70 kg^{-1} (PKR), Straw value: 11 kg^{-1} (PKR), SSP: 60 kg^{-1} (PKR), Potassium: 280 kg^{-1} (PKR), FYM: 1000 ton^{-1} (PKR), Compost: 1300 ton^{-1} (PKR), Wheat residue: 540 ton^{-1} (PKR), BOP: 60 kg^{-1}, Bio-aab: 280 L^{-1}, HA: 550 kg^{-1}

PKR Pakistani rupees, *GY* Grain yield, *SY* Straw yield, *SSP* single super phosphate, *VCR* value cost ratio

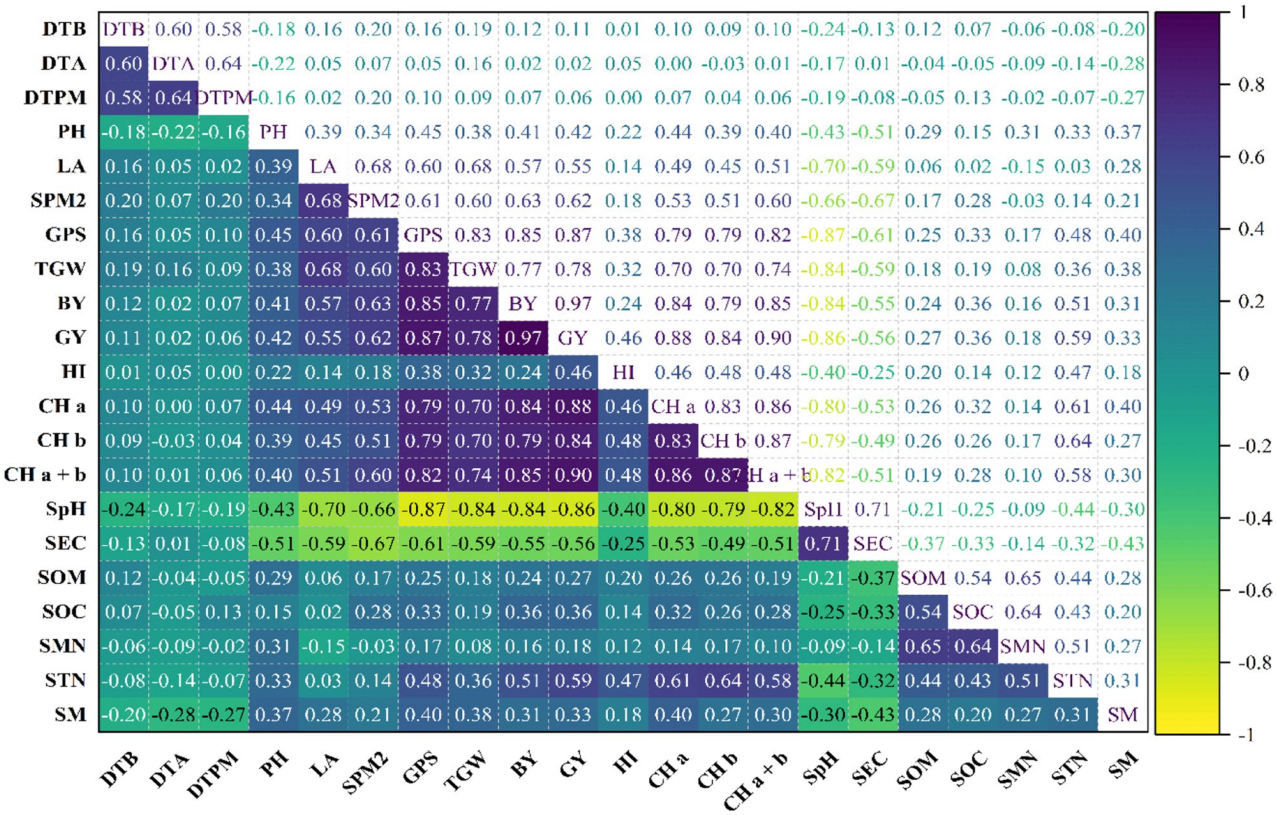

Fig. 9 Correlation coefficient analysis of wheat as effected by organic-amendments matter and decomposition-enhancing materials over the two years

negative correlations with yield components, including grain yield ($r \approx -0.86$), biological yield ($r \approx -0.84$), grains spike^{-1} ($r \approx -0.87$), thousand grain weight ($r \approx -0.84$) and spikes m^{-2} ($r \approx -0.66$). The correlation matrix highlights that improved soil fertility and enhanced photosynthetic traits are closely associated with higher wheat productivity, whereas elevated soil pH and electrical conductivity tend to negatively influence crop performance.

