Original Research Article **CODEN: PJZSAZ e-ISSN: 1331-7776**

Organic manure and biofertilizer enhance growth and yield performance of black gram

Md. Mainul Hasan[1,3], Md. Mamunur Rashid[2*], Humayra Islam[1], Md. Mahmudul Hasan[1], Mr. Shanto Mardi[1], Md. Abu Hasan[1], Abu Khayer Md. Muktadirul Bari Chowdhury[1*]

[1]Department of Crop Physiology & Ecology, Faculty of Agriculture, Hajee Mohammad Danesh Science and Technology University, Dinajpur-5200, Bangladesh

[2]Department of Agronomy, Faculty of Agriculture, Hajee Mohammad Danesh Science and Technology University, Dinajpur-5200, Bangladesh

[3]Bangladesh Sugarcrop Research Institute, Ishwardi -6620, Pabna, Bangladesh

*Correspondence: Abu Khayer Md. Muktadirul Bari Chowdhury (minarbari07@gmail.com), Md. Mamunur Rashid (mamun05.hstu@gmail.com)

Article info:

Received: 23 May 2026

Revised: 5 August 2026

Accepted: 6 August 2026

Available online: 6 August 2026

Academic Editor: Prof. Marina Piria, University of Zagreb Faculty of Agriculture, Croatia

How to Cite:

Hasan M.M., Rashid M.M., Islam H., Hasan M.M., Mardi S., Hasan M.A., Chowdhury A.K.M.M.B. (2026). Organic manure and biofertilizer enhance growth and yield performance of black gram. Agric Conspec Sci 91: e009.

This article is an accepted manuscript and an uncorrected proof that has not undergone copyediting, language editing, or technical checks. The final version of the record may differ from this version.

ABSTRACT

In Bangladesh, sole dependence on inorganic fertilizers has led to declining soil organic matter, nutrient imbalance, and progressive soil health degradation; therefore, nutrient management involving organic manures and biofertilizers is essential for restoring soil fertility and sustaining long-term crop productivity under intensive agricultural systems. In this context, a field experiment was conducted from February to June 2022 to evaluate the effects of organic manures and biofertilizers on growth, physiological attributes, and yield performance of black gram (*Vigna mungo* L.). The experiment was laid out in a two-factor randomized complete block design with three replications. Factor A consisted of three varieties (BARI mash-1, BARI mash-3, and BARI mash-4), while Factor B included five nutrient management treatments: recommended dose of fertilizers (RDF), poultry litter-based compost (PLBC) 7.5 t ha^{-1}, BARI biofertilizer, BINA biofertilizer, and biochar 5 t ha^{-1}. Significant effects of variety, nutrient management, and their interaction were observed for most measured parameters, although the significance varied among traits and growth stages.. PLBC application markedly improved growth and yield attributes, including plant height, branching, root development, pod number, grain yield, straw yield, SPAD value, and thousand-seed weight, in some treatments. Among varieties, BARI mash-1 recorded superior performance with the highest grain yield, whereas BARI mash-4 showed the lowest. The interaction effect revealed the highest yield in BARI mash-1 under PLBC, while the lowest was observed in BARI mash-4 with biochar. Overall, PLBC 7.5 t ha^{-1} demonstrated the most effective nutrient management strategy for enhancing black gram productivity under field conditions.

Keywords: *Vigna mungo*; organic manure; poultry litter compost; sustainable agriculture; soil fertility

INTRODUCTION

Black gram (*Vigna mungo* L.) is a short-duration pulse crop belonging to the family Leguminosae and is widely recognized as an important source of plant-based protein and essential nutrients (Vishwakarma, 2021; Nasir et al., 2022). It contains approximately 26-28% protein along with significant amounts of carbohydrates, minerals, and vitamins (Pande et al., 2012). The crop is primarily cultivated for human consumption, while it also contributes to livestock feed and green manuring. Moreover, black gram enhances soil fertility through biological nitrogen fixation via symbiosis with Rhizobium, thereby improving nutrient availability for subsequent crops (Khatana et al., 2021; Veer et al., 2022).

In developing countries such as Bangladesh, pulses serve as an affordable and major protein source for low-income populations (Siddiq et al., 2022). However, the current per capita availability of pulses (20-22 g day^{-1}) is far below the FAO recommendation (Bokhtiar et al., 2023). National production remains insufficient due to limited cultivation area and low productivity, highlighting the urgent need to enhance pulse yield to meet increasing demand (Emran et al., 2022; Prioty et al., 2023)

Sustainable crop production requires efficient nutrient management that maintains soil fertility while minimizing environmental degradation. Excessive and imbalanced use of chemical fertilizers has led to declining soil health, reduced productivity, and environmental concerns (Krasilnikov et al., 2022). In Bangladesh, soil organic matter content is generally low (1.5%), whereas at least 3-5% is considered optimal for high crop yields (Uddin et al., 2022). Therefore, the utilization of organic and biological nutrient sources is essential for improving soil quality and ensuring long-term agricultural sustainability.

Organic manures such as poultry litter-based compost are valuable sources of macro and micronutrients and contribute to improved soil structure, water-holding capacity, and microbial activity (Aboutayeb et al., 2025; Islam et al., 2025). Composting poultry litter mitigates its negative environmental impacts while enhancing nutrient availability and crop productivity (Kyakuwaire et al., 2019). Biofertilizers, particularly Rhizobium inoculants, play a crucial role in sustainable agriculture by enhancing biological nitrogen fixation, improving soil fertility, and increasing crop yields (Bhardwaj et al., 2014; Kumar et al., 2018). Similarly, biochar, a carbon-rich product derived from biomass, improves soil physicochemical properties, enhances nutrient retention, and reduces nutrient losses, thereby contributing to increased crop productivity (Kapoor et al., 2022; Khan et al., 2024).

Considering the importance of the application of organic manures, biofertilizers, and biochar offers a promising approach to improve soil health and crop productivity. Therefore, the present study was undertaken to evaluate the effects of organic manure and biofertilizers on the growth and yield of blackgram.

MATERIALS AND METHODS

Location

The experiment was conducted at the research field of the Department of Crop Physiology and Ecology, Hajee Mohammad Danesh Science and Technology University, Dinajpur, Bangladesh, during the period from February to June 2022. The experimental site is located in Sadar Upazila, Dinajpur, at 25.39° N latitude and 88.41° E longitude, with an elevation of 37.58 m above mean sea level (Fig. 1).

Soil and climate

The experimental field was classified as medium-high land under Agro-Ecological Zone 1 (AEZ-1), corresponding to the Old Himalayan Piedmont Plain. The soil of the site was sandy loam in texture. The region experiences mild to moderate rainfall during the cropping period from March to June 2022. Detailed information on soil properties and meteorological parameters, including temperature, precipitation, and relative humidity during the crop growth period are presented in Table 1 and Fig. 2, respectively.

Physicochemical characterization of organic amendments

Prior to application, representative samples of the poultry litter-based compost and biochar were collected, air-dried, crushed, and filtered through a 2-mm sieve for physicochemical analysis. The pH and electrical conductivity (EC) of a 1:5 (w/v) amendment-to-distilled water suspension were measured with a calibrated pH meter and an EC meter, respectively. The wet oxidation method developed by Walkley and Black was employed to determine organic carbon. The total nitrogen (N) was measured using the Kjeldahl digestion and distillation method. Following acid digestion, available phosphorus (P) was quantified colorimetrically using the molybdenum blue method, and available potassium (K) was measured using flame photometry. Moisture content was determined by oven drying at 105°C to constant weight, and ash content was measured by combustion in a muffle furnace at 550°C. The carbon-to-nitrogen (C:N) ratio was estimated using the measured organic carbon and total nitrogen content.

