



Research article

Effect of Cow and Poultry Manure Particle Size on Growth and Yield Performance of Barley (*Hordeum vulgare* L.) under Sandy Loam Soil Conditions

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ABSTRACT

The optimization of organic manure application is of great importance for sustainable crop production, but how the agronomic performance will vary according to manure source and particle size is not well explored. The four different particle-size fractions of cow (C1–C4) and poultry (H1–H4) manure, as well as an unfertilized control, were tested for their effects on the growth and yield of the crop barley in a randomized complete block design in sandy loam soil. Organic amendments had a significant ($p < 0.001$) influence on all the measured traits and accounted for 96–99% of the total variance. The particle size was the dominant factor for biological yield, and the manure type $\times$ particle size interaction was the primary determinant of grain quality traits, with particle size also having a significant effect. The use of finer cow manure (C4) and intermediate poultry manure (H3, H4) resulted in the highest biological yield of 1450 g m⁻², the highest spike density, and tillering. In contrast, the coarser fractions (C1, C2, H1, H2) were found to be more supportive of vegetative elongation and grain filling. Multivariate analysis clearly segregated treatments according to biomass versus grain-quality trajectory, and spike density was determined as the most important factor affecting biological yield, as was tillering. In conclusion, making manure particle size adjustments to specific agronomic targets offers a reliable and precise approach to maximizing barley productivity and soil nutrient use.

1. Introduction

Sandy soils are common worldwide and are being used more and more to meet the world's needs for food, fiber, and energy. But growing crops under sandy soil conditions is challenging because the sandy soil has poor water and nutrient holding capacity (El-Akhdar et al., 2024). More than 900

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million hectares of sand are currently in use for crop production worldwide, and for most uses, regular and careful additions of nutrients are necessary to avoid nutrient loss and ensure sustained crop production (Zhao & Naeth, 2024).

The use of organic amendments, such as cow (farmyard) and poultry manures, is an effective and environmentally friendly approach to improve the fertility of soils, reduce land degradation, and increase crop yields, which is widely accepted (Dhaliwal et al., 2023). The application of organic fertilizers in the soil enhances the chemical properties, increases soil organic matter, and makes macronutrients such as nitrogen, phosphorus, and potassium (N-P-K) available for plant uptake (El-Akhdar et al., 2024). In particular, the use of poultry manure has been found to have a positive impact on seedling emergence, physiological characteristics, and nutrient uptake in cereals (Arshad et al., 2024). Likewise, cow and farmyard manures enhance soil biological activity, soil enzymatic functions, and provide sustainable crop productivity and soil health (Dhaliwal et al., 2023; Holatko et al., 2023). Barley (*Hordeum vulgare* L.) is an important grain and forage crop that is grown globally, but is often limited in productivity due to sub-optimal soil conditions (Mench et al., 2023; Shilev et al., 2024). In barley production, the application of organic manures has been shown to be highly effective, as organic amendments have been found to significantly improve barley grain production, biomass production, enhance microbial biomass carbon, and optimize physiological and nitrogen use efficiency (Agegnehu et al., 2016; Seleem et al., 2022).

The independent effects of poultry and cow manure on cereal crops in sandy soils are documented; however, the physical properties of these manures, particularly the particle size, are still an important and under-researched aspect. The literature available indicates that the manures of cow and poultry can significantly improve the soil environment and barley yields, but specific details are lacking about the effect of particle size of these manures on the dynamics of nutrient release and subsequent crop performance. Thus, it is necessary to determine the effect of different sizes of the particles of manure from cow and poultry on mineralization rate for optimizing the use of organic fertilizer.

The main purpose of this study was to determine the combined effect of manure source and physical particle size on the productivity of growth and yield of barley in sandy loam soils. Specifically, the goals were to evaluate the effect of four particle size fractions from cow and poultry manure on various agronomic characteristics such as plant morphology, tillering, spike components, and biological yield. In addition, the effects of the manure type and particle size were analyzed separately and together using factorial and multivariate analyses in order to determine which factors are more important in influencing crop performance. The overall objective of this study was to determine the best organic amendment fraction combinations for the maximal production of various agronomic traits, and to propose an exact, sustainable nutrient management plan for production improvement in Barley in these soils.

2. Materials and Methods

2.1. Experimental Site and Growing Season

The field experiment was carried out at the experimental farm at the Department of Field Crops, College of Agriculture and Marshes, University of Thi-Qar, Iraq, in the winter crop growing season of 2023-2024. The aim of the study was to assess the growth and productivity of barley (*Hordeum vulgare* L.) under sandy loam soil conditions, using cow manure and poultry manure of various particle size classes. The sowing and harvesting dates of barley were 27 November 2023 to 30 April

2024. The soil used for the experiment was sandy loam (78% sand, 15% clay, and 7% silt). Representative composite soil samples were taken from the experimental field before sowing and air-dried, sieved, and analyzed for certain physical and chemical properties. The initial soil properties are shown in Table 1. The soil had relatively low levels of organic matter and nutrients, which made it suitable to assess crop reaction to the application of organic manure.

Table 1. Selected physical and chemical properties of the experimental soil before sowing.

Property	Value
pH	7.61
Electrical conductivity (dS m ⁻¹)	4.00
Organic matter (%)	0.40
Organic carbon (%)	0.29
Total nitrogen (%)	0.07
Total phosphorus (%)	0.008
C/N ratio	20
Lime (%)	5.5
Bulk density (g cm ⁻³)	1.30
Sand (%)	78
Silt (%)	7
Clay (%)	15
Texture class	Sandy loam

2.2. Organic Manure Treatments

In the present study, two organic manure sources, i.e., cow manure and poultry manure, have been tested. Before application, each type of manure was fractionated into four particle-size fractions using a series of sieves. The cow manure treatments consisted of C1 (0.35–4.00 mm), C2 (2.00–4.00 mm), C3 (1.00–2.00 mm), and C4 (0.35–1.00 mm), while the poultry manure treatments included H1 (0.35–4.00 mm), H2 (2.00–4.00 mm), H3 (1.00–2.00 mm), and H4 (0.35–1.00 mm). The unfertilized treatment without organic manure application was kept as a control (CK). In Table 2, the respective manure treatments were applied prior to sowing and were well mixed with the surface soil layer during field preparation to provide a uniform distribution and good contact with the soil. The objective of the study was to assess the effect of the source of manure and particle size on soil properties and barley growth in a field experiment.

Table 2. Chemical properties of cow manure and poultry manure used in the experiment.

Property	Cow manure	Poultry manure
pH	7.42	7.81
EC (dS m ⁻¹)	3.15	4.68
Organic matter (%)	42.50	48.20
Organic carbon (%)	24.65	27.96
Total N (%)	1.25	2.15
Total P (%)	0.62	1.24
Total K (%)	1.10	1.46
C/N ratio	19.72	13.00
Moisture (%)	18.50	15.20

EC = electrical conductivity; N = nitrogen; P = phosphorus; K = potassium.

The manure samples were analyzed before field application to determine their nutrient composition and decomposition potential.

2.3. Experimental Design and Field Layout

The field experiment was designed in a randomized complete block (RCBD) design with three replications. Total number of treatments evaluated = 9 (CK, C1, C2, C3, C4, H1, H2, H3 and H4) and number of experimental units = 27. The experimental field was plowed twice in opposite directions, and land leveling and demarcation of the plots were done before sowing. Adjacent plots were separated by soil bunds about 50 cm high to minimize the movement of irrigation water and nutrients between plots. Each experimental plot comprised six rows 2 m long with row spacings of 15 cm. All plots were seeded with barley seeds of a local cultivar and seeded manually at a uniform seeding density. The irrigation method used was surface irrigation applied throughout the growing season, with seven irrigation operations applied during the growing season based on crop water requirements and rainfall conditions. The experimental treatments were the only ones that varied from the other practices in the field.

2.4. Mineral Fertilization and Crop Management

A basal application of mineral fertilizers was made to all treatments to reduce nutrient deficiencies other than those related to the organic manure treatments and to assure that the nutrient supply was uniform throughout all treatments. Phosphorus was applied at a rate of 100 kg ha⁻¹ and potassium at 80 kg ha⁻¹ as triple superphosphate (46% P₂O₅) and potassium sulfate (50% K₂O), respectively. Nitrogen fertilizer application rate was 100kg ha⁻¹ and applied as recommended. Manual hand weeding was done where necessary throughout the growing season for weed control. No serious pest or disease problems were noted throughout the experimental period, and no pesticide or fungicide applications were required. All agronomic practices, except those applied as treatments, were the same on all test plots.

2.5. Soil sampling and laboratory analysis.

Soil samples were taken before sowing from several points in the experimental area and mixed well to get a representative composite soil sample. All the samples collected were air-dried, ground, and then sieved through a 2 mm mesh before being analyzed in the laboratory. The soil pH was determined on saturated paste extracts by pH meter, and the electrical conductivity (EC) was determined by using an EC meter. The organic carbon content was measured by the Walkley–Black wet oxidation method, and the organic matter content was calculated based on the measured values of organic carbon. The soil texture and particle-size distribution were measured by the hydrometer method, and the bulk density was measured by the core sampling method. Total Nitrogen content was analyzed by the Kjeldahl digestion and distillation method, and Calcium Carbonate (lime) content was determined by the acid neutralization method. Additionally, total phosphorus was measured according to the standard laboratory methods. Soil physicochemical properties analyzed were pH, electrical conductivity (EC), organic matter (OM), organic carbon (OC), total nitrogen (TN), total phosphorus (TP), carbon-to-nitrogen (C/N) ratio, lime content, particle-size distribution, soil texture class, and soil bulk density.

2.6. Measured Growth and Yield Traits

The barley growth and yield characteristics were assessed at the appropriate growth stages and at physiological maturity to assess the response of barley to the various organic manure treatments. Plant height (from soil surface to base of the spike) and plant length (from soil surface to the top of the plant) were taken with a measuring tape. Five plants were randomly harvested from the central rows of each plot of the experimental design for both traits, and the value was taken in centimeters (cm). The area of flag leaves was assessed at full flag leaf expansion in five randomly selected plants per plot and calculated as flag length $\times$ flag width $\times$ correction factor; the correction factor used was the one adopted for the selected reference or measurement protocol. Tillers per plant were counted when the plants were at physiological maturity from five randomly selected plants and expressed as tillers per plant⁻¹. Spikes m⁻² were calculated by counting all the spikes in a representative 1 m² sample area in the middle of each plot.