Principal component analysis

The principal component analysis (PCA) revealed substantial variation among measured traits with the first two principal components explaining 58.06% of the total variance (PC1 = 44.73% and PC2 = 13.33%) (Fig. 10). The higher contribution of PC1 Indicates that it is the dominant axis separating treatments based on yield, physiological and soil fertility attributes. The first principal component (PC1) was mainly associated with yield and physiological traits which included leaf area, plant height, grains spike^{-1}, thousand grain weight, biological yield, grain yield, harvest index and chlorophyll contents as well as soil fertility indicators such as soil organic matter, soil mineral nitrogen and soil total nitrogen. These traits were positively loaded on the positive side of PC1, indicating their stronger contribution to improved wheat productivity. In contrast, soil pH and electrical conductivity were positioned on the negative side of PC1, showing an inverse relationship with growth and yield related attributes. The second principal component (PC2) was mainly associated with phenological traits, including days to anthesis days to booting and days to physiological maturity, which were positioned towards the upper region of the biplot. These traits were clearly separated from yield related variables, including an independent variation pattern in crop development. The treatment distribution showed clear clustering patterns. Improved nutrient and amendment treatments such as FYM combined with humic acid, compost, bio-organic phosphate and Bio-aab were mainly positioned on the positive side of PC1, indicating their positive influence on yield and physiological traits. In contrast, control, no residue and wheat residue treatments were generally located on the negative side of PC1, reflecting lower performance. Year-wise separation was also evident, where Y2 (2023–2024) treatments were mostly associated with higher yield and physiological performance, while Y1 (2022–2023) showed relatively higher association with phenological variation and lower yield attributes, Overall, the PCA biplot demonstrates that improved soil fertility and enhanced physiological traits were closely linked with higher wheat productivity, whereas higher soil pH and electrical conductivity were negatively associated with crop performance. Although

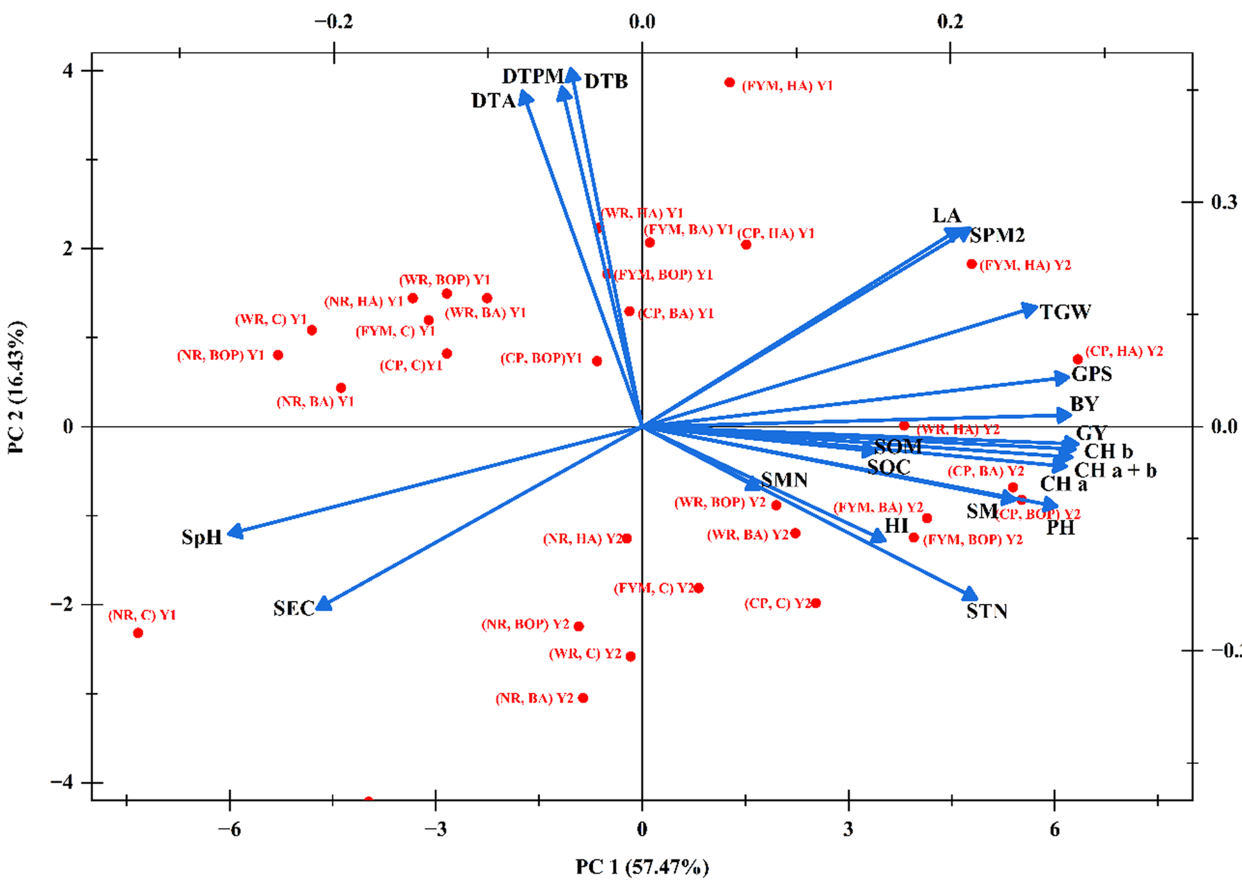

Fig. 10 Principal component analysis for the studied traits of wheat under different OM and DM. NR = No residue, FYM = Farmyard, CM = Compost, WR = Wheat residue, C= Control, BOP = Bio-organic phosphate, BA = Bio-aab, HA = Humic acid, Y1 =2022-2023, Y2 = 2023-2024

PC1 and PC2 together explained 58.06% of the total variance, a substantial proportion (42%) remained unaccounted for, indicating that additional variability exists beyond the two principal components. Therefore, the PCA biplot should be interpreted as a simplified representation of the relationships among variables rather than a complete depiction of system variability.