Experimental design and layout

The experiment was conducted as a two-factor factorial experiment in a Randomized Complete Block Design (RCBD) with three replications. The experimental unit was defined as an individual plot measuring 3 m × 1 m. A total of 45 experimental plots were established. The spacing between blocks and plots was maintained at 50 cm and 25 cm, respectively. The treatments consisted of two factors. Factor A comprised five fertilization treatments: F_1 = recommended dose of fertilizer (RDF), consisting of urea, triple superphosphate (TSP), and muriate of potash (MOP) applied at rates of 40, 90, and 40 kg ha^{-1}, respectively; F_2 = poultry litter-based compost at 7.5 t ha^{-1}; F_3 = BARI biofertilizer at 85 g kg^{-1} seed; F_4 = BINA biofertilizer at 85 g kg^{-1} seed; and F_5 = biochar at 5 t ha^{-1}. Factor B included three blackgram varieties: V_1 = BARI Mash-1, V_2 = BARI Mash-3, and V_3 = BARI Mash-4.

The physicochemical characteristics of the poultry litter-based compost and biochar used in this study are presented in Table 2. Poultry litter-based compost exhibited higher nutrient contents (N, P, and K) and a lower C:N ratio, whereas biochar was characterized by higher pH, organic carbon content, and C:N ratio, indicating their complementary roles as soil amendments.

Additionally, BARI and BINA biofertilizers were peat-based Rhizobium inoculants obtained from the Soil Microbiology Laboratory of BARI and BINA, respectively. The inoculants contained viable Rhizobium populations of approximately 10^8 CFU g^{-1} carrier material and were applied as seed inoculants according to the recommended procedure.

Fertilization

During final land preparation, the fertilizers were applied as a basal dose, where urea, TSP, MOP are applied at 40 kg ha^{-1}, 90 kg ha^{-1}, and 40 kg ha^{-1}, respectively, in recommended fertilizer dose replicated plots. The poultry litter-based compost and biochar were applied during final land preparation at 7.5 ton ha^{-1} and 5 ton ha^{-1} in respective plots. All the fertilizers were applied by broadcasting and mixed thoroughly with soil.

Seed inoculations and sowing of seeds

For each plot, 9 g of blackgram seed was required, based on the recommended seed rate of 30 kg ha^{-1}. Seeds were weighed and packed into 45 individual polythene bags. Eighteen packets were designated for inoculation with BARI and BINA biofertilizers (six packets per variety: BARI Mash-1, BARI Mash-3, and BARI Mash-4).

The seeds were first soaked in molasses, after which 0.77 g of biofertilizer was thoroughly mixed with the seeds to form a uniform, thick coating. The inoculated seeds were then air-dried in a cool, dry place before sowing. Sowing was performed on 3 March 2022 in furrows, which were subsequently covered with soil. The sowing depth was maintained at 2-2.5 cm from the soil surface.

Crop management

Weeding and thinning were performed to ensure proper plant growth and reduce competition. The first weeding and thinning were carried out at 20 days after sowing (DAS), followed by a second weeding at 40 DAS. These practices improved soil aeration, reduced weed competition, and helped conserve soil moisture.

Irrigation was applied three times during the crop growth period: at 7, 20, and 35 DAS. During the early growth stage, some plants were affected by hairy caterpillar infestation and root rot. Infected leaves were removed and destroyed manually, and chemical control was applied using Malathion 57 EC at 1.5 L ha^{-1} and Indofil M45 at 2 g L^{-1} at 35 and 50 DAS, respectively.

Data collection

Plant samples were first collected at 30 days after sowing (DAS) and subsequently at 15-day intervals. From each plot, three plants were randomly selected and carefully uprooted using a *khurpi*. Roots were gently washed with water to remove adhering soil, and nodules on each plant were counted. Plant height was measured from the ground level to the tip of the uppermost leaf, while root length was measured from the base of the stem to the root tip. Plants were separated into leaves, shoots, and roots, and the number of leaves and branches $plant^{-1}$ was recorded for each sampled plant. Fresh weights of shoots and roots were measured immediately using an electronic balance, and samples were then oven-dried at 72°C for 72 hours to determine dry biomass. For each sampling date, the measurements obtained from the three plants within each plot were averaged to generate a single plot-level value, which was used as the experimental unit in all statistical analyses. Thus, individual plants were not considered independent replicates. Second and third plant samplings were conducted at 45 and 60 DAS, respectively, following the same procedures.

Various growth, yield, and physiological parameters were recorded during the experiment. Growth measurements at 30, 45, and 60 DAS were obtained through independent destructive sampling, in which different plants were sampled at each observation date. Consequently, separate statistical analyses were performed for each sampling date. Chlorophyll content was estimated using a SPAD meter on fully expanded leaves. At maturity, the number of pods $plant^{-1}$ was counted, and pod length was measured on ten randomly selected pods $plant^{-1}$, with the average value calculated. Thousand-grain weight was determined by weighing 1000 grains using an electronic balance. Grain and straw yields were recorded from each plot and expressed in tons ha^{-1}. All measurements were performed following standard agronomic procedures to ensure accuracy and consistency.

Statistical analysis

The collected data were analyzed using Statistix 10 software. Because independent destructive sampling was performed at 30, 45, and 60 DAS, data from each sampling date were analyzed separately. A two-factor factorial analysis of variance (ANOVA) based on a Randomized Complete Block Design (RCBD) was performed using the model:

$$Yijk = \mu + Bi + Vj + Fk + (VF)jk + \varepsilon ijk$$

Where *B* represents the block (replication) effect, *V* the fixed effect of variety, *F* the fixed effect of fertilizer treatment, *(VF)* their interaction, and *ε* the random error. Blocks were included to account for field variability. Before ANOVA, the assumptions of normality of residuals and homogeneity of variances were assessed, and the data satisfied these assumptions; therefore, no data transformation was required. When treatment effects were significant, mean separation was performed using Tukey's Honest Significant Difference (HSD) test at the 5% significance level ($p \leq 0.05$). Pearson's correlation analysis, Principal Component Analysis (PCA), and hierarchical cluster analysis were performed using OriginPro 2026 (OriginLab Corporation, Northampton, MA, USA). PCA was performed using treatment means for all treatment combinations. PCA was conducted using the correlation matrix. The variables included plant height, straw yield, leaf number, grain yield, branch number, pod number, root length, dry matter, pod length, SPAD value, nodule number, root fresh weight, shoot fresh weight, and 1000-seed weight.

RESULTS

Growth attributes

Plant height

Plant height was significantly ($p \leq 0.05$) influenced by variety, fertilization, and their interaction at all growth stages. Among the varieties, V_3 produced the tallest plants at 30 DAS (14.40 cm) and at harvest (42.07 cm), whereas V_2 recorded the greatest plant height at 45 DAS (23.56 cm) and 60 DAS (36.07 cm). Fertilization treatments also showed significant variation, where F_2 resulted in greater plant height at early stages (14.24 cm at 30 DAS and 24.22 cm at 45 DAS), while F_3 exhibited higher values at later stages (37.62 cm at 60 DAS and 41.56 cm at final harvest), and the lowest plant height at final harvest was recorded under F_5 (37.55 cm). The interaction effect showed pronounced differences among treatment combinations, with the tallest plants observed in V_3F_1 (46.43 cm) and V_2F_2 (43.45 cm), followed by V_3F_3 (43.29 cm) and V_3F_4 (42.85 cm), whereas the lowest plant height was recorded in V_2F_4 (35.00 cm) (Table 3).