Fruits were evaluated for yield components at maturity. Spikes were measured on five randomly chosen spikes to the tip of the spike (excluding awns), and the average length in cm was recorded using a ruler. A sensitive balance was used to measure spike weight (g spike⁻¹) for all five spikes. Grains of spiked grain were counted manually from the selected spikes, and the average of the counts was reported as grain spike⁻¹. The grains collected from the sampled spikes were weighed, and the grain weight per spike was calculated as the number of grams of grain collected from each spike. The 100-grain weight (g) was determined by taking a random sample of 100 grains, counting them, and weighing them on a precision balance. Biological yield was calculated as the weight of all the aboveground parts of the plants harvested from a 1 m² plot in each experimental plot and immediately placed on a laboratory balance after harvest, and expressed in g m⁻². Where available, grain yield was measured separately and expressed as g m⁻² or t ha⁻¹. Harvest index was determined according to the formula: Harvest Index (%) = (Grain Yield / Biological Yield) $\times$ 100, which is an estimate of the proportion of total biomass that is recovered in the grain yield.

2.7. Statistical Analysis

All experimental data were submitted for analysis using analysis of variance (ANOVA) on the randomized complete block design (RCBD) to determine if treatment effects were significant. Treatment means were compared when there were significant differences among the treatments by using Tukey's Honest Significant Difference (HSD) at $P \leq 0.05$ significance level. All test treatments were compared to the control treatment to quantify the relative response of each treatment by calculating the percentage increase over the control treatment. A factorial ANOVA was used to further explore the individual and combined effects of manure source and particle size, excluding the control treatment. The normality and homogeneity of variance were checked before conducting the ANOVA test with Shapiro-Wilk and Levene's tests, respectively. Pearson correlation analysis was done to evaluate the correlation between growth and yield parameters. Standardized variables were used for principal component analysis (PCA) to provide a summary of treatment responses and determine the major sources of variation between the treatments. Biplots of the treatment means were created for the PCA to help interpret multivariate relationships. Furthermore, hierarchical cluster analysis (HCA) was performed on the standardized treatment means, based on the Euclidean distance between treatments with Ward's linkage method to classify the treatments from the overall performances, given in Table 3. All the statistical analyses and graphical visualizations have been conducted with

JupyterLab (Python) packages: pandas, NumPy, SciPy, statsmodels, scikit-learn, matplotlib, and openpyxl.

Table 3. Statistical models and equations used for data analysis

Analysis	Model/Equation
RCBD ANOVA model	$Y_{ij} = \mu + T_i + B_j + e_{ij}$
Definition of terms	Y_{ij} = observed value; μ = overall mean; T_i = treatment effect; B_j = block effect; e_{ij} = experimental error
Percentage increase over control	Increase over control (%) = [(Treatment mean – Control mean) / Control mean] × 100
Factorial ANOVA model	$Y_{ijk} = \mu + M_i + S_j + (MS)_{ij} + B_k + e_{ijk}$
Definition of terms	M_i = manure type effect; S_j = particle-size effect; $(MS)_{ij}$ = interaction between manure type and particle size; B_k = block effect; e_{ijk} = experimental error
Assumption testing	Shapiro–Wilk test for normality of residuals; Levene’s test for homogeneity of variances
Multivariate analyses	Pearson correlation analysis, principal component analysis (PCA), and hierarchical cluster analysis (Ward’s method with Euclidean distance)

3. Results and Discussion

3.1 Descriptive statistics

The field experiment was laid out in a randomized complete block design having three replications and nine treatments, resulting in 27 experimental units. Four particle-size classes of cow manure and four of the corresponding particle-size classes of poultry manure were applied, along with an unfertilized control. The design of this structure agrees with the experimental design mentioned in the study, in which 27 experimental units were allotted in three blocks in RCBD.

The application of all the organic manures with varying particle sizes showed significant differences in their growth parameters in comparison to the control in Figure 1. Plant height showed significant improvement in all manure treatments, varying from 51.80cm to 59.77cm, as compared to the 39.17cm control, which is 32-53% higher. The H1 treatment produced the tallest plants (59.77 ± 0.91 cm), followed by C2 (57.87 ± 0.87 cm) and C3 (56.50 ± 0.70 cm). The coefficient of variation (CV%) for plant height was not too high among treatments (1.24-2.42%), implying uniformity of plant height response within replicates.

A similar positive trend was observed in plant length, ranging from 70.40cm in H4 to 83.60cm in C2, while 67.20cm was observed in the control. The C2 treatment achieved the maximum plant length (83.60 ± 1.40 cm), closely followed by H2 (83.30 ± 1.18 cm) and H1 (81.30 ± 0.75 cm). In particular, the lowest variation (CV = 0.93%) was observed for the H1 treatment, indicating a very uniform development of plants under this treatment condition.

The photosynthetic area, as indicated by flag leaf area, was significantly improved by manure application. The flag leaf area in the control treatment was the lowest (17.73 ± 0.55 cm²), followed by treatments ranging from 17.97 cm² (C4) to 26.40 cm² (H2). The H2 treatment produced the largest flag leaves (26.40 ± 0.66 cm²), representing a 49% increase over the control, followed by C3 (25.60 ± 0.66 cm²) and C2 (25.47 ± 0.61 cm²). Variability among replicates was moderate (2.37% to 3.38%) for the CV of flag leaf area.

Yield Components

In addition, spike density (spikes/m²) significantly improved with organic manure. The control treatment yielded 100.67 ± 4.04 spikes/m², and the manure treatments yielded between 123 spikes/m² (C1) and 173 spikes/m² (C4). C4 treatment had the highest spike density (173 ± 4.58 spikes/m²), which is 72% increase over the control treatment, followed by C3 (163 ± 4.58 spikes/m²) and H3 (162 ± 5.00 spikes/m²). The CV for this parameter was 2.28% to 4.01%, with control having the greatest variation.

Dramatic improvement was observed in spike weight with manure application, with the control having 1.95 ± 0.06 g, while the treatment range was from 3.36 g to 3.60 g. The C4 treatment produced the heaviest spikes (3.60 ± 0.09 g), followed by H3 (3.57 ± 0.12 g) and C2 (3.52 ± 0.07 g). Increase in spike weight by 85% with C4 treatment as compared to control. Treatment C2 had the least variation (CV = 1.89%), which means that the development of spikes was consistent.

The length of the spike was significantly greater in the manure treatments (10.67-12.17 cm) than in the control (8.33 ± 0.21 cm). The longest spike length of 12.17 cm was obtained in three treatments (C2, C4, and H4), which were 46% higher than the control. The C2 treatment had the lowest CV (1.26%), whereas the control had a higher CV (CV = 2.50%), indicating uniformity in the treatment.

The number of grains per spike enhanced from 37.27 ± 0.71 to between 41.37 and 54.17 in manure treatments. The H1 treatment produced the highest number of grains per spike (54.17 ± 0.67), followed by C4 (53.70 ± 0.96) and H2 (53.43 ± 0.65), representing 31-45% improvements over the control. The H1 treatment was very uniform (CV value = 1.23%).

Hundred grain weight ranged from 4.37 ± 0.10 g in the control to 4.57 – 5.85 g in manure treatments. The C1 treatment achieved the highest test weight (5.85 ± 0.13 g), followed by H2 (5.82 ± 0.11 g) and C3 (5.67 ± 0.14 g), representing 26-34% improvements. The CV values (1.91–2.66%) were relatively low for all the treatments, pointing towards consistent grain filling.

The number of tillers/plant was significantly improved, ranging from 5.67-6.67 tillers/plant in the manure treatments versus 3.67 ± 0.32 tillers/plant in the control. H3 treatment resulted in the highest tillering (6.67 ± 0.25 tillers/plant), followed by C3 and C4 (6.33 tillers/plant, both with 54-82% higher than the control). The variability (CV) of the C4 treatment was the lowest, 1.82%.

Biological Yield

The use of manure treatments showed the greatest influence on biological yield, ranging from 833 ± 20.66 g/m² for the control to 1,137-1,450 g/m² in the treated plots. The C4 treatment achieved the highest biological yield ($1,450 \pm 37.75$ g/m²), closely followed by H4 ($1,447 \pm 35.59$ g/m²) and H3 ($1,433 \pm 37.04$ g/m²), representing 71-74% increases over the control. Acceptable CV values were obtained for all treatments (2.22-3.02%), which means there were reliable yield responses.

Comparative Performance of Manure Types and Particle Sizes

The data shows clear differences between the performance of cow manure (C1-C4) and poultry manure (H1-H4). Cow manure treatments, especially C2, C3, and C4, always performed better with respect to spike production and biological yield. The C4 treatment proved to be the best overall one with the highest spike density (173 spikes/m²), spike weight (3.60 g), spike length (12.17 cm), and biological yield (1,450 g/m²).