Structural Equation Model

Latent variables in the structural equation model were constructed based on biological relevance and functional similarity among measured parameters. Soil-related physicochemical properties (pH, EC, SOM, SOC, SMN, STN, and SM) were grouped into the "soil" construct to represent overall soil fertility status. Chlorophyll traits and leaf area were grouped as the "Plant" construct to reflect physiological and photosynthetic performance. Morphological and reproductive traits contributing directly to productivity were grouped into the "yield components" construct, while developmental timing variables were assigned to the "Phenological" construct. Structural paths among latent variables were specified a priori based on established agronomic understanding that soil properties influence plant physiological performance, which subsequently affects yield components and final grain yield. The structural equation model (SEM) was applied to examine the relationships among soil properties, plant physiological traits, yield components, phenological characteristics and grain yield (GY) (Fig. 11). In this model, four latent constructs were defined: soil, plant, yield components and phenological traits. The soil construct was represented by soil fertility indicators including pH (0.91), soil electrical conductivity (SEC; 0.90), soil organic matter (SOM; 0.95), soil organic carbon (SOC), soil mineral nitrogen (SMN; 0.51), soil total nitrogen (STN; 0.99) and soil moisture (SM; 0.91), indicating that these variables strongly contributed to the soil fertility status. The plant construct included physiological attributes such as chlorophyll a (CH a; 0.76), chlorophyll b (CH b; 0.92), total chlorophyll (CH a + b) and leaf area (LA; 0.70), reflecting the photosynthetic efficiency and plant growth performance. The yield component construct was represented by plant height (PH; 0.99), spikes per square meter (SPM^2; 0.97), grains per spike (GPS), thousand grain weight (TGW), biological yield (BY), and harvest index (HI), which are major determinants of crop