Leaf number

Leaf number was also significantly influenced by variety and interaction effects at all growth stages, while fertilization showed non-significant variation at 45 DAS but was significant at other stages. Among the varieties, V_1 consistently produced the highest number of leaves, recording 49.88 leaves at final harvest, followed by V_3 (47.39 leaves), whereas V_2 showed the lowest leaf number (46.13). Fertilization treatments indicated that F_2 produced the highest leaf number at final harvest (50.21), followed by F_1 (48.74), while comparatively lower values were recorded under F_4 (48.03) and F_5 (46.90). The interaction effect revealed that V_1F_4 (53.67) and V_1F_2 (51.71) produced the highest leaf numbers, followed by V_1F_1 (50.58) and V_3F_2 (50.24), whereas the lowest leaf number was observed in V_2F_4 (40.97). Additionally, the highest number of leaves at harvest (53.67) was recorded in V_1F_4, whereas the lowest (40.97) was observed in V_2F_4 (Table 3).

Number of branches plant^{-1}

Branches plant^{-1} was significantly influenced ($p \leq 0.05$) by variety, fertilization, and their interaction, except for the non-significant varietal effect at final harvest. Among the varieties, V_1 produced the highest number of branches at 30 DAS (2.79) and 60 DAS (7.18), whereas V_2 recorded the highest values at 45 DAS (4.52) and V_3 got the maximum at final harvest (7.52), although the varietal effect at final harvest was not significant. Fertilization F_1 produced the highest number of branches at 30 DAS (2.85), F_3 at 45 DAS (4.74), F_2 at 60 DAS (8.67) and final harvest (9.00). The interaction effect showed that V_1F_3 produced the highest number of branches at 30 DAS (3.56), V_2F_1 and V_3F_3 at 45 DAS (5.22), V_3F_2 (9.45) at 60 DAS, and V_2F_2 (9.78) at final harvest, whereas the lowest values were recorded in V_1F_4 (2.22) and V_2F_5 (2.22) at 30 DAS, V_3F_5 (3.11) at 45 DAS, V_2F_1 (5.55) at 60 DAS, and V_2F_3 (6.56) at final harvest (Table 4).

Root length

Root length was notably affected by fertilization and interaction effects at all stages, while varietal differences were mostly non-significant except at 45 DAS, where V_3 showed higher root length (13.11 cm). Fertilization F_2 produced longer roots at 30 DAS (11.71 cm) and 45 DAS (13.66 cm), whereas F_1 was superior at 60 DAS (22.17 cm); the lowest value was observed under F_3 at 60 DAS (17.99 cm). Interaction effects revealed that V_3F_1 and V_3F_2 produced maximum root length (up to 23.68 cm), while V_2F_3 recorded the minimum (17.19 cm) (Table 4).

Nodule number

Nodule number plant^{-1} was significantly ($p \leq 0.05$) affected by variety, fertilization, and their interaction at all growth stages, as represented in Fig. 3. Nodulation increased with plant age, reaching maximum at 60 DAS. Among varieties, V_3 produced the highest nodule number at 30 DAS (17.14), whereas V_1 was superior at 45 and 60 DAS (13.71 and 15.17); V_2 consistently recorded lower values (11.13-14.13). Fertilization markedly influenced nodulation, with F_5 and F_2 producing higher nodule numbers (up to 17.09 and 15.93 at 60 DAS, respectively), while F_1 and F_3 resulted in lower values (≈11.00-11.11). Interaction effects further confirmed that V_1F_5, V_2F_2, and V_3F_2 produced the highest nodulation, with a maximum of 20.78 nodules plant^{-1} (V_1F_5 at 60 DAS), whereas V_2F_3 showed the lowest value (7.44). Overall, both varietal differences and fertilization regimes markedly influenced nodulation dynamics in blackgram.

Physiological trait

SPAD Value

The graphical analysis of SPAD values at 30, 45, and 60 DAS (Fig. 4) revealed notable ($p < 0.05$) variation among varieties, fertilization treatments, and their interactions, indicating strong temporal and treatment-dependent responses across growth stages. Among varieties, V_3 (BARI mash-4) consistently exhibited the highest SPAD values (41.38 at 30 DAS, 35.22 at 45 DAS, and 38.33 at 60 DAS), followed by V_2, whereas V_1 recorded the lowest values (38.19-35.81). Fertilization also significantly influenced chlorophyll content, with higher SPAD values observed under F_3 and F_4 at 30 DAS (41.41 and 41.13), F_2 at 45 DAS (36.16), and F_1 as well as F_3 at 60 DAS (38.38–38.40), while F_5 consistently produced the lowest readings (36.87-33.69-37.15). Interaction effects were pronounced, with the highest SPAD values recorded in

V_3F_3 at 30 DAS (46.97), V_2F_2 at 30 DAS (43.93), and V_3F_2 at 45 DAS (37.50), whereas the lowest values were observed in V_2F_3 at 45 DAS (31.67) and V_1F_4 at 60 DAS (33.83), indicating strong variety × fertilization interactions affecting chlorophyll accumulation and leaf physiological status.

Biomass accumulation

Root fresh weight

Root fresh weight was markedly influenced ($p \leq 0.05$) by variety, fertilization, and their interaction at all growth stages (Table 5). Among varieties, V_3 recorded the highest root fresh weight at 30 DAS (0.33 g) and 60 DAS (2.31 g), whereas V_2 showed the lowest values (0.25-1.88 g). Fertilization treatments F_2 and F_3 produced higher root fresh weight at 30 DAS (0.34-0.35 g), while F_1, F_2, and F_5 recorded comparatively higher values at 60 DAS (2.21-2.23 g), with F_4 showing the lowest (1.74 g). Interaction effects indicated that V_2F_2 (0.47 g) and V_3F_3 (0.47 g) produced the highest root fresh weight at 30 DAS, while V_3F_5 (2.86 g) showed the maximum at 60 DAS; in contrast, V_2F_5 recorded the lowest values (0.16 g at 30 DAS and 1.42 g at 60 DAS).

Shoot fresh weight

Shoot fresh weight varied substantially ($p \leq 0.05$) among treatments. V_3 produced the highest shoot biomass at 60 DAS (52.23 g), whereas V_2 recorded the lowest (47.54 g). Fertilization F_1 resulted in the highest shoot fresh weight across stages, particularly at 60 DAS (53.53 g), while F_4 showed the lowest values (47.24 g). Interaction effects revealed that V_3F_3 (59.72 g) and V_3F_1 (56.39 g) produced the maximum shoot biomass, whereas V_2F_4 (41.13 g) and V_2F_5 (42.71 g) exhibited the lowest performance (Table 5).

Total Dry Matter

The graphical analysis of total dry matter accumulation at 30, 45, and 60 DAS (Fig. 5) revealed significant ($p \leq 0.05$) variation among varieties, fertilization treatments, and their interactions. Total dry matter increased progressively with crop growth, although the rate of accumulation differed across treatments. Among varieties, V_3 produced the highest dry matter at 30 DAS (0.47 g), while V_1 recorded the maximum biomass at 45 and 60 DAS (2.29 and 11.97 g), closely followed by V_3 at 60 DAS (11.82 g); V_2 consistently showed lower values across stages (0.40-10.50 g). Fertilization significantly affected biomass production, where F_1 and F_3 resulted in higher dry matter at 30 DAS (0.47 and 0.46 g), F_5 showed the highest accumulation at 45 DAS (2.46 g), and F_3 recorded the maximum at 60 DAS (12.33 g), whereas F_2, F_4, and F_5 generally remained lower at later stages (10.63-10.98 g). Interaction effects indicated marked variability, with the highest total dry matter recorded in V_3F_1 at 30 DAS (0.56 g) and 60 DAS (14.44 g), while V_2F_2 showed superior performance at 45 DAS (2.73 g); in contrast, the lowest values were observed in V_2F_5 at 60 DAS (9.28 g) and V_3F_3 at 45 DAS (1.60 g), indicating strong genotype × fertilization interactions in biomass accumulation.