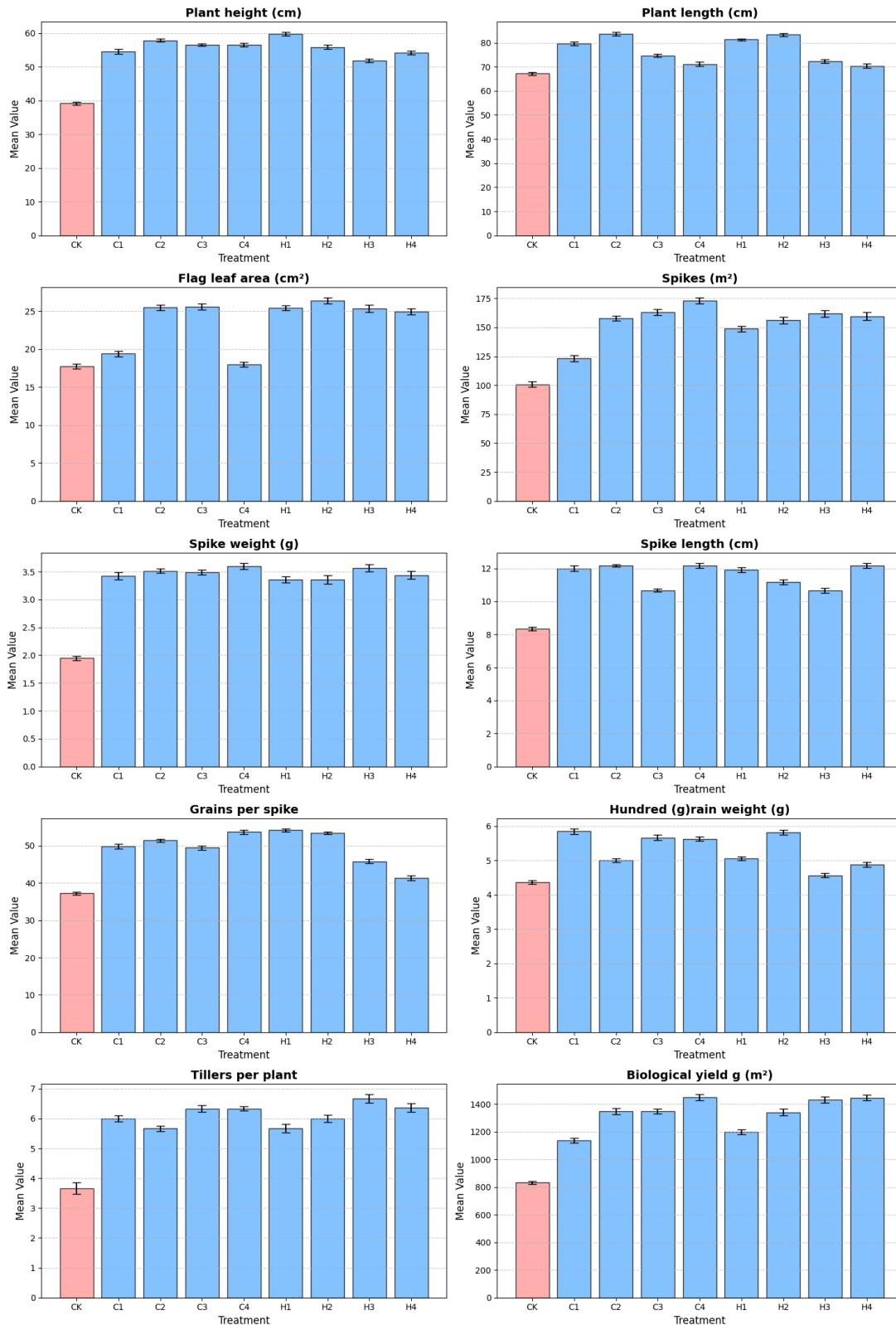


Figure 1. Effects of different particle-size fractions of cow manure (C1–C4) and poultry manure (H1–H4) on growth and yield parameters of barley cultivated in sandy loam soil. CK = unfertilized control; C1–C4 = cow manure particle sizes (0.35–4.00, 2.00–4.00, 1.00–2.00, and 0.35–1.00 mm, respectively); H1–H4 = poultry manure particle sizes (0.35–4.00, 2.00–4.00, 1.00–2.00, and 0.35–1.00 mm, respectively). Error bars represent the standard error of the mean (n = 3).

The vegetable growth parameters and grain number were superior when using poultry manure treatments. The plants under H1 (59.77 cm) had the tallest plants, and H2 had the highest flag leaf area (26.40 cm²) and a good hundred grain weight (5.82 g). The treatment with H3 was the most successful in the tiller production (6.67 tillers/plant).

The particle size effect seems to be treatment-specific, with finer size (C4 and H4) having a better effect on yield components, whereas medium size (C2, H1, H2) has a better effect on vegetative growth parameters. This indicates that there is an optimum particle size range for various growth conditions and parameters.

Variability and Consistency Analysis

The coefficient of variation (CV) analysis is informative with regard to treatment consistency. The experimental precision and treatment consistency of most of the parameters were good with CVs < 4%. Plant height and plant length exhibited much less variability (CV < 2.5 % in most cases), indicating consistent responses to manure application.

Organic amendments led to more uniform tillering patterns as indicated by the lower CV for the number of tillers per plant in these treatments (CV = 1.82-4.44%) than in the control (CV = 8.77%). For the same reason, manure application resulted in the greater uniformity (CV = 4.01%) of the spikes/m² compared to most treatments.

Analysis of Variance (ANOVA) Results

Statistical Significance of Treatment and Block Effects

The analysis of variance showed that there were highly significant differences among the barley plants grown in various organic manure treatments in all growth and yield parameters (Figure 2). The effects of the treatments were highly significant for all the traits (p-values from 1.69×10^{-21} to 2.56×10^{-17}), much lower than the customary p-value threshold of $P < 0.001$. The block effects were also statistically significant ($p < 6.77 \times 10^{-9}$) for all parameters, which means that there is some spatial variation in the experimental field, which was addressed in the experimental design.

Magnitude of Treatment Effects

The treatment effects were very high in all the measured parameters, as evidenced by the very high F-values (the ratio of treatment variance to error variance) (Figure 2A). Flag leaf area exhibited the highest F-value ($F = 2906.88$), followed by hundred grain weight ($F = 1962.05$), spikes per square meter ($F = 1888.20$), and biological yield ($F = 1492.25$). The extremely high F-values suggest that the differences between the means of the treatments were significantly larger than the differences within the treatments, which provides strong evidence that the differences were due to the manure treatments and not to chance. Moderately high F-values were observed for spike length ($F = 1118.17$), spike weight ($F = 1048.49$), plant height ($F = 1036.21$), grains per spike ($F = 1035.65$), and plant length ($F = 926.52$). The treatment effect was extremely high, even for tillers per plant, which has the lowest F value (446.21), with the mean square for treatment being 446 times greater than the error mean square.

Statistical Significance Levels

Treatment effects were statistically significant (Figure 2B) when presented as the negative log transformation of P values ($-\log_{10}P$). Treatment effects for all traits had $-\log_{10}P$ values above 19, and a few above 21. This corresponds to real p-values less than 10^{-19} , meaning that the chance of getting such extreme F values from a random sample is nearly impossible. The statistical significance of block effects was also extremely high with $-\log_{10}P$ values between 8.2 and 12.1, although the effect was not as strong as that of the treatments. Block effect was most significant for hundred grain weight ($-\log_{11}P = 12.1$) and spikes per meter ($-\log_{11}P = 11.7$), indicating that there was some spatial variation in the field that was measurable for these yield components. A randomized complete block design was used for this experiment, and the successful detection and accounting of block effects support the use of such a design.

Variance Partitioning and Contribution to Total Variability

The partitioning of total variance between the treatment, block, and residual components showed that the treatment component of the variance was the overwhelming majority of the variance observed in each of the measured parameters (Figure 2C). The overall variance of all traits was mainly explained by the treatment effect, and the contribution was 96-99% in all traits, showing that the type of manure and particle size had a dominating effect on barley growth and yield performance. Variance contributions from treatment were highest for flag leaf area (around 99%), hundred grain weight (around 99%), and spikes per square meter (around 98.5%), suggesting that these were more sensitive to the organic amendments. For tillers per plant (which had the smallest treatment variance contribution), treatments accounted for about 96% of the total variation.

There was some variability among the traits around block effects, generally 1-3% of the variance. Spatial variability in soil conditions, soil moisture, or other environmental factors was the most likely cause of the highest block contributions for grains per spike and plant height, indicating that these parameters were likely more sensitive to soil conditions across the experimental field. The residual variance was always small, with values of less than 2% of the total variance in all parameters. This low error variance shows high experimental precision, good control of environmental variability, and high reliability of the comparison of the environmental effect on the treatments. The low residual variance also indicates the success of the blocking approach to minimizing spatial variability and uniformity in treatment responses.

Comparative Strength of Treatment versus Block Effects

The ratio of the treatment F-values to the block F-values will give some indication of treatment vs. spatial variability. Block F-values were considered very small when compared to treatment F-values, which ranged from 10-20 times higher, indicating that the manure type and particle size had a much stronger influence on barley performance than did spatial variation in the field. The highest ratios of treatment-to-block were obtained for flag leaf area (10.6:1), hundred grain weight (7.8:1), and spike weight (9.5:1), which showed that these parameters were sensitive to management and less to environmental fluctuations. Grain per spike had a relatively smaller ratio (15.3:1), which was mainly

attributed to the high block effect, indicating that this trait had more management and environmental influences.

Implications for Experimental Design and Interpretation

The analysis of variance (ANOVA) results statistically validate the experimental results. The very low p-values and high F-values for the treatment effects indicate that the differences between the manure treatments observed with regard to the growth and yield parameters are real and repeatable and not due to random variation. The large block effects indicate that a blocked design rather than a completely randomized design was warranted because there was spatial variation in the experimental field. Inconsistently high treatment variance contributions (96-99%) for all the parameters suggest that organic manure application is the major factor influencing barley performance in this study, with environmental variability the minor factor. The discovery is also relevant to practice as it indicates that farmers would be able to get similar and predictable responses under different field conditions.

The low residual variance and high experimental precision give greater confidence in the order of the treatments and provide evidence that these data can be used for recommending which manure and particle size for barley production is best suited for sandy loam soils. The strength of the results with respect to statistics gives a good foundation for the subsequent discussion on the treatment means and the practical advice that follows.

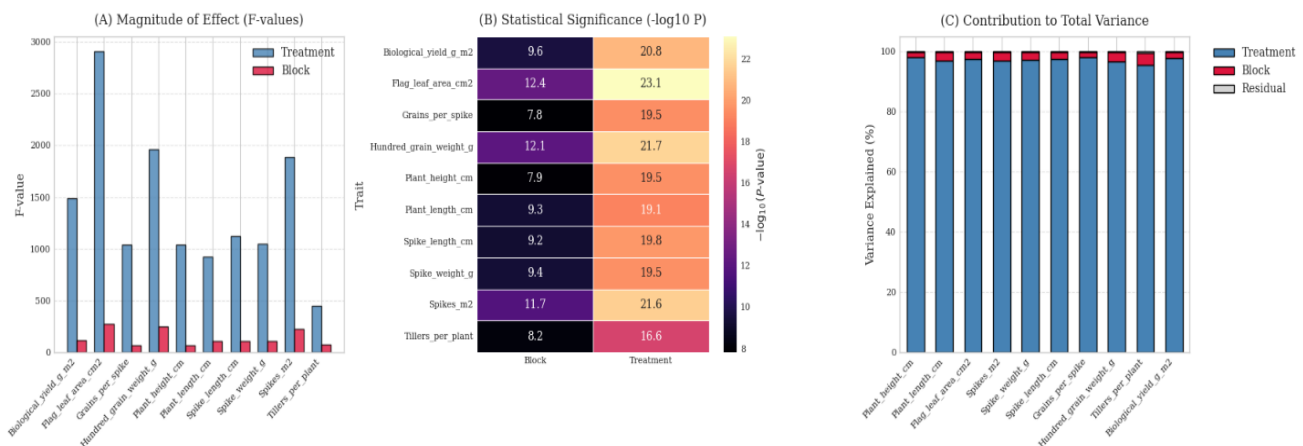


Figure 2. Treatment and block effects ANOVA analysis

3.2 Effect of cow and poultry manure particle size on barley growth traits

All growth parameters of barley were significantly influenced by organic manure treatments (plant height, plant length, flag leaf area, and tillers/plant). In Figure 3, the barley vegetative growth in terms of plant height, plant length, flag leaf area, and tillering was found to be highly significant in the RCBD ANOVA, making clear that the vegetative growth of barley was greatly affected by both manure source and particle-size class. All organic manure treatments resulted in significantly taller plants when compared to the control. The minimum plant height was achieved with the control treatment at 39.17cm on average. The highest value was obtained in H1 and C2, at 59.77 cm and 57.87 cm,

respectively. These findings suggest that vegetative growth increased with application of organic manure, with the extent of the response varying with manures and particle-size classes.