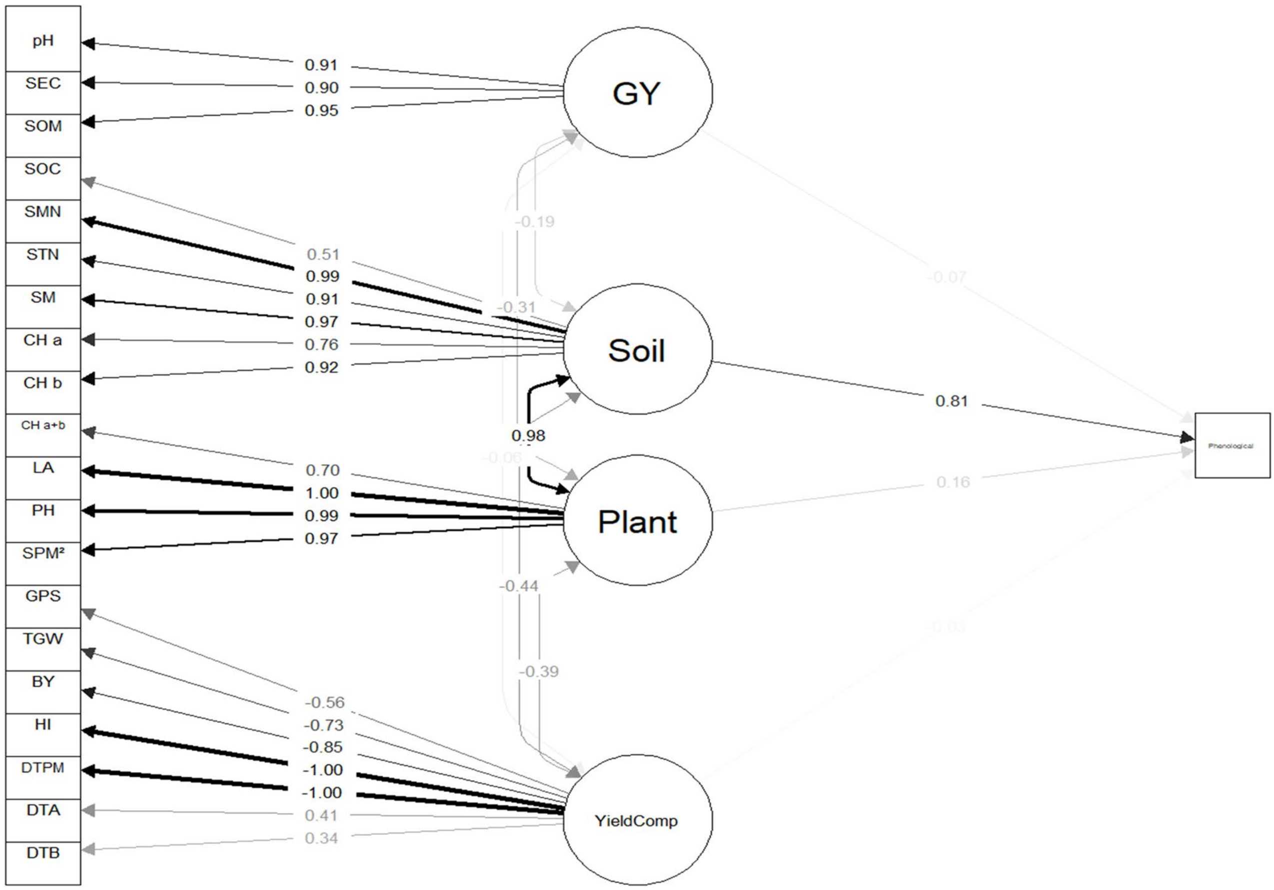

Fig. 11 Structural equation model showing the relationships among soil health, plant phenological, physiology, yield components and grain yield of of wheat. DTB; days to booting, DTA; days to anthesis, DTPM; days to physiological maturity, PH; plant height, LA; leaf area, SPM2; spikes m-2, GPS; grains spike-1, TGW; Thousand grain weight (g), BY; biological yield (kg ha-1), GY; grain yield (kg ha-1), HI = harvest index (%), CH a; chlorophyll a, CH b; chlorophyll b, CH a + b ; chlorophyll a + b, SpH; soil pH, SEC = Soil electrical conductivity (dS m-1), SOM; soil organic matter (%), SOC; soil organic carbon (%), SMN; soil mineral nitrogen (mg kg-1), STN; soil total nitrogen (%), SM; soil moisture content (%)

productivity. The phenological construct included days to booting (DTB; 0.34), days to anthesis (DTA; 0.41), and days to physiological maturity (DTPM; −1.00), describing the developmental timing of the crop. The structural relationships indicated that soil had a strong positive direct effect on grain yield (GY) with a standardized path coefficient of 0.81, suggesting that improved soil fertility significantly enhances crop productivity. Additionally, soil strongly influenced plant traits (0.98) and showed moderate relationships with yield components (-0.31). Plant traits also exhibited interactions with yield components (-0.44), indicating their role in influencing yield-related attributes. Phenological traits had a relatively weak direct relationship with grain yield (-0.07) and yield components (-0.39), suggesting that developmental stages influence yield mainly through indirect pathways rather than direct effects. The SEM analysis demonstrates that soil fertility is the most influential factor affecting grain yield, followed by yield component traits, while plant physiological characteristics and phenological development contribute indirectly to crop productivity. The negative direct path coefficient observed between plant traits and yield components (-0.44) likely reflects statistical partitioning of shared variance among highly correlated latent constructs, particularly the strong association between soil and plant traits (0.98), rather than indicating a biologically adverse effect of plant physiological performance on yield formation. This may further suggest that vegetative enhancement alone did not proportionally translate into reproductive yield components after accounting for soil-mediated effects. The negative direct path from soil to yield components (-0.31) likely reflects statistical partitioning of shared variance among correlated variables in the SEM, where soil effects are largely mediated through plant traits, rather than indicating a true negative biological relationship.

Discussion

The application of organic amendments, particularly farmyard manure and compost, has been shown to enhance wheat growth and development (Figs. 2 and 3) by improving soil nutrient availability through gradual nutrient mineralization and improved soil structure. Higher rates of FYM (8–12 t ha^{-1}) generally increase plant height, leaf area and vegetative growth is likely due to sustained nitrogen supply, often slightly delaying phenological stages due to prolonged vegetative development as continuous nutrient availability favors vegetative over reproductive growth [30, 31]. Similar positive effects on soil fertility and crop growth have been reported with other organic sources, including compost and co-composted biochar, which also improve soil quality and yield by increasing microbial activity and nutrient retention capacity [32, 33]. Nonetheless, the response to organic matter can vary depending on existing soil nutrient status because basline fertility influences the magnitude of crop response. For example, combining FYM with mineral fertilizers has been shown to further enhance plant height and growth due to the complementary effect of immediate nutrient supply from fertilizers and slow release from FYM [34], while in nutrient-rich soils, uniform nutrient availability may limit observable differences among treatments despite organic-amendments matter as crop nutrient demand is already satisfied [35]. These observations indicate that OM applications generally support vegetative growth and soil health, primary by improving nutrient dynamics and soil biological activity, although their effects on wheat phenology and growth parameters are influenced by soil fertility and integrated nutrient management strategies.

The application of humic substances, particularly humic acid (Figs. 3 and 4), has been reported to enhance wheat growth and yield components, including spikes m^{-2} and grain weight, highlighting their role in improving crop productivity [36, 37]. While different Bio-organic fertilizers may vary in their effectiveness, humic acid is known to enhance nutrient availability and uptake, particularly phosphorus through chelation and improved root permeability, thereby positively influencing yield components [38]. In the present study, the combined use of compost or farmyard manure with humic acid substantially increased grains per spike, thousand grain weight, and biological yield (Fig. 4), likely due to improved nutrient availability which enhanced root growth and microbial activity, assimilate translocation during grain filling, and overall soil health. These results are consistent with earlier findings that reported improved grain yield and biomass accumulation under organic-amendments matter [39–42]. The reported increased in plant growth and biological yield by humic acid application might be due to its bio-stimulatory effect as a result which influenced plant growth regulators and enhanced both shoot and root [43]. Similarly, conservation agricultural practices, including residue retention and organic matter incorporation, improve soil physical and chemical conditions, such as water retention, lower bulk density, better aggregation, and enhanced nutrient recycling which collectively improve resource use efficiency, all of which further support grain yield increases [44]. Despite these improvements in yield components, harvest index was largely unaffected by OM or DM (Fig. 5), which aligns with previous reports indicating limited influence of organic-amendments matter on harvest index as both grain and biomass increase proportionally [45].