Yield and yield-contributing characters

All yield and yield-related traits were influenced ($p \leq 0.05$) by variety, fertilization, and their interaction, as demonstrated in Table 6.

Pod number and pod length

Pod number and pod length showed clear variation among treatments. V_1 produced the highest pod number (46.33 pods plant^{-1}), whereas V_3 recorded the lowest (37.45). In contrast, V_3 exhibited the longest pods (5.35 cm), followed by V2 (4.95 cm), while V_1 had the shortest pods (4.84 cm). Among fertilization treatments, F_2 resulted in the highest pod number (45.56), while F_5 showed the lowest (33.04). Pod length was the greatest under F_1 (5.25 cm). Interaction effects indicated that V_1F_2 produced the maximum pod number (57.30), whereas V_3F_1 recorded the longest pods (5.53 cm) (Table 6).

1000-seed weight

1000-seed weight differed across treatments. V_3 recorded the highest value (46.69 g), followed by V_2 (43.26 g), while V_1 showed the lowest (41.07 g). Among fertilization treatments, F_1 produced the highest seed weight (45.68 g), whereas F_5 recorded the lowest (41.64 g). The interaction effect revealed that V_3F_4 produced the maximum 1000-seed weight (50.27 g), followed by V_3F_1 (48.66 g) (Table 6).

Grain yield

Grain yield was influenced by all factors. V_1 produced the highest grain yield (2.00 t ha^{-1}), followed by V_2 (1.77 t ha^{-1}), whereas V_3 recorded the lowest (1.53 t ha^{-1}). Among fertilization treatments, F_2 resulted in the highest grain yield (2.11 t ha^{-1}), while F_4 showed the lowest (1.41 t ha^{-1}). Interaction effects indicated that V_1F_2 produced the maximum grain yield (2.56 t ha^{-1}), whereas V_3F_5 recorded the lowest (1.12 t ha^{-1}) (Table 6).

Straw yield

Straw yield was also affected by all treatments. V_1 recorded the highest straw yield (4.21 t ha^{-1}), followed by V_3 (3.61 t ha^{-1}), while V_2 showed the lowest (3.42 t ha^{-1}). Among fertilization treatments, F_2 produced the highest straw yield (4.31 t ha^{-1}), whereas F_4 recorded comparatively lower values (3.61 t ha^{-1}). Interaction effects revealed that V_1F_2 produced the maximum straw yield (5.03 t ha^{-1}), while V_2F_4 showed the minimum (2.37 t ha^{-1}) (Table 6).

Multivariate analysis

The correlation matrix demonstrated considerable interrelationships among growth, physiological, and yield-contributing traits of black gram under different treatment combinations (TC) in Fig. 6. Plant height (PH) showed positive associations with dry matter accumulation (DM; r = 0.50), shoot fresh weight (SFW; r = 0.53), pod length (PL; r = 0.48), and 1000-seed weight (1000_SW; r = 0.46), indicating that vigorous vegetative growth contributed positively to reproductive performance. Leaf number (LN) exhibited strong positive correlations with pod number (PN; r = 0.64) and straw yield (SY; r = 0.69), suggesting the importance of leaf development in biomass production and yield enhancement. SPAD value was positively correlated with pod length (PL; r = 0.61) and 1000_SW (r = 0.59), reflecting the role of chlorophyll content in seed development and assimilate accumulation. Pod number (PN) showed strong positive relationships with grain yield (GY; r = 0.50) and straw yield (SY; r = 0.77), identifying it as a key determinant of productivity. Additionally, pod length (PL) had the highest positive correlation with 1000_SW (r = 0.84), indicating that longer pods contributed to better seed weight. Grain yield (GY) was strongly associated with straw yield (SY; r = 0.77), implying that treatments promoting vegetative biomass also enhanced economic yield. In contrast, nodule number (NN) showed negative correlations with shoot fresh weight (SFW; r = -0.61), pod length (PL; r = -0.36), and 1000_SW (r = -0.37). Overall, the findings suggest that pod number, shoot biomass, and vegetative growth traits were the major contributors to yield improvement in black gram under integrated nutrient management practices.

Principal component analysis (PCA) was conducted using treatment mean values of the measured traits. The first two principal components (PC1 and PC2) accounted for 51.16% of the total variance, with PC1 explaining 27.55% and PC2 explaining 23.61% (Fig. 7). The variable loadings for the retained principal components are presented in Supplementary Table S1. Based on the loading values, PC1 was mainly associated with grain yield (GY), straw yield

(SY), leaf number (LN), pod number (PN), plant height (PH), dry matter (DM), and shoot fresh weight (SFW), whereas PC2 was primarily associated with pod length (PL), SPAD value, and 1000-seed weight (1000_SW). Nodule number (NN) and branch number (BN) exhibited negative loadings relative to the major yield-related traits. The treatment combinations were distributed across the ordination space according to their multivariate trait values. V_1F_2, V_1F_1, and V_2F_2 were located in the direction of the GY, SY, LN, and PN vectors, indicating positive associations with these traits, whereas V_2F_4 and V_3F_5 were positioned in the opposite region of the biplot (Fig. 7). Overall, the PCA summarized the multivariate relationships among the measured traits and treatment combinations.

The cluster dendrogram classified the treatment combinations into two major clusters, reflecting considerable variability among the treatments based on the studied traits (Fig. 8). V_1F_2 was grouped within the principal cluster and showed close association with V_1F_1 and V_1F_4, indicating a similar and comparatively favorable response pattern. The close clustering of V_1F_2 with these treatments suggests its consistency with the major high-performing group. In contrast, V_2F_4 and V_3F_5 formed a distinct separate cluster, indicating comparatively divergent trait performance from the remaining treatment combinations.

DISCUSSION

Growth attributes

The observed variation in plant height, leaf number, branch formation, and root length among varieties and fertilization treatments reflects differential genetic potential and nutrient-use efficiency under varying soil nutrient regimes. Poultry litter-based compost (PLBC) significantly enhanced early plant height, likely due to improved nutrient mineralization dynamics, particularly nitrogen release, which stimulates meristematic activity and cell elongation. Similar findings have been reported in previous studies (Lindquist, 2024; El-Mahrouky et al., 2025). In later growth stages, biofertilizer further promoted plant height, indicating enhanced rhizospheric microbial activity and improved nutrient acquisition efficiency, as previously reported by Fasusi et al. (2021). Increased leaf production under PLBC suggests a sustained nutrient supply that supports continuous leaf initiation and delayed senescence, whereas varietal differences indicate strong genetic control over vegetative growth patterns, consistent with Roberts (1999). Enhanced branching under PLBC may be attributed to improved nitrogen availability and optimized assimilate partitioning, thereby increasing sink sites for reproductive development, similar to results reported by Liu et al. (2025). Root length was predominantly influenced by fertilization, where PLBC and RDF treatments improved soil physical conditions and nutrient availability, facilitating deeper root penetration and efficient resource uptake (Masmoudi et al., 2020). In contrast, nodulation was markedly enhanced by biochar application (Głodowska et al., 2017), which may be attributed to improved soil structure, increased cation exchange capacity, and a more favorable microbial habitat, collectively enhancing biological nitrogen fixation (Chang et al., 2025; Tian et al., 2025).