The application of manure also had a significant effect on plant length. The plant length for the control treatment was found to be the shortest, with 67.20 cm. The highest plant length was observed in C2 (83.60 cm), H2 (83.30 cm), and H1 (81.30 cm). The highest statistical group was formed by these treatments, indicating that some intermediate particle-size fractions might have been more effective in causing elongation of plants. There was a definite response to manure application in the flag leaf area. The control treatment yielded the lowest leaf area for the flag (17.73 cm²). The highest values were recorded under H2, C3, C2, H1, H3, and H4, ranging from 24.93 to 26.40 cm². However, C1 and C4 were not statistically different from the control for this trait, demonstrating that the response to particle size and leaf expansion was not consistent between the manure types.

Organic manure application resulted in a significant increase in tiller number per plant. Only 3.67 tillers plant⁻¹ were recorded in the control treatment, and the maximum tillers plant⁻¹ were recorded in H3, H4, C3, and C4, which ranged from 6.33 to 6.67 tillers plant⁻¹. This shows that the application of manure improved the tillering ability, which is an important factor affecting the formation of spikes and ultimate yield in barley.

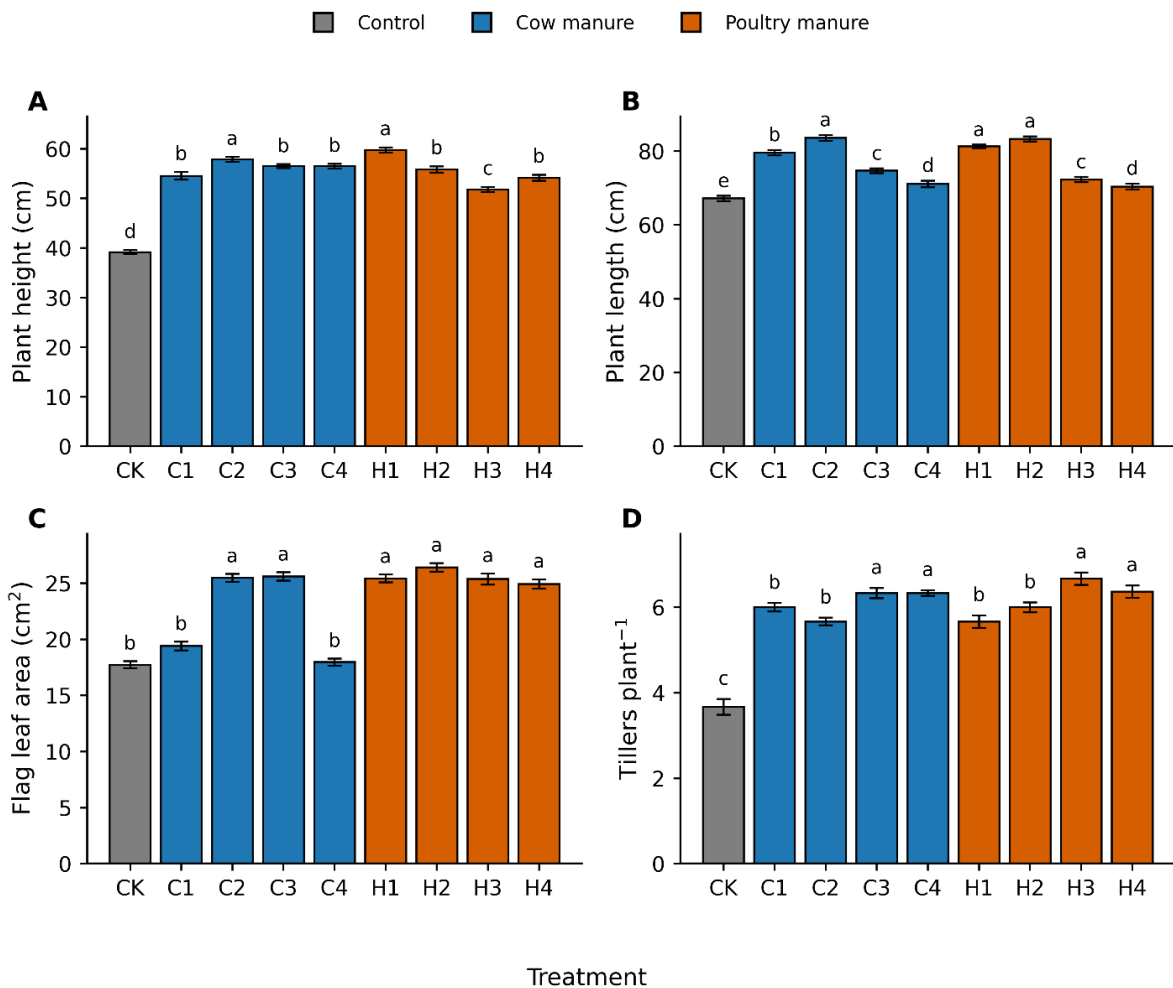


Figure 3. Multi-panel bar figure for growth traits.

3.3 Effect of organic manure treatments on yield components and biological yield

The treatments of organic manure significantly influenced all the yield components measured (Figure 4): number of spikes per square meter, spike weight, spike length, number of grains per spike, 100-grain weight, and biological yield. The results indicated that applying manure promoted yield formation primarily by increasing spike density and spike biomass, tillering, and total BEP.

The lowest number of spikes m^{-2} ($100.67 \text{ spikes m}^{-2}$) was obtained in the control treatment. The number of spikes was increased in all manure treatments compared with the control. The highest spike number was recorded in C4, $173.00 \text{ spikes m}^{-2}$, followed by C3, $163.00 \text{ spikes m}^{-2}$, and then by H3, $162.00 \text{ spikes m}^{-2}$. They were represented in the highest statistical group, which means the fraction of smaller particle sizes from cow manure and the intermediate particle size fraction from poultry manure had a special effect on increasing spike density. There was a significant spike in weight gain after the manure application. This is the lowest for the control treatment at 1.95 g, while all manure treatments had significantly higher spike weight between 3.36 and 3.60 g. C4 had the highest numerical, followed by H3 and C2. The manure treatments were not statistically different for spike weight but were better than the check, proving that organic fertilization benefits spike production greatly.

In the case of organic manure application, an increase in spike length was observed as well. The minimum length of spike was obtained for the control treatment, which was 8.33 cm. The highest group included C1, C2, C4, H1, and H4, each recording values close to 12 cm. C3, H2, and H3 had intermediate values of spike length but were greater than the control.

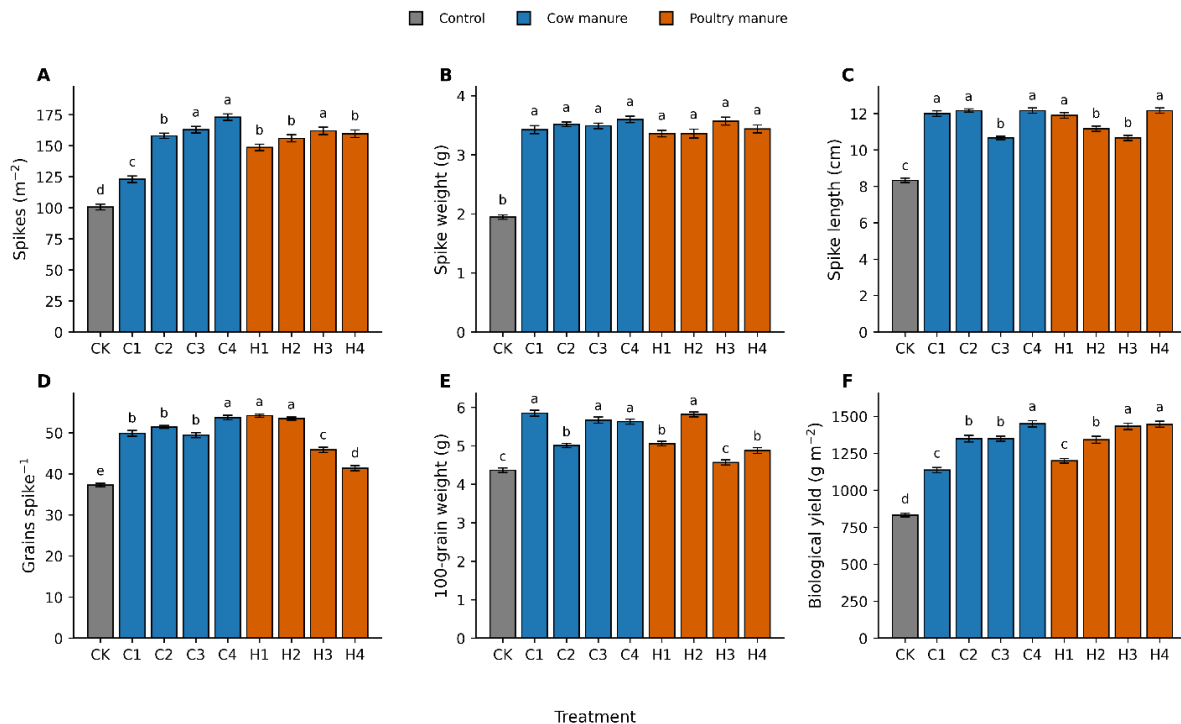


Figure 4. Multi-panel bar figure for yield components

Manure treatment had a significant effect on the number of grains per spike. The highest amounts (54.17, 53.70, and 53.43 grains spike⁻¹) were recorded in H1, C4, and H2, respectively, with the control treatment recording a value of 37.27 grains spike⁻¹. This indicates that some treatments of poultry manure and the smaller treatment of cow manure improved grain set in the spike. Most manure treatments also resulted in an improvement in the 100-grain weight. The highest values recorded were in the C1, H2, C3, and C4 treatments, with values 5.63 g to 5.85 g and 4.37 g for the control treatment. This did not differ among treatments, treatment H3, which was the control, suggesting that the impact of particle size of poultry manure on grain filling depended on the particle size. The organic manure application had a significant impact on biological yield. Control treatment had the lowest biological yield of 833 g m⁻². The highest biological yield was observed in C4, H4, and H3 of 1450, 1447, and 1433 g m⁻², respectively. This group of treatments was the highest for the statistical group. The results showed that cow manure (C4) was the most consistent treatment that was applied to the most yield-related traits, and the most productive poultry manure treatments were H3 and H4.