Chlorophyll content was significantly influenced by the application of OM sources and DM across both experimental seasons (Fig. 6). These findings are consistent with reports that OM, including compost and farmyard manure, enhance chlorophyll concentrations, thereby improving photosynthetic efficiency and biomass accumulation in wheat through increased nitrogen availability which is a key component of chlorophyll synthesis [46]. Similarly, humic acid has been shown to increase chlorophyll content (Fig. 6), promoting photosynthesis and overall plant growth by stimulating enzymatic activity and nutrient uptake [47]. The results align with Rathor et al. [48], indicating that the combined use of organic-amendments matter and DM not only elevates specific chlorophyll components but also contributes to higher photosynthetic performance which is likely due to improved nutrient dynamics and leaf physiology, supporting improved vegetative growth and crop yield. Soil chemical properties were favorably influenced by the application of OM sources and decomposition-enhancing materials (Figs. 7 and 8). Soil pH remained within the optimal range for wheat cultivation, reflecting the buffering capacity of organic-amendments matter, which supply organic acids and enhance cation exchange capacity, thereby stabilizing soil conditions and promoting nutrient availability [49]. The treatments also significantly improved soil mineral nitrogen across both seasons (Fig. 8). OM, such as compost and FYM, provide organic nitrogen that gradually mineralizes into ammonium and nitrate through microbial decomposition processes, while wheat residues further contribute to mineral N through decomposition, enhancing the soil nitrogen pool [50, 51]. The integrated use of organic fertilizers with microbial inoculants has been shown to improve soil organic matter and nutrient availability by up to 15–30%, further supporting enhanced soil fertility and wheat productivity [52]. Plots receiving higher SOM inputs particularly those amended with compost, FYM and wheat residues also exhibited moderate electrical conductivity (Fig. 8), suggesting improved soil chemical balance. Compost enhances soil structure and promotes leaching of soluble salts, whereas humic acid further decreases EC by improving cation exchange and soil aggregation [53, 54]. Application of OM and DM substantially enhanced soil organic carbon (Fig. 8), which could be due to the addition of organic inputs and as a result organic matter stabilization enhanced along with carbon sequestration via microbially processes [55]. Beneficial microbial inoculants, such as Bio-aab, further enhance soil nutrient cycling and nitrogen availability by accelerating decomposition and nutrient performance, contributing to improved soil quality and crop performance [56]. The results are aligned with the earlier studies that have proven the multiple benefits of organic matter and DM intervention in making crops more sustainable and complementary to the soil health [10, 50]. Despite these improvements in soil nutrients and structure, soil moisture content was not significantly affected by the treatments (Fig. 8). This may be attributed to the timing of moisture measurements, which might not have captured short-term variations following irrigation or rainfall events and due to soil texture properties, that can restrict the expression of treatments effects on water retention, thereby masking a potential difference among treatments [57]. Although organic matter enhances water retention and structural stability, these effects are often dependent on field conditions and may not always result in measurable differences in soil moisture under wheat cropping system [58]. These results highlight that combining OM sources with DM improves soil fertility, nutrient cycling and chemical balance, through enhanced microbial activity and nutrient availability, creating favorable conditions for wheat growth and yield.

Conclusion

The two growing seasons study demonstrates that organic-amendments matter, combined with effective decomposition-enhancing materials (humic acid, Bio-aab and Bio-organic phosphate), significantly enhance wheat physiology, yield, and soil fertility. Farmyard manure and compost consistently outperformed no-residue treatments, while humic acid was the most effective for promoting crop growth and yield. The combination of FYM and compost with humic acid resulted in the highest yields, yield components, and chlorophyll content, reflecting improved plant performance. For soil fertility, Bio-aab and Bio-organic phosphate in combination with FYM and compost effectively increased soil mineral nitrogen, organic carbon and total nitrogen. These findings highlight the potential of integrating tailored OM and DM as sustainable strategies for enhancing wheat productivity. Farmers should prioritize FYM or compost with humic acid for crop growth, while Bio-aab or Bio-organic phosphate can be used to improve soil fertility, reducing dependency on chemical fertilizers. Economic analysis indicated higher net and improved cost ratio under integrated treatments, confirming their economic viability. Policy support for adoption through extension services and community initiatives is essential for widespread implementation.

Acknowledgements
The authors are thankful to the Department of Agronomy and Soil and Environmental Sciences, Faculty of Crop Production, The University of Agriculture Peshawar for the providing the necessary materials for research, lab and facility for sample analysis.

Clinical trial number
Not applicable.

Authors' contributions
M.K., M.K. and H.A: Writing – original draft, Data curation, Methodology, Formal Analysis. M.A., S.A., M.T.A., M.F.J., and W.L.: Writing – review & editing, Software, Methodology, Visualization. W.L.: Funding acquisition. All authors wrote and reviewed the paper.

Funding
This study has been supported by the Recep Tayyip Erdoğan University Development Foundation (Grant number: 02026004006224).