Physiological trait

The significant increase in SPAD values under biofertilizer application indicates improved chlorophyll synthesis and nitrogen assimilation efficiency (Mthiyane et al., 2024; Pérez-Álvarez et al., 2024). This response is likely driven by enhanced symbiotic microbial activity, which improves nitrogen availability and uptake, thereby strengthening photosynthetic capacity and overall physiological performance of the crop compared with other nutrient sources.

Biomass accumulation

Root fresh weight was generally higher under PLBC and RDF treatments, suggesting improved rhizosphere conditions and enhanced nutrient uptake efficiency, which promote greater carbon allocation to belowground biomass. Shoot fresh weight was maximized under the recommended fertilizer dose, likely due to a rapid and readily available nitrogen supply that stimulates early vegetative growth and biomass accumulation. However, organic treatments exhibited more balanced growth patterns, reflecting gradual nutrient release and sustained physiological activity. Total dry matter accumulation was highest under biofertilizer treatments, indicating improved nutrient use efficiency and prolonged photosynthetic activity, potentially mediated through enhanced microbial nutrient cycling (Schütz et al., 2018; Ikan et al., 2024).

Yield and yield-contributing characters

Significant improvements in pod number under PLBC are likely associated with enhanced vegetative vigor and branching intensity, which increases the number of reproductive sinks. In contrast, pod length was largely genetically regulated, indicating limited responsiveness to nutrient management, consistent with Banerjee et al. (2021). Thousand-seed weight exhibited significant variability across treatments, reflecting both genetic influence and nutrient availability during grain filling; comparatively higher values under control conditions may be due to immediate nutrient accessibility during reproductive development (Szemerits et al., 2025). Grain yield was maximized under PLBC, driven by improved growth attributes, higher pod formation, and enhanced assimilate partitioning efficiency (Islam et al., 2024). The superior performance of BARI mash-1 under PLBC further highlights a strong genotype × nutrient interaction, indicating better nutrient responsiveness and yield potential under organic amendment. Similarly, straw yield followed a comparable trend to grain yield, reflecting enhanced total biomass accumulation and improved overall plant productivity under PLBC-based nutrient management.

Multivariate Analysis

Correlation analysis revealed strong positive relationships among growth, physiological, and yield traits. Plant height, leaf number, and SPAD value were positively associated with key yield traits such as pod number, pod length, and seed weight (Panda et al., 2015; Panwar et al., 2018). Pod number emerged as a major determinant of both grain and straw yield, while grain yield closely followed straw yield. In contrast, nodule number showed negative associations with several yield traits.

The PCA explained 51.16% of the total variation, with PC1 (27.55%) and PC2 (23.61%) accounting for the largest proportions of variance. The strong positive loadings of grain yield, straw yield, leaf number, pod number, plant height, dry matter, and shoot fresh weight on PC1 indicate that these traits were the primary contributors to variation along this axis, whereas pod length, SPAD value, and 1000 seed weight contributed more strongly to PC2. The score pattern showed that treatment combinations V_1F_2, V_1F_1, and V_1F_4 were positioned in the direction of the positive PC1 loadings, indicating their association with the yield-related trait group, while V_2F_4 and V_3F_5 were located in a different region of the ordination space, reflecting contrasting multivariate trait profiles. These score patterns are consistent with the trait loadings identified for the first two principal components.

Cluster analysis confirmed similar grouping patterns. Overall, pod number, biomass accumulation, and chlorophyll content were the main contributors to yield improvement under optimum nutrient management in black gram.

CONCLUSION

The study indicates that organic nutrient management can contribute to improved growth and yield performance of black gram under the experimental conditions. Among the nutrient management options evaluated, poultry litter-based compost at 7.5 t ha^{-1} combined with BARI mash-1 produced favorable growth and yield responses, suggesting its potential as an effective nutrient management option. The observed varietal differences further indicate that crop response to nutrient management practices may vary depending on genotype. However, because the experiment was conducted at a single location during one growing season, additional multi-location and multi-year studies are required to validate these findings under diverse agroecological conditions before broader recommendations can be made.

ACKNOWLEDGEMENT: The authors sincerely acknowledge the Chairman, Department of Crop Physiology and Ecology, Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh, for providing necessary support and facilities that ensured the smooth conduct of the experiment.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT: Md. Mainul Hasan: Data curation, Investigation, Formal analysis, Software, Validation, Writing - Original Draft. Md. Mamunur Rashid: Data curation, Formal analysis, Software, Visualization, Writing - Original Draft. Humayara Islam: Investigation, Data curation, Validation. Md. Mahmudul Hasan: Investigation, Data curation, Validation. Mr. Shanto Mardi: Investigation, Data curation, Validation. Md. Abu Hasan: Supervision, Methodology, Conceptualization, Writing - Review & Editing. Abu Khayer Md. Muktadirul Bari Chowdhury: Project administration, Supervision, Resources, Funding acquisition, Methodology, Conceptualization, Writing - Review & Editing.

FUNDING: This research was financially supported by the Institute of Research and Training (IRT), Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur-5200, Bangladesh.

DECLARATION OF COMPETING INTEREST: The authors have declared that no competing interests exist.

ETHICAL APPROVALS AND RESEARCH PERMITS: Not applicable.

DATA AVAILABILITY STATEMENT: The data for this study are available from the corresponding Author.

AI USE STATEMENT: The DeepL tool was used only for language editing purposes (grammar correction and language refinement). All scientific content, analysis, and conclusions remain the sole responsibility of the authors.

REFERENCES

Aboutayeb R., Fijahi S., Hssaini L., Azim K. (2025). Quality assessment of poultry manure compost: focus on organic amendment and bioremediation roles toward sustainable agriculture. Euro-Mediterr J Environ Integr 10 (3): 1383–1405. https://doi.org/10.1007/s41207-024-00698-7

Banerjee P., Venugopalan V. K., Nath R., Althobaiti Y. S., Gaber A., Al-Yasi H., Hossain A. (2021). Physiology, growth, and productivity of spring–summer black gram (Vigna mungo L. Hepper) under heat and moisture stress. Agronomy 11 (11): 2329. https://doi.org/10.3390/agronomy11112329

Bhardwaj D., Ansari M. W., Sahoo R. K., Tuteja N. (2014). Biofertilizers as key players in sustainable agriculture improving soil fertility and crop productivity. Microb Cell Fact 13 (1): 66. https://doi.org/10.1186/1475-2859-13-66

Bokhtiar S. M., Islam S. M. F., Molla M. M. U., Salam M. A., Rashid M. A. (2023). Demand and supply projection of pulses and oil crops in Bangladesh by 2030 and 2050. Sustainability 15 (10): 8240. https://doi.org/10.3390/su15108240

Chang Y., Lin L., Shen J., Lin Z., Deng X., Sun W., Xu Z. (2025). Enhanced nitrogen fixation and Cd passivation by biochar-loaded bacteria. J Hazard Mater 481: 136588. https://doi.org/10.1016/j.jhazmat.2024.136588

El-Mahrouky M., Al-Barakah F. N., Schoenau J. J., Ahmed I., Alotaibi K. D., Fahad S. (2025). Poultry litter-based fertilizers in calcareous soil and their effects on corn growth. Appl Environ Soil Sci 2025: 1590143. https://doi.org/10.1155/aess/1590143

Farthouse J., Hasna M. K., Khalil M. I., Haque M. M., Nabi M. K. E., Haque M. A. (2024). Efficacy of phospho-vermicompost, biofertilizer, biopesticides and their integration against root rot of lentil. *Bangladesh J Nucl Agric* 38 (2): 65–80. https://doi.org/10.3329/bjnag.v38i2.79556