3.4 Mean comparison and treatment superiority

There were statistically significant differences between the treatments for all growth and yield parameters of barley measured using Tukey's Honest Significant Difference (HSD) test. The control (CK), which lacked manure fertilization, generally had the lowest or one of the lowest means for all traits, thus reflecting the high potential positive effect of the use of organic manures. The effectiveness of the different organic amendments varied with manure source and particle size, and the superiority of the respective treatments was observed for each of the agronomic traits (Table 4). As regards vegetative growth parameters, the plant height was significantly maximum (57.87 and 59.77 cm, respectively) for the H1 and C2 treatments and statistically compared to the other manure treatments and control. Likewise, plant length was highest in C2, H2, and H1 (83.60 cm, 83.30 cm, and 81.30 cm, respectively), being in the same top statistical group. Most of the manure treatments significantly improved flag leaf area, an important measure of photosynthetic potential. Treatments H2, C3, C2, and H1, H3, and H4 yielded the highest flag leaf area (24.93 to 26.40 cm²) and were in the highest statistical group, with significantly lower flag leaf area resulting from treatments C1, C4, and CK.

The treatments showed different effects on the yield components. The treatment with the highest number of spikes per square meter (173 spikes m⁻²) was the C4 treatment, which was not significantly different from C3 and H3, and significantly better than the other treatments. Interestingly, the weight of the spike did not significantly differ among any of the manure treatments (from 3.36 g to 3.60 g), with all being significantly heavier than the control (1.95 g). C2, C4, H4, C1, and H1 produced the longest spikes (11.90 to 12.17 cm) and were not significantly different. The highest number of grains per spike occurred in H1, C4, and H2 (54.17, 53.70, and 53.43 grains, respectively) and were significantly higher than in C2, C1, and C3, whereas spike H3 and H4 demonstrated a significant reduction in this trait. H1, C2, and H4 had intermediate grain weight, while C1, H2, C3, and C4 had the heaviest grains (5.63g to 5.85g) that were statistically different from the others, whereas H3 and CK had the lightest grains. The treatments also had significant effects on tillering capacity and total plant biomass accumulation. The highest number of tillers per plant was found in H3, C3, C4, and H4 (6.33 to 6.67 tillers), which were not significantly different from each other, but were significantly superior to C1, H2, H1, and C2. Biological yield, which was defined as total above-ground biomass, was largest

in C4, H4, and H3 (1450, 1447, and 1433 g m⁻², respectively). There was a significant difference between these three treatments and the rest of the treatments, including C2, C3, and H2, and they yielded the highest biomass, while C1, H1, and CK yielded the lowest biomass.

Table 4. Effect of different manure sources and particle-size fractions on growth, yield components, and biological yield of barley (*Hordeum vulgare* L.) under field conditions.

Treatment	Plant_height_cm	Plant_length_cm	Flag_leaf_area_cm ²	Spikes_m ²	Spike_weight_g	Spike_length_cm	Grains_per_spike	Hundred_grain_weight_g	Tillers_per_plant	Biological_yield_g_m ²
CK	39.17 ± 0.43 d	67.20 ± 0.70 e	17.73 ± 0.32 b	100.67 ± 2.33 d	1.95 ± 0.04 b	8.33 ± 0.12 c	37.27 ± 0.41 e	4.37 ± 0.06 c	3.67 ± 0.19 c	833.00 ± 11.93 d
C1	54.53 ± 0.76 b	79.60 ± 0.71 b	19.40 ± 0.38 b	123.00 ± 2.65 c	3.43 ± 0.07 a	12.00 ± 0.15 a	49.83 ± 0.71 b	5.85 ± 0.08 a	6.00 ± 0.10 b	1137.00 ± 17.67 c
C2	57.87 ± 0.50 a	83.60 ± 0.81 a	25.47 ± 0.35 a	158.00 ± 2.08 b	3.52 ± 0.04 a	12.17 ± 0.09 a	51.40 ± 0.36 b	5.01 ± 0.06 b	5.67 ± 0.09 b	1350.00 ± 21.79 b
C3	56.50 ± 0.40 b	74.70 ± 0.62 c	25.60 ± 0.38 a	163.00 ± 2.65 a	3.49 ± 0.05 a	10.67 ± 0.09 b	49.43 ± 0.61 b	5.67 ± 0.08 a	6.33 ± 0.12 a	1350.00 ± 17.32 b
C4	56.50 ± 0.47 b	71.10 ± 0.90 d	17.97 ± 0.32 b	173.00 ± 2.65 a	3.60 ± 0.05 a	12.17 ± 0.15 a	53.70 ± 0.56 a	5.63 ± 0.06 a	6.33 ± 0.07 a	1450.00 ± 21.79 a
H1	59.77 ± 0.52 a	81.30 ± 0.44 a	25.43 ± 0.35 a	148.67 ± 2.60 b	3.36 ± 0.06 a	11.90 ± 0.15 a	54.17 ± 0.38 a	5.06 ± 0.06 b	5.67 ± 0.15 b	1200.00 ± 16.07 c
H2	55.83 ± 0.64 b	83.30 ± 0.68 a	26.40 ± 0.38 a	156.00 ± 2.89 b	3.36 ± 0.08 a	11.17 ± 0.15 b	53.43 ± 0.38 a	5.82 ± 0.06 a	6.00 ± 0.12 b	1342.00 ± 23.43 b
H3	51.80 ± 0.52 c	72.30 ± 0.72 c	25.37 ± 0.49 a	162.00 ± 2.89 a	3.57 ± 0.07 a	10.67 ± 0.15 b	45.83 ± 0.61 c	4.57 ± 0.07 c	6.67 ± 0.15 a	1433.00 ± 21.39 a
H4	54.17 ± 0.61 b	70.40 ± 0.81 d	24.93 ± 0.41 a	159.67 ± 3.18 b	3.44 ± 0.07 a	12.17 ± 0.15 a	41.37 ± 0.64 d	4.88 ± 0.08 b	6.37 ± 0.15 a	1447.00 ± 20.55 a

3.5 Percentage increase over the unfertilized control

Barley growth and yield parameters compared with the unfertilized control (CK) showed that the use of organic manure led to significant increases in all growth and yield parameters of barley. The extent of these improvements depended on manure source (cow vs. poultry) and the type of treatment that was applied, as shown in the percentage increase analysis in Figure 5.

Vegetative Growth Parameters

The vegetative traits were highly sensitive to organic amendments. The height of the plants increased by 32.3% to 52.6% higher than the control. The treatment with poultry manure treatment (H1) showed maximum increase (52.6%), followed by cow manure treatment (C2) with 47.7% increase. Up to 24.4% (C2) and 4.8% (H4) improvements in plant length, with most elongation in the treatments C2 and H2. The variability in flag leaf area, an important factor to photosynthetic capacity, was the most pronounced, with treatment H2 up 44–49%, treatment C2, and treatment C4 up only 1.3%. Tillering capacity has been significantly improved, varying between 54.5% and 81.8%. The highest

rate of tiller production (81.8%) was found with treatment H3 and followed closely by C3 and C4 (72.7%).

Yield Components

Consistent high magnitude gains were observed with yield-related traits. The number of spikes per square meter increased by 22.2% to 71.9%, the highest being for treatment C4 (71.9% increase). There were outstanding gains in spike weight for all manure treatments, ranging from 72.6% to 84.9%. C4 (84.9%) and H3 (83.4%) had the greatest increases. There was a 28% increase in spike length, with treatments C2, C4, and H4 having the most significant increases (46%). The number of grains per spike increased by 11.0% to 45.4%. Treatment H1 was the most effective (45.4% growth) while treatment H4 was the least (11.0% growth). The test weight (hundred grain weight) rose 4.6% to 33.9. The heaviest grain was produced in treatments C1 (33.9%) and H2 (33.2%), and the least improvement was achieved in treatment H3 (4.6%).

Biological Yield and Treatment Superiority

The biological yield (total above-ground biomass) was 74.1% higher than the control with an increase of 36.5%. The treatments C4 (74.1%), H4 (73.7%), and H3 (72.0%) yielded the highest biomass production, which was considered to be the most efficient conversion of the nutrients to total plant mass.

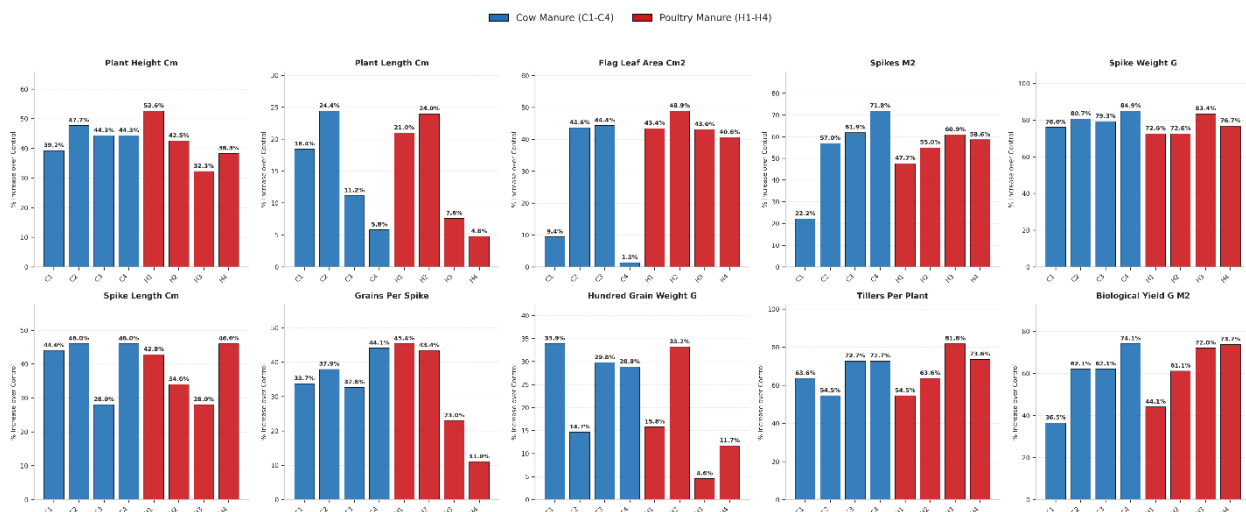


Figure 5. Percentage increase in growth and traits of Barley over the unfertilized control

3.6 Comparison of manure treatments with the control

The effects of the eight treatments (C1–C4; H1–H4) of organic manure on growth and yield traits compared to the unfertilized control (CK) expressed as percentage increase and significant (Holm adjusted $p < 0.05$) are shown in Figure 6. In general, the organic amendments had a significant effect on the majority of the measured parameters, especially the yield components. The most consistent and significant response was observed in spike weight, which increased between 72.6% and 84.9% for all the treatments. A significant improvement was also observed in biological yield and tillers per plant; in many instances, the difference was more than 60% (e.g., Treatment C4 had a 74.1% increase in

biological yield and H3 had an 81.8% increase in tillers). But some characteristics showed inconsistent responses to treatment. Increased plant length was not significant (NS) with treatment C4 and C5 (range of 1.3% to 5.8%), and increased flag leaf area was not significant (NS) with treatments C1 and C4. Also, the 100-grain weight was not significant in treatment H3 (4.6% increase), suggesting that biomass and vegetative growth were generally induced, but the grain filling quality was less responsive to certain poultry manure treatments.