Data availability
All data generated or analyzed during this study are included in this article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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Received: 21 March 2026 / Accepted: 14 May 2026
Published online: 21 May 2026

References

1. Bohra A, Choudhary M, Bennett D, Joshi R, Mir RR, Varshney RK. Drought-tolerant wheat for enhancing global food security. Funct Integr Genomics. 2024;24:212.
2. Sharma K, Sharma P. Wheat as a nutritional powerhouse: Shaping global food security. IntechOpen; 2025. p. 1–20.
3. Shah SAA, Wu H, Farid MF, Tareen WUH, Badar IH. Climate trends and wheat yield in Punjab, Pakistan: Assessing the change and impact. Sustainability. 2024;16(11):4443.
4. GOP. Economic Survey of Pakistan. 2021. p. 6–8. https://tolaassociates.com/wp-content/uploads/2022/06/Analysis-on-Economic-Survey-2021-22.pdf.
5. Hamza A, Khan K. Assessment of soil fertility status based on NPK levels: A case study at agricultural research farm, Malakandher, Peshawar. Curr Res Agric Sci. 2025;12(2):135–44.

6. Ampong K, Thilakaranthna MS, Gorim LY. Understanding the role of humic acids on crop performance and soil health. Front Agron. 2022;4:848621.
7. El-Akhdar I, Shabana MM, El-Khateeb NM, Elhawat N, Alshaal T. Sustainable wheat cultivation in sandy soils: impact of organic and biofertilizer use on soil health and crop yield. Plants. 2024;13(22):3156.
8. Piccolo A, Drosos M. The essential role of humified organic matter in preserving soil health. Chem Biol Technol Agric. 2025;12(1):21.
9. Feng H, Han X, Zhu Y, Zhang M, Ji Y, Lu X, Zou W. Effects of long-term application of organic materials on soil water extractable organic matter, fulvic acid, humic acid structure and microbial driving mechanisms. Plant Soil. 2024;501(1):323–41.
10. Salihi MS, Hamim H, Serat SM. Impacts of humic acid on growth and yield of wheat: A review. J Nat Sci Rev. 2024;2(3):87–96.
11. Ma Y, Cheng X, Zhang Y. The impact of humic acid fertilizers on crop yield and nitrogen use efficiency: A meta-analysis. Agronomy. 2024;14(12):2763.
12. Ma L, Li Y, Zhang Y, Li Y, Wei J, Liu Z, Tan D. Synergistic application of humic acid and microbial fertilizers improve soil quality, reshape microbial network, and enhance wheat yield in coastal saline–alkali soils. Microorganisms. 2025;13(12):2716.
13. Matheus R, Kantur D. Effectiveness of organic fertilizer enriched with humic acid on soil chemical quality, nutrient uptake, and shallot yield in calcareous soils. J Tek Pertan Lampung. 2025;14(1):309–18.
14. Lamlom SF, Irshad A, Mosa WFA. The biological and biochemical composition of wheat (*Triticum aestivum*) as affected by the bio and organic fertilizers. BMC Plant Biol. 2023;23(1):111. https://doi.org/10.1186/s12870-023-04120-2.
15. Ahmad S, Urooj L, Ullah B, Amjad M, Ali M. Integrative Assessment of Organic, Inorganic and Bio-fertilizers on wheat Phenological, growth and Yield Indices under Semi-Arid Agroecosystems. Intern J Agric Sustain Develop. 2025;7(2):281–91. https://journal.xdgen.com/index.php/ijasd/article/view/279.
16. Bhunia S, Bhowmik A, Mallick R, Mukherjee J. Agronomic efficiency of animal-derived organic fertilizers and their effects on biology and fertility of soil: A review. Agronomy. 2021;11(5):823.
17. Albano X, Whitmore AP, Sakrabani R, Thomas CL, Sizmur T, Ritz K, Haefele SM. Effect of different organic amendments on actual and achievable yields in a cereal-based cropping system. J Soil Sci Plant Nutr. 2023;23(2):2122–37.
18. Sheoran S, Prakash D, Raj D, Yadav PK, Singh R, Gupta RK, Alamri S, Siddiqui MH, Khan S. Organic manure and fertilizer N management strategies improve soil health at different growth stages of pearl millet under pearl millet-wheat sequence. BMC Plant Biol. 2025;25(1):117. https://doi.org/10.1186/s12870-025-06128-2.
19. El-Sheref GF, El-Sherif STI, Mohamed GA. Effect of organic manures and chemical fertilizers on soil properties and crop yield in a wheat–maize cropping sequence. Int J Plant Soil Sci. 2025;37(7):441–59. https://doi.org/10.9734/ijpss/2025/v37i75590.
20. Ahmad S, Ullah B, Ali S, Zaid A, Ahmad Z, Usaid M, Ullah S. Impact of nitrogen and organic sources with and without beneficial microbes on wheat crop. Sarhad J Agric. 2023;39(4):876–82.
21. Tahir M, Khalid U, Ijaz M, Shah GM, Naeem MA, Shahid M, Kareem F. Combined application of bio-organic phosphate and phosphorus solubilizing bacteria (Bacillus strain MWT 14) improve the performance of bread wheat with low fertilizer input under an arid climate. Braz J Microbiol. 2018;49:15–24.
22. Bremner JM. Nitrogen-total. In: Sparks DL, editor. Methods of Soil Analysis: Part 3 Chemical Methods. Madison, WI: Soil Science Society of America; 1996. pp. 1085–121.
23. Lichtenthaler HK. Chlorophylls and carotenoids pigments of photosynthetic biomembranes. Meth Enzymol. 1987;148:350–82.
24. Thomas GW. Soil pH and soil acidity. In: Sparks DL, editor. Methods of soil analysis Part 3. Amer Soc Agron. 1996;16:475–490. https://doi.org/10.2136/sssabookser5.3.c16.
25. Rhoades JD. Salinity: Electrical conductivity and total dissolved solids. Methods soil analysis: Part 3 Chem methods. 1996;5:417–35.