Fasusi O. A., Cruz C., Babalola O. O. (2021). Microbial biofertilizers in rhizosphere management for agricultural sustainability. Agriculture 11 (2): 163. https://doi.org/10.3390/agriculture11020163

Głodowska M., Schwinghamer T., Husk B., Smith D. (2017). Biochar-based inoculants improve soybean growth and nodulation. Agricultural Sciences 8 (9): 1048–1064. https://doi.org/10.4236/as.2017.89076

Ikan C., Soussani F. E., Ouhaddou R., Ech-Chatir L., Errouh F., Boutasknit A., Meddich A. (2024). Biofertilizers improve photosynthesis, yield and drought tolerance in wheat. Agronomy 14 (6): 1316. https://doi.org/10.3390/agronomy14061316

Islam H., Rashid M. M., Hasan M. M., Hasan M. M., Bahadur M. M., Chowdhury A. K. M. M. B. (2025). Integrated application of organic and inorganic fertilizers for onion production. Turk J Agric Food Sci Technol 13 (6): 1443–1452. https://doi.org/10.24925/turjaf.v13i6.1443-1452.7508

Islam S., Hasan M. M., Sayed M. Z. I., Sikder S., Chowdhury A. K. M. M. B. (2024). Poultry litter compost mitigates water deficit stress in lentil. Turk J Agric Food Sci Technol 12 (6): 1080–1087. https://doi.org/10.24925/turjaf.v12i6.1080-1087.6739

Khan S., Irshad S., Mehmood K., Hasnain Z., Nawaz M., Rais A., Ibrar D. (2024). Biochar production and its impacts on soil health and crop yield. Plants 13 (2): 166. https://doi.org/10.3390/plants13020166

Khatana R. N. S., Thomas T., Barthwal A., Kumar T. (2021). Effect of NPK and *Rhizobium* on soil properties and yield of black gram. J Pharm Innov 10: 1555–1561.

Kapoor A., Sharma R., Kumar A., Sepehya S. (2022). Biochar to improve soil fertility and crop productivity: a review. J Plant Nutr 45 (15): 2380–2388. https://doi.org/10.1080/01904167.2022.2027980

Krasilnikov P., Taboada M. A., Amanullah. (2022). Fertilizer use, soil health and agricultural sustainability. Agriculture 12 (4): 462. https://doi.org/10.3390/agriculture12040462

Kumar M. S., Reddy G. C., Phogat M., Korav S. (2018). Role of biofertilizers in sustainable agricultural development. J Pharmacogn Phytochem 7 (6): 1915–1921.

Kyakuwaire M., Olupot G., Amoding A., Nkedi-Kizza P., Ateenyi Basamba T. (2019). Safety of chicken litter as organic fertilizer: a review. Int J Environ Res Public Health 16 (19): 3521. https://doi.org/10.3390/ijerph16193521

Lindquist A. L. (2024). Evaluation of a poultry-derived fertilizer. MSc Thesis. Auburn University, Auburn, AL, USA.

Liu Y., Chen Y., Chen Y., Feng Y., Sun H. (2025). Cyanobacterial sludge incorporation and nutrient retention during composting. Agronomy 15 (10): 2429. https://doi.org/10.3390/agronomy15102429

Masmoudi S., Magdich S., Rigane H., Medhioub K., Rebai A., Ammar E. (2020). Effects of compost and manure on soil properties and productivity. Waste Biomass Valorization 11 (5): 1883–1894. https://doi.org/10.1007/s12649-018-0543-z

Mthiyane P., Aycan M., Mitsui T. (2024). Integration of biofertilizers enhances photosynthesis and gene expression in rice. Sustainability 16 (21): 9297. https://doi.org/10.3390/su16219297

Nasir M., Sidhu J. S., Sogi D. S. (2022). Processing and nutritional profile of pulses. In: Siddiq M., Uebersax M. A. (eds.). *Dry beans and pulses: production, processing and nutrition*, pp. 431–452. https://doi.org/10.1002/9781119776802.ch17

Panda D., Sen A., Dhakre D. S., Mondal S. (2015). Correlation analysis of some growth, physiological parameters, yield and yield attributes of chick pea (*Cicer arietinum* L.). Int J Bio-res Env Agril Sci 1 (3): 90–95.

Pande R., Mishra H. N., Singh M. N. (2012). Microwave drying improves nutritional quality of green gram seed. J Agric Food Chem 60 (14): 3809–3816. https://doi.org/10.1021/jf204540n

Panwar A., Mishra A. C., Negi S. (2018). Correlation studies on seed quality, pod and seed yield in germplasm of pea (*Pisum sativum* L.). Int J Bio-resource Stress Manag 9 (1): 98–102. https://doi.org/10.23910/IJBSM/2018.9.1.3C0753

Pérez-Álvarez S., Ochoa-Chaparro E. H., Anchondo-Páez J. C., Escobedo-Bonilla C. M., Rascón-Solano J., Magallanes-Tapia M. A., Sánchez E. (2024). Nitrogen assimilation and yield response to biofertilizers in maize. Nitrogen 5 (4): 1031–1047.

Prioty J. K., Rahman K. S., Miah M. A. M. (2023). Growth and instability of black gram in Bangladesh. Bangladesh J Agric 48 (2): 30–38. https://doi.org/10.3329/bjagri.v48i2.70156

Roberts W., Duthie J., Edelson J., Shrefler J. (1999). Limitations of poultry litter as fertilizer for vegetables. HortScience 34 (3): 465.

Schütz L., Gattinger A., Meier M., Müller A., Boller T., Mäder P., Mathimaran N. (2018). Biofertilization improves yield and nutrient use efficiency: meta-analysis. Front Plant Sci 8: 2204. https://doi.org/10.3389/fpls.2017.02204

Siddiq M., Uebersax M. A., Siddiq F. (2022). Global production and nutritional profile of pulses. In: Siddiq M., Uebersax M. A. (eds.). *Dry beans and pulses: production, processing and nutrition*, pp. 1–28. https://doi.org/10.1002/9781119776802.ch1

Szemerits B., Kukorelli G., Kabato W. S., Molnár Z. (2025). Seed rate and row spacing effects on sorghum yield. Seeds 4 (4): 61. https://doi.org/10.3390/seeds4040061

Tian L., Wang Y., Jin D., Zhou Y., Mukhamed B., Liu D., Feng B. (2025). Biochar and organic fertilizer influence soil microbial diversity. Biochar 7 (1): 6. https://doi.org/10.1007/s42773-024-00398-z

Uddin M. J., Hooda P. S., Mohiuddin A. S. M., Haque M. E., Smith M., Waller M., Biswas J. K. (2022). Soil organic carbon dynamics under land use intensification in Bangladesh. J Environ Manage 305: 114427. https://doi.org/10.1016/j.jenvman.2021.114427

Veer D., Habib K., Kumar K. (2022). Response of black gram to Rhizobium and nutrients: a mini review. Int J Plant Environ 8 (1): 81–86. https://doi.org/10.18811/ijpen.v8i01.10

Vishwakarma K. (2021). Molecular characterization of mungbean genotypes for virus resistance. MSc Thesis. Jawaharlal Nehru Krishi Vishwa Vidyalaya (JNKVV), Jabalpur, India.

Table 1. Physicochemical properties of the soil at the experimental site.