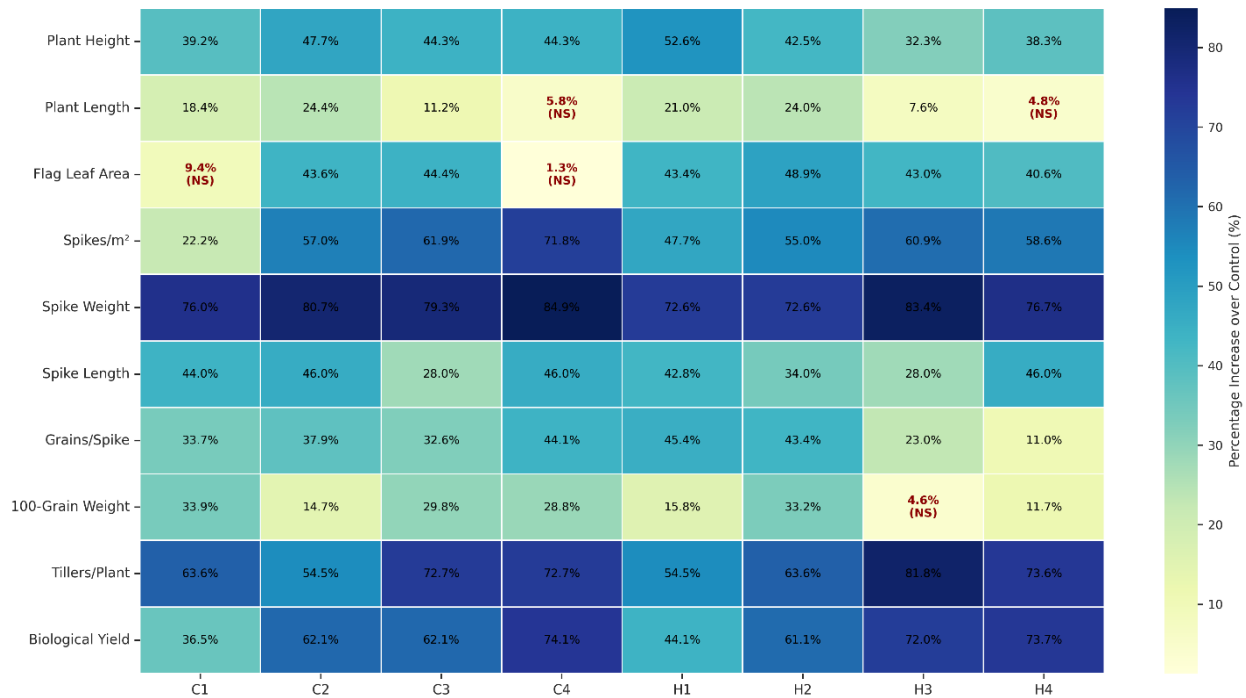


Figure 6. Percentage increase in growth and yield traits over the control with statistical significance

3.7 Factorial effect of manure type, particle size, and their interaction

The analysis of variance (ANOVA), presented as $-\log_{10}(P\text{-value})$, showed that the manure type, particle size, block, and interaction between manure type and particle size significantly ($P < 0.05$) affected all growth and yield parameters of barley in Figure 7. Overall, particle size was the most significant factor affecting crop performance, with several important traits having the highest level of significance, such as biological yield ($-\log_{11}(P) = 19.9$), spikes m^{-2} (18.3), plant length (18.0), and spike length (14.0). The results show that the physical size distribution of manure particles was a key to the nutrient availability and, consequently, nutrient use for crop growth and productivity. Manure type by particle size was also very significant and accounted for most of the variation for some yield-related traits. The interaction effect was most significant in 100-grain weight ($-\log_{11}(P) = 18.7$), in grains spike⁻¹ (16.2), and in plant height (14.4), indicating that the effect of the manure source was dependent upon the particle-size fraction used. The results emphasize the need to consider both in concert when developing optimized practice protocols for organic manure.

The type of manure had a particularly strong effect on flag leaf area, with its contribution to the source of variation being the most significant ($-\log_{11}(P) = 19.9$), and it was also highly significant for 100-grain weight (17.0). However, the relative effect was lower for tiller plant⁻¹ (about 2.5) and plant

length, suggesting that this was more influenced by the particle size and interaction effects than by the manure source alone. The block effect was also large for all the measured traits, and ranged from $-\log_{10}(P) = 6.5$ to 12.4. Among the factors, block exerted the greatest influence on spike weight (8.9), indicative of intra-field variation in the experimental field. The importance of the block effect reinforces the appropriateness of the randomized complete block (RCBD) design for allowing for the treatment of environmental variation and greater precision for treatment comparisons. As a whole, the results show that the source and size of manure and their interaction are key factors affecting barley growth and yield.

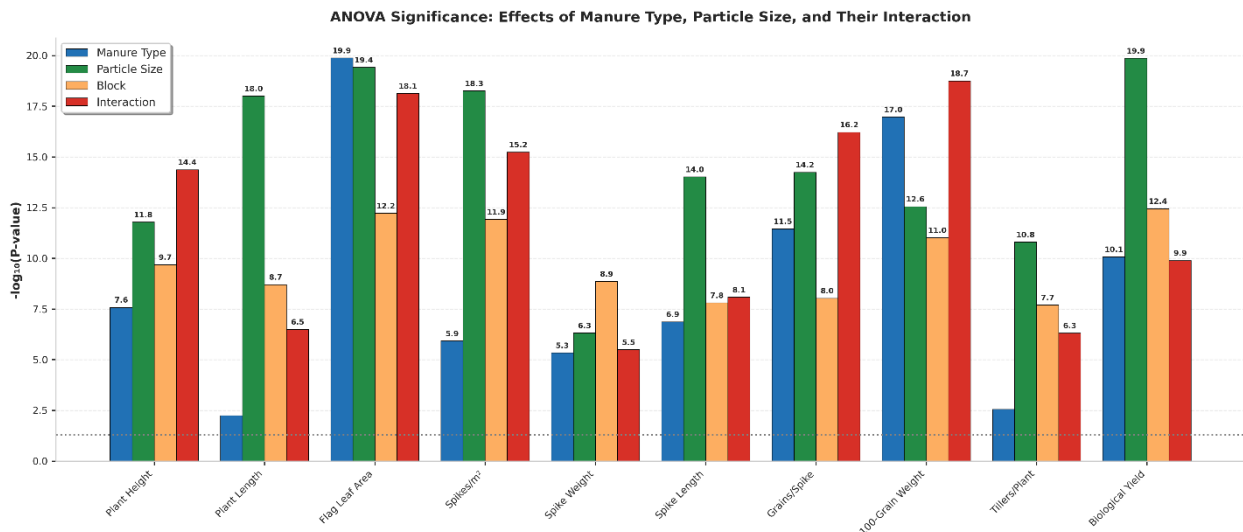


Figure 7. Factorial ANOVA excluding the control.

3.8 Correlation analysis among growth and yield traits

Figure 8 illustrates strong positive correlations between some growth and yield-related characters under Pearson correlation. The number of spikes m^{-2} , tillers per plant, and spike weight were strongly and positively correlated with biological yield. Biological yield showed the highest positive correlation ($r = 0.961$) with spike number, followed by tillers per plant ($r = 0.909$) and spike weight ($r = 0.887$).

Spike weight was also strongly correlated with tillers per plant ($r = 0.947$), plant height ($r = 0.893$), spike length ($r = 0.853$), and number of spikes m^{-2} ($r = 0.845$). The correlations showed that treatments which stimulated vegetative growth, tillering, also stimulated spike development and production of biomass.

Biological yield was not strongly related to plant length ($r = 0.179$); hence, plant elongation was not a principal factor in determining the biological yield. In contrast, improvements in yield were more correlated to spike number, tillering, spike weight, and vegetative biomass.

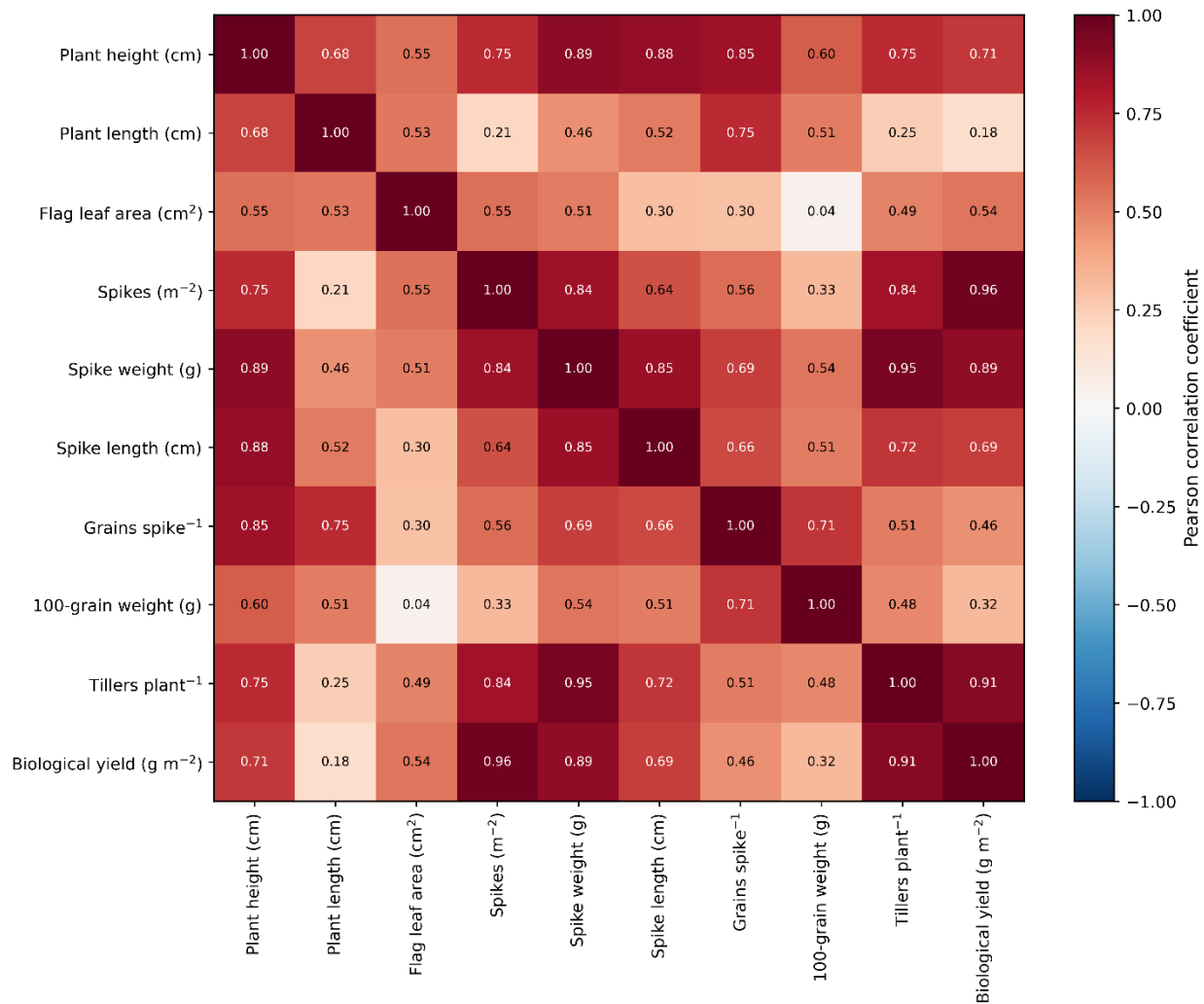


Figure 8. Correlation heatmap among barley growth and yield

3.9 Principal component analysis

The multivariate response of barley growth and yield variables to manure treatments was summarized using principal component analysis. The first two principal components explained 80.79% of the total variation in Figure 9. The PCA biplot was found to represent the main structure of the treatment responses, with PC1 accounting for 65.37% of the variation and PC2 for 15.43%.