26. Nelson DW, Sommer LE. Total C, organic C and organic matter. In: Sparks DL, editor. Methods of Soil Analysis Part 3. Amer Soc Agron. 1996;34:961–1010.
27. Keeney DR, Nelson DW. Nitrogen—inorganic forms. Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties. 9th ed. 1982:643–698. https://doi.org/10.2134/agronmonogr9.2.2ed.c33.
28. Bremner JM, Mulvaney CS. Nitrogen—total. Methods of soil analysis: part 2 chemical and microbiological properties. 1982;9:595–624.
29. Jan MT, Shah P, Hollington PA, Khan MJ, Sohail Q. Agriculture Research: Design and Analysis, A Monograph. NWFP Agricultural University Peshawar; 2009. p. 232.
30. Khan S, Mazhar SA, Irshad S, Nawaz M, Bashir S, Saddiq MS, Bushkh A. Integrated usage of farm yard manure and urea improves wheat yield and soil properties. Intl Lett Nat Sci. 2020;80:25–35. 10.18052/. www.scipress.com/ILNS.80.25.
31. Khan S, Khan A, Nadeem T, Akbar H, Hussain Z. Phenology, crop stand, and dry matter production of wheat in response to beneficial microbes and organic matter sources. SABRAO J Breed Genet. 2023;55:463–75. https://doi.org/10.54910/sabrao2023.55.2.18.
32. Shehzad RA, Sarwar G, Shah SH, Tahir MA, Sabah N, Muhammad S, Aftab M, Manzoor MZ, Shehzad I, Saleem U. Growth and yield response of wheat to organic manures (farm yard manure, phospho-compost (PROM) and press mud) alone and in combination with mineral fertilizer. Pak J Agric Res. 2023;36:1–8. https://doi.org/10.17582/journal.pjar/2023/36.1.1.8.
33. Bashir A, Rizwan M, ur Rehman MZ, Zubair M, Riaz M, Qayyum MF, Alharby HF, Bamagoos AA, Ali S. Application of co-composted farm manure and biochar increased the wheat growth and decreased cadmium accumulation in plants under different water regimes. Chemosphere. 2020;246:125809. https://doi.org/10.1016/j.chemosphere.2019.125809.
34. Dhaliwal SS, Sharma S, Sharma V, Shukla AK, Walia SS, Alhomrani M, Gaber A, Toor AS, Verma V, Randhawa MK, Pandher LK. Long-term integrated nutrient management in the maize–wheat cropping system in alluvial soils of North-Western India: Influence on soil organic carbon, microbial activity and nutrient status. Agronomy. 2021;11:2258. https://doi.org/10.3390/agronomy11112258.
35. Wahid F, Sharif M, Fahad S, Adnan M, Khan IA, Aksoy E, Ali A, Sultan T, Alam M, Saeed M, Ullah H. Arbuscular mycorrhizal fungi improve the growth and phosphorus uptake of mung bean plants fertilized with composted rock phosphate fed dung in alkaline soil environment. J Plant Nutr. 2019;42:1760–9. https://doi.org/10.1080/01904167.2019.1643371.
36. Iqbal A, Raza H, Zaman M, Khan R, Adnan M, Khan A, Khalil SK. Impact of nitrogen, zinc and humic acid application on wheat growth, morphological traits, yield and yield components. J Soil Plant Environ. 2022;1:50–71. https://doi.org/10.56946/jspae.v1i1.11.
37. Shafi MI, Adnan M, Fahad S, Wahid F, Khan A, Yue Z, Danish S, Zafar-ul-Hye M, Brtnicky M, Datta R. Application of single superphosphate with humic acid improves the growth, yield and phosphorus uptake of wheat (*Triticum aestivum* L.) in calcareous soil. Agronomy. 2020;10(9):1224. https://doi.org/10.3390/agronomy10091224.
38. Gao S, Zhang S, Yuan L, Li Y, Zhao L, Wen Y, Xu J, Hu S, Zhao B. Effects of humic acid–enhanced phosphate fertilizer on wheat yield, phosphorus uptake, and soil available phosphorus content. Crop Sci. 2023;63:956–66. https://doi.org/10.1002/csc2.20909.
39. Abbas Q, Shafique A. Integrated use of organic and inorganic fertilizers improves soil health, growth, and yield of wheat (*Triticum aestivum* L). Adv Agric Biol. 2019;2. https://doi.org/10.63072/aab.19007.
40. Merwad ARM. Using humic substances and foliar spray with moringa leaf extract to alleviate salinity stress on wheat. In: Sustainability of agricultural environment in Egypt: Part II: Soil-water-plant nexus. 2018:265–286. https://doi.org/10.1007/698_2018_298.
41. Dawar K, Khalil Z, Mian IA, Khan B, Ali S, Rahi AA, Tahir MS, Ahmed N, Fahad S, Danish S, Syed A. Effects of farmyard manure and different phosphorus inorganic fertilizer application rates on wheat cultivation in phosphorus-deficient soil. Sustainability. 2022;14(15):9030. https://doi.org/10.3390/su14159030.
42. Rathor P, Upadhyay P, Ullah A, Gorim LY, Thilakarathna MS. Humic acid improves wheat growth by modulating auxin and cytokinin biosynthesis pathways. AoB Plants. 2024;16(2):18. https://doi.org/10.1093/aobpla/plae018.
43. Gupta RK, Sraw PK, Kang JS, Kaur J, Sharma V, Pathania N, Kalia A, Al-Ansari N, Alataway A, Dewidar AZ, Mattar MA. Interactive effects of long-term management of crop residue and phosphorus fertilization on wheat productivity and soil health in the rice–wheat system. Sci Rep. 2024;14(1):1399. https://doi.org/10.1038/s41598-024-51399-8.
44. Zhou J, Xu H, Zhang M, Feng R, Xiao H, Xue C. Impact of organic amendments on black wheat yield, grain quality, and soil biochemical properties. Agronomy. 2025;15:961. https://doi.org/10.3390/agronomy15040961.
45. Srivastav P, Gangwar S. Effect of organic manures on improving growth and yield of wheat (*Triticum aestivum* L). Asian J Microbiol Biotechnol Environ Sci. 2025;27. https://doi.org/10.53550/AJMBES.2025.v27i01-02.012.
46. Ozfidan-Konakci C, Yildiztugay E, Bahtiyar M, Kucukoduk M. The humic acid-induced changes in the water status, chlorophyll fluorescence and