General characters	Description	Interpretation
Location	Crop Physiology and Ecology Field	-
AEZ	Old Himalayan Piedmont Plain (AEZ-1)	-
General soil type	Non-Calcareous Brown Floodplain Soil	-
Parent material	Piedmont alluvium	-
Soil series	Ranishankail	-
Drainage	Moderately well-drained	-
Flood level	Above flood level	-
Topography	High land	-
Physical characteristics	**Value**	**Interpretation**
Bulk density (g cm^-3)	0.86-1.07	-
Sand (2-0.02 mm)	60.0	-
Silt (0.02-.002 mm)	27.0	-
Clay (< 0.002)	13.0	-
Textural class	Sandy loam	-
Chemical characteristics	**Value**	**Interpretation**
PH	5.40-5.50	Moderately acidic
Organic carbon (%)	0.69	Low
Organic matter (%)	1.19	Low
CEC(meq/ 100g soil)	5.60	Low
Total N (%)	0.07	Very low
Available P (ppm)	16.75	Medium
Exchangeable K (meq/100g soil)	0.17	Medium low

Table 2. Physicochemical characteristics of poultry litter-based compost and biochar

Parameter	Poultry litter-based compost	Biochar
pH	7.10-8.51	8.4-10.5
EC (dS m^{-1})	3.10-8.10	0.51-2.15
Organic carbon (%)	24.0-33.5	60.5-80
Total N (%)	2.15-4.35	0.25-1.5
Available P (%)	1.0-2.62	0.01-0.55
Available K (%)	1.55-3.51	0.10-1.00
C:N ratio	10.2-18.2	50-200
Moisture (%)	19.5-35.2	2.0-10
Ash (%)	-	5.5-20

Table 3. Effect of varieties and fertilizations on Plant height and Leaf number of blackgram at different days after sowing (DAS)

Treatment	**Plant height (cm) at**				**Leaf number at**			
Variety	**30DAS**	**45DAS**	**60DAS**	**Final Harvest**	**30DAS**	**45DAS**	**60DAS**	**Final Harvest**
V_1	12.35c	22.52b	33.89c	39.17b	6.24a	16.24a	40.89a	49.88a
V_2	12.74b	23.56a	36.07a	39.09b	5.51c	13.79b	36.58b	46.13c
V_3	14.40a	22.56b	35.44b	42.07a	5.91b	14.16b	36.45b	47.39b
Level of significance	*	*	*	*	*	*	*	*
Fertilizations								
F_1	13.42b	23.85b	34.72b	40.88b	6.17a	16.11a	39.07b	48.74b
F_2	14.24a	24.22a	34.39c	40.53c	5.43b	15.15a	42.18a	50.21a
F_3	13.01c	22.13d	37.62a	41.56a	6.18a	14.18a	34.92c	45.11e
F_4	13.46b	21.71e	34.68b	40.04d	6.07a	13.87a	35.01c	48.03c
F_5	11.69d	22.48c	34.24c	37.55e	5.57b	14.33a	38.67b	46.90d
Level of significance	*	*	*	*	*	NS	*	*
Interactions between Variety and Fertilizations								
V_1F_1	12.87c-e	23.95c	32.63j	38.68h	6.43b-d	15.00a-d	39.56c	50.58bc
V_1F_2	13.31b-d	22.68ef	31.49k	36.48k	5.67b-g	16.11a-d	42.76ab	51.71b
V_1F_3	12.79de	21.78h	34.25g	40.23g	8.22a	20.64a	37.41d	44.11i
V_1F_4	11.72gh	22.49fg	34.71f	42.27d	5.56c-g	13.00b-d	43.6a	53.67a
V_1F_5	11.08h	21.67h	36.35d	38.19i	5.32e-g	16.44a-d	41.11bc	49.31de
V_2F_1	12.10fg	24.69b	33.35i	37.52j	5.76b-f	17.33a-c	41.98ab	48.04fg
V_2F_2	13.89b	26.19a	39.09b	43.45b	5.11fg	15.11a-d	41.18bc	48.67ef
V_2F_3	12.7d-f	23.31d	38.17c	41.16f	5.56c-g	11.11cd	36.66de	45.64h
V_2F_4	13.49bc	21.32i	35.94e	35.00m	6.22b-e	11.06cd	27.99h	40.97j
V_2F_5	11.53gh	22.29g	33.78h	38.31i	4.89fg	14.33a-d	35.08ef	47.31g
V_3F_1	15.30a	22.91e	38.16c	46.43a	6.33b-d	16.00a-d	35.68de	47.59fg
V_3F_2	15.52a	23.77c	32.59j	41.65e	5.50d-g	14.22b-d	42.61ab	50.24cd
V_3F_3	13.54bc	21.28i	40.45a	43.29b	4.78g	10.78d	30.69g	45.59h
V_3F_4	15.16a	21.33i	33.39hi	42.85c	6.44bc	17.56ab	33.44f	49.45c-e
V_3F_5	12.48ef	23.48d	32.59j	36.14l	6.5b	12.22b-d	39.83c	44.09i
Level of significance	*	*	*	*	*	*	*	*
CV (%)	1.70	0.34	0.38	0.28	5.25	14.39	1.83	0.80

Note: Means followed by the same letter(s) within a column are not significantly different at the 5% probability level according to Tukey's HSD test. * indicates significance at $p \leq 0.05$. F_1 = Recommended Dose (RDF); F_2 = Poultry Litter-Based Compost (PLBC) 7.5 t ha^{-1}; F_3 = BARI biofertilizer; F_4 = BINA biofertilizer; F_5 = Biochar 5 t ha^{-1}. V_1 = BARI Mash-1; V_2 = BARI Mash-3; V_3 = BARI Mash-4.

Table 4. Effect of varieties and fertilizations on number of branches plant^{-1} and Root length (cm) of black gram at different days after sowing (DAS)

Treatment	Number of branches per plant at				Root length (cm) at		
Variety	**30DAS**	**45DAS**	**60DAS**	**Final Harvest**	**30DAS**	**45DAS**	**60DAS**
V_1	2.79a	4.27b	7.18a	7.45a	11.38a	12.02b	20.02a
V_2	2.47b	4.52a	6.82b	7.50a	11.04a	12.69a	20.16a
V_3	2.62ab	4.04c	7.07a	7.52a	11.43a	13.11a	20.35a
Level of significance	*	*	*	NS	NS	*	NS
Fertilizations							
F_1	2.85a	4.56ab	6.37c	6.88c	11.21ab	12.59b	22.17a
F_2	2.70ab	4.26bc	8.67a	9.00a	11.71a	13.66a	20.20bc
F_3	2.74ab	4.74a	6.78b	7.04bc	11.44ab	12.39b	17.99d
F_4	2.52ab	3.96cd	6.68b	7.15bc	11.03b	12.00b	19.84c
F_5	2.33b	3.87d	6.63bc	7.37b	11.04b	12.41b	20.68b
Level of significance	*	*	*	*	*	*	*
Interactions between Variety and Fertilizations							
V_1F_1	2.56bc	3.89d-f	7.1b-d	7.25b-e	10.92b-d	11.43d	21.55b
V_1F_2	3.22ab	4.44b-e	7.44bc	7.55bc	11.50a-c	12.50b-d	19.23d-f
V_1F_3	3.56a	5.11ab	7.56b	7.78b	11.31a-d	12.03cd	18.21fg
V_1F_4	2.22c	4.22c-f	7.25bc	7.56bc	11.56a-c	12.15b-d	19.61c-e
V_1F_5	2.43bc	3.67fg	6.56de	7.11b-e	11.62a-c	11.99cd	21.52b
V_2F_1	2.78a-c	5.22a	5.55f	6.77c-e	12.09ab	13.70a-c	21.29b
V_2F_2	2.33bc	4.56a-d	9.11a	9.78a	12.16ab	13.87ab	20.35b-d
V_2F_3	2.33bc	3.89d-f	6.56de	6.56e	10.43cd	12.64b-d	17.19g
V_2F_4	2.67a-c	4.11d-f	6.33e	6.78c-e	10.59cd	11.73d	20.83bc
V_2F_5	2.22c	4.83a-c	6.56de	7.62b	9.90d	11.54d	21.13b
V_3F_1	3.22ab	4.55a-d	6.44de	6.63de	10.62cd	12.65b-d	23.68a
V_3F_2	2.56bc	3.78e-g	9.45a	9.68a	11.46a-c	14.60a	21.03b
V_3F_3	2.33bc	5.22a	6.22e	6.78c-e	12.57a	12.49b-d	18.56ef
V_3F_4	2.67a-c	3.56fg	6.44de	7.11b-e	10.93b-d	12.12b-d	19.09d-f
V_3F_5	2.32bc	3.11g	6.78c-e	7.39b-d	11.59a-c	13.69a-c	19.40d-f
Level of significance	*	*	*	*	*	*	*
CV (%)	12.10	5.40	3.13	3.60	4.15	4.64	2.24