Manure-treated plots were clearly separated from the unfertilized control along PC1 using the PCA biplot of treatment means. The control was then placed on the negative side of PC1, where it had the lowest scores for most growth and yield parameters. All manure treatments, however, were on the positive side of PC1, which supports the general improvement in barley performance of the treatments. The positive loadings of most of the traits on PC1 showed that this component reflects growth and yield performance in general. Plant height, spike weight, tillers/plant, biological yield, spike number, and spike length were among the traits that were significant. PC2 discriminated against treatments based on their differences in trait composition. The biological yield, spike number, and tillers per plant were more strongly associated with the negative direction of PC2, while plant length,

100-grain weight, and grains per spike were more strongly associated with the positive direction of PC2.

The treatments C3, C4, H3, and H4 were more closely related to spike number, tillering, spike weight, and biological yield, respectively. C1, C2, H1, and H2, however, were more closely related to plant length, number of grains per spike, and 100-grain weight. The multivariate patterns also upheld the results of the univariate ANOVA, with C4, H3, and H4 showing the best results for the yield-related traits.

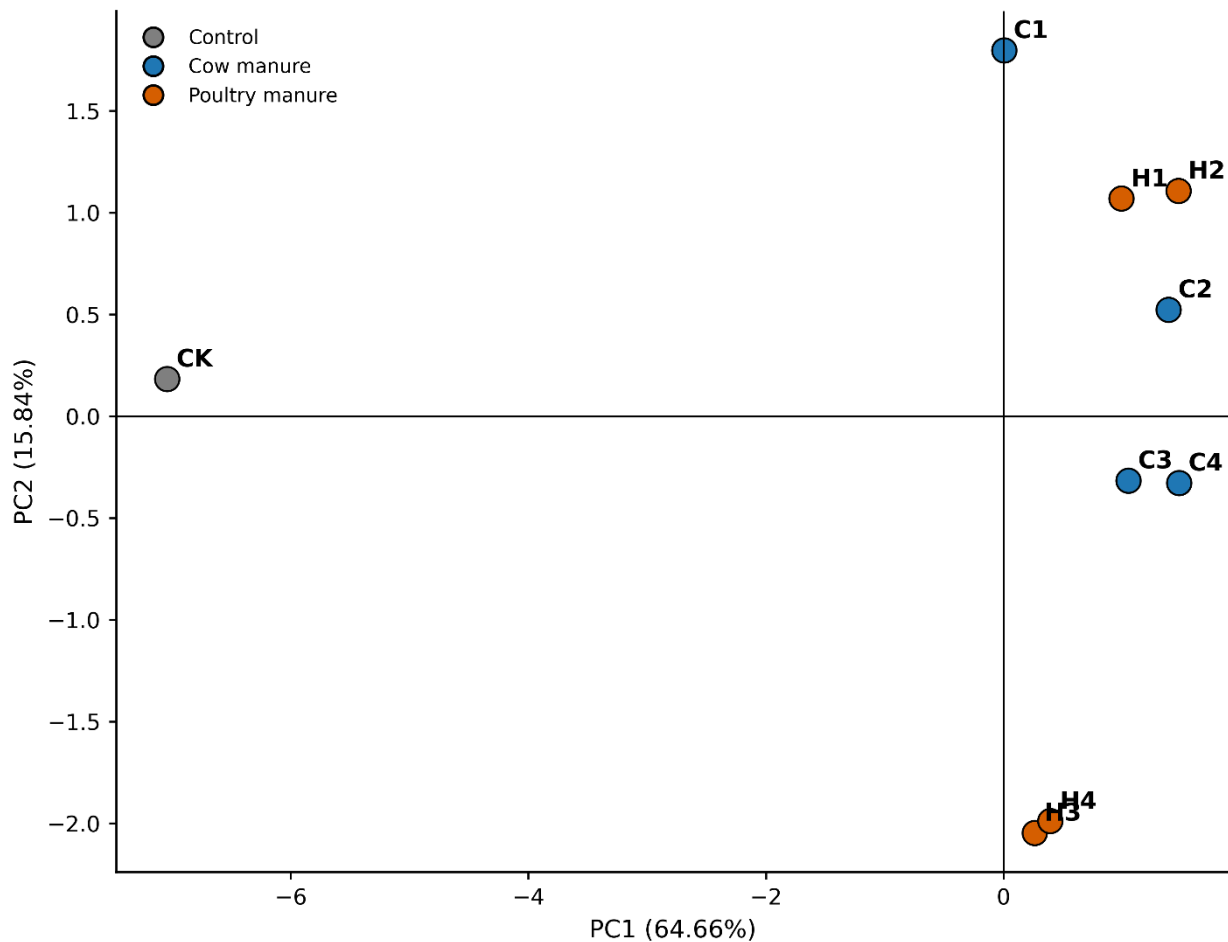


Figure 9. PCA biplot based on treatment means.

3.10 Cluster analysis of treatments

Figure 10 shows the hierarchical cluster analysis of the treatments based on their similarity in all the measured growth and yield traits. The control was distinctively different from the manure treatments, validating the lower performance of the control treatment for all the traits evaluated. This separation confirms the ANOVA and PCA results, which show that there is a distinct positive impact from the application of organic manure on barley growth and productivity. Within the fertilized treatments, high-performing treatments (C4, H3, and H4) tended to group together as they had the highest biological yield, spike number, and capacity to till. The treatments, C1, C2, H1, and H2, were more closely associated with plant length, the number of grains per spike, and 100-grain weight. Thus, the

cluster analysis also indicated that the manure treatments were not only different in individual traits but also in the multivariate performance.

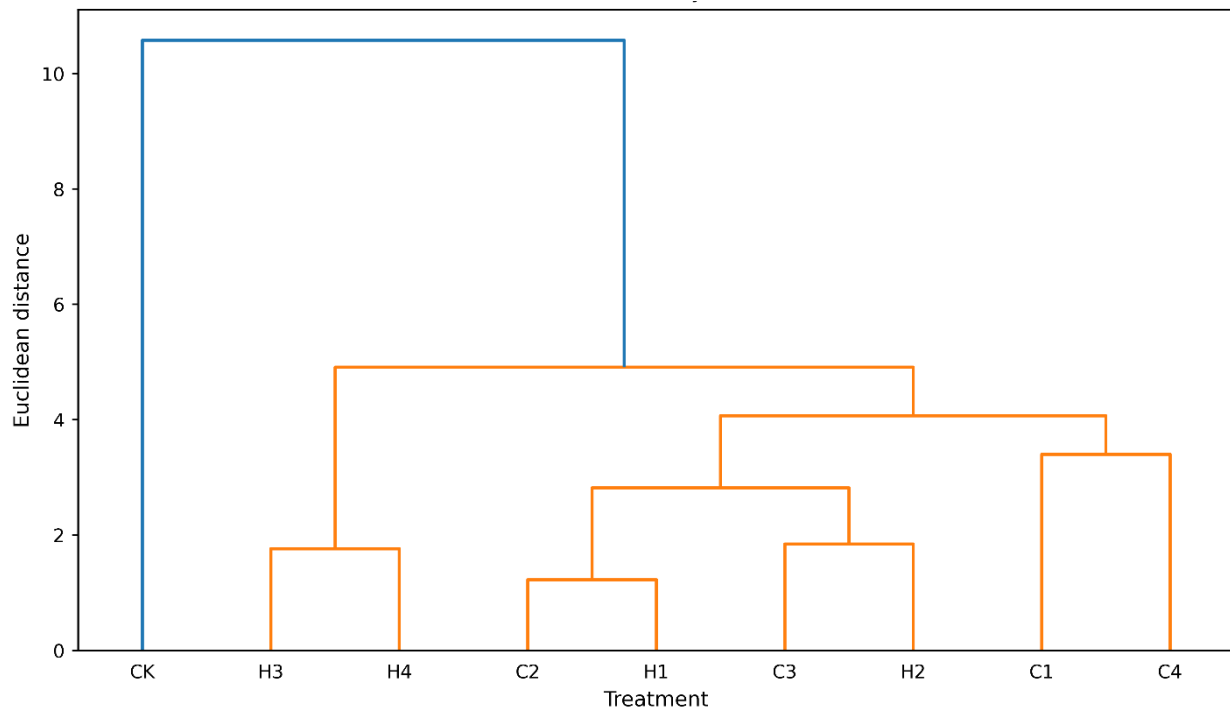


Figure 10. Cluster dendrogram.