antioxidant defense systems of wheat leaves with cadmium stress. Ecotoxicol Environ Saf. 2018;155:66–75. https://doi.org/10.1016/j.ecoenv.2018.02.071.
47. Verma S, Pradhan SS, Singh A, Kushuwaha M. Effect of organic manure on different soil properties: A review. Int J Plant Soil Sci. 2024;36(5):182–7. https://doi.org/10.9734/IJPSS/2024/v36i54515.
48. Rajput R, Pokhriya P, Panwar P, Arunachalam A, Arunachalam K. Soil nutrients, microbial biomass, and crop response to organic amendments in rice cropping system in the Shiwaliks of Indian Himalayas. Int J Recycl Org Waste Agric. 2019;8(1):73–85. https://doi.org/10.1007/s40093-018-0230-x.
49. Cuartero J, Özbolat O, Sánchez-Navarro V, Weiss J, Zornoza R, Pascual JA, Vivo JM, Ros M. Long-term compost amendment changes interactions and specialization in the soil bacterial community, increasing the presence of beneficial N-cycling genes in the soil. Agronomy. 2022;12:316. https://doi.org/10.3390/agronomy12020316.
50. Xu J, Li Y, Li L. A comprehensive review of the effects of organic amendments on soil health and fertility: Mechanisms, greenhouse gas emissions, and implications for sustainable agriculture. Agronomy. 2025;15(12):2705. https://doi.org/10.3390/agronomy15122705.
51. Zaremanesh H, Akbari N, Eisvand HR, Ismaili A, Feizian M. The Effect of humic acid on soil physicochemical and biological properties under salinity stress conditions in pot culture of Satureja khuzistanica Jamzad. Ecopersia. 2025;8(3):147–54.
52. Dai Y, Wu X, Li S, Li Y, Wang L, Hu Y, Liu K, Yang Z, Cai L, Xu K, Cui M. Optimizing Resource Management with Organic Fertilizer and Microbial Inoculants to Enhance Soil Quality, Microbial Diversity, and Crop Productivity in Newly Cultivated Land. Plants. 2025;14(19):Pp3032.
53. Choudhary R, Naresh RK. Changes in soil organic carbon, labile carbon pools, and microbial community as influenced by tillage systems, organic and synthetic fertilizers, and straw alterations in sub-tropical agro-ecosystem: A review. J Pharm Innov. 2021;10:1476–85.
54. Azeem I, Khan AA, Bibi H, Azeem K, Naz F, Khan K, Shah SAA, Shah K. Nitrogen sources and bioaab inclined yield and nutrients uptake specifically in *Triticum aestivum*. Pure Appl Biol. 2019;8(4):2311–25. https://doi.org/10.19045/bspab.2019.80178.
55. Luo G, Li L, Friman VP, Guo J, Guo S, Shen Q, Ling N. Organic amendments increase crop yields by improving microbe mediated soil functioning of agroecosystems: A meta-analysis. Soil Biol Biochem. 2018;124:105–15. https://doi.org/10.1016/j.soilbio.2018.06.002.
56. Aytenew M, Bore G. Effects of organic amendments on soil fertility and environmental quality: A review. J Plant Sci. 2020;8(5):112–9. https://doi.org/10.11648/j.jps.20200805.12.
57. Sohail S, Chenyun B, Hanyang T, Khosa SY, Ali MF, Abbas MM, Ahamd ST, Iqbal M, Xiaoyang H, Yuanjun Z. Enhancing wheat drought resilience through organic amendments: integrating soil health improvement and antioxidant defense activation. BMC Plant Biol. 2026;26(1). https://doi.org/10.1186/s12870-026-08307-1.
58. Zhou H, Chen C, Wang D, Arthur E, Zhang Z, Guo Z, Peng X, Mooney SJ. Effect of long-term organic amendments on the full-range soil water retention characteristics of a Vertisol. Soil Tillage Res. 2020;202:104663. https://doi.org/10.1016/j.still.2020.104663.

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