Discussion

The present study shows that the use of fractionated organic manures had a significant effect on the growth, yield, and biological production of barley in a nutrient-deficient sandy loam soil. The performance of the unfertilized control was consistently lower for all the measured traits, which indicates the importance of the use of organic amendments to improve the soil with low inherent organic matter (0.40%) and total nitrogen (0.07%) (Tadele et al., 2026). The sources of variation indicated that treatment effects explained 96–99% of the total variance for all traits, suggesting that manure source and, most importantly, particle size play a major role in determining crop performance in this agro-ecological environment. The ability to account for the spatial variability by means of a randomized complete block design (RCBD) further confirms the robustness and repeatability of these findings (Festing, 2014). The vegetative parameters (plant height, plant length, flag leaf area) showed a positive response to organic fertilization and improved results in poultry manure fertilizations (especially H1 and H2). The higher amount of nitrogen (2.15%) and phosphorus (1.24%) content in the poultry manure is due to the pre-application chemical analysis of the manure, which shows that the chemical content of the manure is higher than that of the cow manure (1.25% N, 0.62% P). These nutrients were rapidly mineralized, which could have contributed to early vigor and leaf growth (Ning et al., 2022). In addition, physical fractionation of the particles has the potential to significantly affect the surface area for microbial colonization, which in turn, can lead to faster decomposition rates and the subsequent release of plant-available nutrients (Rostaei et al., 2024). While the overall trend suggests that the finest fraction of cow manure (C4) may not be all that effective, the non-significant

effect of C4 on flag leaf area indicates that nutrient release is not always linear, and that the wider C/N ratio of 19.72 in cow manure can temporarily trap N during the initial decomposition phase (Mgolozeli et al., 2024).

Tillering capacity and spike density are very important for yield formation in barley. The above-mentioned improvements in tillers per plant (up to 81.8%) and spikes per square meter (up to 71.9%) were directly reflected in a significant increase in biological yield (up to 74.1%). The best cow manure fraction (C4) was found to be the most consistent and best treatment for the highest density of spike, weight of spike, and total biological production. Fine particles of organic matter serve as a slow-release nutrient source and, at the same time, help to enhance soil structure, water holding capacity, and cation exchange capacity (CEC) in sandy loam soils that are prone to leaching of nutrients and poor water holding capacity (Laghari et al., 2025).

On the other hand, the finest fractions (such as H3, H4) of poultry manure had variable or non-significant increases in 100-grain weight over the control. The difference may be related to the electrical conductivity ($EC = 4.68 \text{ dS m}^{-1}$) of poultry manure. In fine fractions, the quick dissolution of soluble salts can cause mild osmotic stress during the critical grain filling period, and the early release of nitrogen can cause premature senescence, which will significantly reduce the amount of carbohydrate translocated to the grains (Sohail et al., 2026). On the other hand, the moderate C/N ratio and lower EC of cow manure (C4) released nutrients more in line with the crop's needs during reproductive growth, which explains its ability to optimize both the number of spikes and grain filling (Xing et al., 2025). One of the novel and critical findings of this study is that particle size as a main effect was more significant than manure source on the biological yield, spike number, and plant elongation. This indicates that the physical state of the organic amendment is very important for determining its agronomic effectiveness, as it defines the microbial breakdown and mineralization of nutrients (Liu et al., 2025). The PCA biplot and the hierarchical cluster analysis effectively distinguished the treatments into 2 functional groups. The best cluster (C4, H3, and H4) was significantly linked with biomass production, tillering, and spike density, and was considered the optimal treatment for increased total production. The second (C1, C2, H1, H2) cluster had a closer relationship with plant length, grains per spike, and 100-grain weight, which are treatments for grain quality and individual spike production that are different from the sheer biomass. This multivariate segmentation is very valuable for breeding and agronomic programs, because it allows for managing in a targeted manner according to the specific production objectives (Cen et al., 2020).

This study successfully separated the effects of particle size of manures on the short term, but further research should be conducted into the residual long-term effects of these fractionated manures on soil microbiome diversity, carbon sequestration, and the accumulation of stable soil organic matter. In addition, economic evaluations of the cost of mechanical manure fractionation to yield premiums would further confirm the potential for the practice to be adopted broadly in agriculture.

4. Conclusion

Finally, the results of this field experiment proved that organic manure applied in various forms and rates greatly affects the growth, yield of barley, and the productivity of the soil under sandy loam conditions. The use of organic amendments significantly affected all agronomic characteristics and explained up to 99% of the variation in the agronomic traits. Most importantly, particle size had a significant impact on biomass accumulation and density of the spikes, while the effect of the interaction between manure type and particle size on the grain quality parameters was mainly. In particular, the fine cow manure fraction C4 and the intermediate poultry fractions H3 and H4 had the best effect on increasing the biological yield, tillering, and spike density. In contrast, coarser particle fractions C1, C2, H1, and H2 were more effective in improving vegetative elongation and individual grain filling. The results indicated that strategic fractionation and targeted application of organic manures are able to create a specific nutrient release based on the developmental stage of the crop. In the end, the manipulation of the particle size of manure is a very beneficial and sustainable agronomic tool to maximize barley productivity and soil fertility management.

References

- Agegehu, G., Nelson, P. N., & Bird, M. I. (2016).** The effects of biochar, compost, and their mixture and nitrogen fertilizer on yield and nitrogen use efficiency of barley grown on a Nitisol in the highlands of Ethiopia. *Science of The Total Environment*, 569-570, 869-879. <https://doi.org/10.1016/j.scitotenv.2016.05.033>
- Arshad, M. J., Khan, M. I., Ali, M. H., Farooq, Q., Hussain, M. I., Seleiman, M. F., & Asghar, M. A. (2024).** Enhanced wheat productivity in saline soil through the combined application of poultry manure and beneficial microbes. *BMC Plant Biology*, 24(1), 548. <https://doi.org/10.1186/s12870-024-05137-x>
- Cen, Y., Guo, L., Liu, M., Gu, X., Li, C., & Jiang, G. (2020).** Using organic fertilizers to increase crop yield, economic growth, and soil quality in a temperate farmland. *PeerJ*, 8, e9668. <https://doi.org/10.7717/peerj.9668>
- Dhaliwal, S. S., Sharma, V., Verma, V., Kaur, M., Singh, P., Gaber, A., Laing, A. M., & Hossain, A. (2023).** Impact of manures and fertilizers on yield and soil properties in a rice-wheat cropping system. *PLoS One*, 18(11), e0292602. <https://doi.org/10.1371/journal.pone.0292602>
- El-Akhdar, I., Shabana, M. M. A., El-Khateeb, N. M. M., Elhawat, N., & Alshaal, T. (2024).** Sustainable Wheat Cultivation in Sandy Soils: Impact of Organic and Biofertilizer Use on Soil Health and Crop Yield. *Plants*, 13(22), 3156. <https://doi.org/10.3390/plants13223156>
- Festing M. F. (2014).** Randomized block experimental designs can increase the power and reproducibility of laboratory animal experiments. *ILAR journal*, 55(3), 472–476. <https://doi.org/10.1093/ilar/ilu045>
- Holatkó, J., Hammerschmidt, T., Mustafa, A., Kintl, A., Skarpa, P., Ryant, P., Baltazar, T., Malicek, O., Latal, O., & Brtnický, M. (2023).** Time-dependent impact of co-matured manure with elemental sulfur and biochar on the soil agro-ecological properties and plant biomass. *Scientific Reports*, 13(1), 4327. <https://doi.org/10.1038/s41598-023-31348-7>
- Liu, Q., Wu, P., Guo, X., Qu, Y., Zheng, J., Xing, Y., Dong, Z., Yu, W., Zhang, G., & Zhang, X. (2025).** Impact of Particle Size on the Aerobic Decomposition and Fertilizer Efficiency of Corn Cobs: A

- Sustainable Waste-to-Resource Approach. *Biology*, 14(11), 1610.
<https://doi.org/10.3390/biology14111610>
- Mench, M., Matin, S., Szulc, W., Rutkowska, B., Persson, T., Sæbø, A., Burges, A., & Oustriere, N. (2023).** Field assessment of organic amendments and spring barley to phytomanage a Cu/PAH-contaminated soil. *Environmental Geochemistry and Health*, 45(1), 19-39.
<https://doi.org/10.1007/s10653-022-01269-x>
- Mgolozeli, S., Nciizah, A. D., Wakindiki, I. I. C., & Mudau, F. N. (2024).** Nitrogen Mineralization of Selected Organic Materials and Their Combined Effects with Nitrogen Fertilizer on Spinach Yield. *Plants (Basel, Switzerland)*, 13(14), 1974. <https://doi.org/10.3390/plants13141974>
- Ning, L., Xu, X., Zhang, Y., Zhao, S., Qiu, S., Ding, W., Zou, G., & He, P. (2022).** Effects of chicken manure substitution for mineral nitrogen fertilizer on crop yield and soil fertility in a reduced nitrogen input regime of North-Central China. *Frontiers in plant science*, 13, 1050179.
<https://doi.org/10.3389/fpls.2022.1050179>
- Rostaei, M., Fallah, S., Carrubba, A., & Lorigooini, Z. (2024).** Organic manures enhance biomass and improve content, chemical compounds of essential oil and antioxidant capacity of medicinal plants: A review. *Heliyon*, 10(17), e36693. <https://doi.org/10.1016/j.heliyon.2024.e36693>
- Seleem, M., Khalafallah, N., Zuhair, R., Ghoneim, A. M., El-Sharkawy, M., & Mahmoud, E. (2022).** Effect of integration of poultry manure and vinasse on the abundance and diversity of soil fauna, soil fertility index, and barley (*Hordeum aestivum* L.) growth in calcareous soils. *BMC Plant Biology*, 22(1), 492. <https://doi.org/10.1186/s12870-022-03881-6>
- Shilev, S., Mitkov, A., Popova, V., Neykova, I., Minev, N., Szulc, W., Yordanov, Y., & Yanev, M. (2024).** Fertilization Type Differentially Affects Barley Grain Yield and Nutrient Content, Soil and Microbial Properties. *Microorganisms*, 12(7), 1447.
<https://doi.org/10.3390/microorganisms12071447>
- Sohail, S., Chenyun, B., Hanyang, T., Khosa, S. Y., Ali, M. F., Abbas, M. M., Ahamd, S. T., Iqbal, M., Xiaoyang, H., & Yuanjun, Z. (2026).** Enhancing wheat drought resilience through organic amendments: integrating soil health improvement and antioxidant defense activation. *BMC plant biology*, 26(1), 607. <https://doi.org/10.1186/s12870-026-08307-1>
- Tadele, H., Feyisa, T., Tsegaye, L., & Musie, S. (2026).** Maize (*Zea mays* L.) productivity and profitability response to inorganic N-P nutrients, biochar and vermicompost levels in acidic soils of Northwestern Ethiopia. *BMC plant biology*, 26(1), 445. <https://doi.org/10.1186/s12870-026-08261-y>
- Xing, Y., Xie, Y., & Wang, X. (2025).** Enhancing soil health through balanced fertilization: a pathway to sustainable agriculture and food security. *Frontiers in microbiology*, 16, 1536524.
<https://doi.org/10.3389/fmicb.2025.1536524>
- Zhao, Y., & Naeth, M. A. (2024).** Synergistic effects of coal waste derived humic substances and inorganic fertilizer as soil amendments for barley in sandy soil. *Heliyon*, 10(8), e29620.
<https://doi.org/10.1016/j.heliyon.2024.e29620>