Note: Means followed by the same letter(s) within a column are not significantly different at the 5% probability level according to Tukey's HSD test. * indicates significance at $p \leq 0.05$. F_1 = Recommended Dose (RDF); F_2 = Poultry Litter-Based Compost (PLBC) 7.5 t ha^{-1}; F_3 = BARI biofertilizer; F_4 = BINA biofertilizer; F_5 = Biochar 5 t ha^{-1}. V_1 = BARI Mash-1; V_2 = BARI Mash-3; V_3 = BARI Mash-4

Table 5. Effect of varieties and fertilizations and their interactions on root fresh weight and shoot fresh weight (g) of black gram at different days after sowing (DAS)

Treatment	**Root fresh weight (g) at**			**Shoot fresh weight (g) at**		
Variety	**30 DAS**	**45 DAS**	**60 DAS**	**30 DAS**	**45DAS**	**60 DAS**
V_1	0.26b	0.62a	2.06b	1.94a	7.83a	51.00b
V_2	0.25b	0.54b	1.88c	1.62b	7.76a	47.54c
V_3	0.33a	0.55b	2.31a	1.86a	6.93b	52.23a
Level of significance	*	*	*	*	*	*
Fertilizations						
F_1	0.22c	0.61a	2.23a	2.15a	8.87a	53.53a
F_2	0.35a	0.62a	2.21a	1.78b	7.23b	52.20b
F_3	0.34a	0.58b	2.01b	1.75b	7.34b	53.39ab
F_4	0.24b	0.52c	1.74c	1.69b	6.21c	47.24c
F_5	0.26b	0.51c	2.22a	1.65b	7.88b	44.90d
Level of significance	*	*	*	*	*	*
Interactions between Variety and Fertilizations						
V_1F_1	0.22d	0.66bc	2.44c	1.87cd	9.61a	52.78cd
V_1F_2	0.22d	0.52fg	2.21d	1.88cd	6.16e	55.53b
V_1F_3	0.37b	0.65bc	1.62g	2.46b	8.39a-d	48.34ef
V_1F_4	0.29c	0.68ab	1.63g	1.43e	5.85e	53.89bc
V_1F_5	0.22d	0.58de	2.38c	2.08c	9.15ab	44.46gh
V_2F_1	0.21de	0.61cd	2.15de	1.82cd	8.53a-c	51.42cd
V_2F_2	0.47a	0.72a	2.26d	1.63de	9.59a	50.32de
V_2F_3	0.19de	0.55ef	1.82f	1.40e	6.68de	52.11cd
V_2F_4	0.24d	0.39h	1.77f	1.78d	6.54e	41.13i
V_2F_5	0.16e	0.41h	1.42h	1.44e	7.45b-e	42.71hi
V_3F_1	0.23d	0.55ef	2.10e	2.75a	8.45a-d	56.39b
V_3F_2	0.36b	0.61cd	2.15de	1.82cd	5.96e	50.75de
V_3F_3	0.47a	0.55ef	2.61b	1.38e	6.96c-e	59.72a
V_3F_4	0.20de	0.49g	1.82f	1.88cd	6.24e	46.73fg
V_3F_5	0.4b	0.54e-g	2.86a	1.45e	7.04c-e	47.53f
Level of significance	*	*	*	*	*	*
CV (%)	5.71	2.95	1.75	5.31	7.98	1.78

Note: Means followed by the same letter(s) within a column are not significantly different at the 5% probability level according to Tukey's HSD test. * indicates significance at $p \leq 0.05$. F_1 = Recommended Dose (RDF); F_2 = Poultry Litter-Based Compost (PLBC) 7.5 t ha^{-1}; F_3 = BARI biofertilizer; F_4 = BINA biofertilizer; F_5 = Biochar 5 t ha^{-1}. V_1 = BARI Mash-1; V_2 = BARI Mash-3; V_3 = BARI Mash-4

Table 6. Effect of variety, fertilization, and their interaction on pod number, pod length, 1000-seed weight, grain yield, and straw yield of black gram.

Variety	Pod number (cm)	Pod length (cm)	1000 seed weight (g)	Grain yield (t/ha)	Straw yield (t/ha)
V_1	46.33a	4.84c	41.07c	2.00a	4.21a
V_2	37.77b	4.95b	43.26b	1.77b	3.42c
V_3	37.45b	5.35a	46.69a	1.53c	3.61b
Level of significance	*	*	*	*	*
Fertilizations					
F_1	44.16a	5.25a	45.68a	1.74c	3.76b
F_2	45.56a	4.99bc	43.19c	2.11a	4.31a
F_3	41.42b	4.99bc	42.87d	1.65d	3.52e
F_4	38.39c	4.97c	45.01b	1.41e	3.61c
F_5	33.04d	5.03b	41.64e	1.93b	3.55d
Level of significance	*	*	*	*	*
Interactions between Variety and Fertilizations					
V_1F_1	46.33bc	4.96fg	42.30g	2.03e	4.34d
V_1F_2	57.30a	4.84i	42.22g	2.56a	5.03a
V_1F_3	45.87bc	4.74j	38.42j	1.70g	3.65h
V_1F_4	47.87b	4.82i	41.32h	1.26j	3.87f
V_1F_5	34.27f	4.86hi	41.10h	2.46b	4.17e
V_2F_1	43.00b-d	5.26d	46.08d	1.64gh	3.76g
V_2F_2	45.50bc	5.02f	44.68e	2.35c	4.49c
V_2F_3	36.63ef	4.80ij	42.58g	1.33j	2.78k
V_2F_4	25.83g	4.74j	43.46f	1.30j	2.37l
V_2F_5	37.87d-f	4.93gh	39.53i	2.22d	3.72g
V_3F_1	43.13b-d	5.53a	48.66b	1.55h	3.197j
V_3F_2	33.87f	5.12e	42.67g	1.43i	3.39i
V_3F_3	41.77c-e	5.44b	47.60c	1.913f	4.12e
V_3F_4	41.47c-e	5.34c	50.27a	1.66g	4.59b
V_3F_5	27.00g	5.30cd	44.29e	1.12k	2.76k
Level of significance	*	*	*	*	*
CV (%)	4.39	0.51	0.49	1.77	0.61

Note: Means followed by the same letter(s) within a column are not significantly different at the 5% probability level according to Tukey's HSD test. * indicates significance at $p \leq 0.05$. F_1 = Recommended Dose (RDF); F_2 = Poultry Litter-Based Compost (PLBC) 7.5 t ha^{-1}; F_3 = BARI biofertilizer; F_4 = BINA biofertilizer; F_5 = Biochar 5 t ha^{-1}. V_1 = BARI Mash-1; V_2 = BARI Mash-3; V_3 = BARI Mash-4

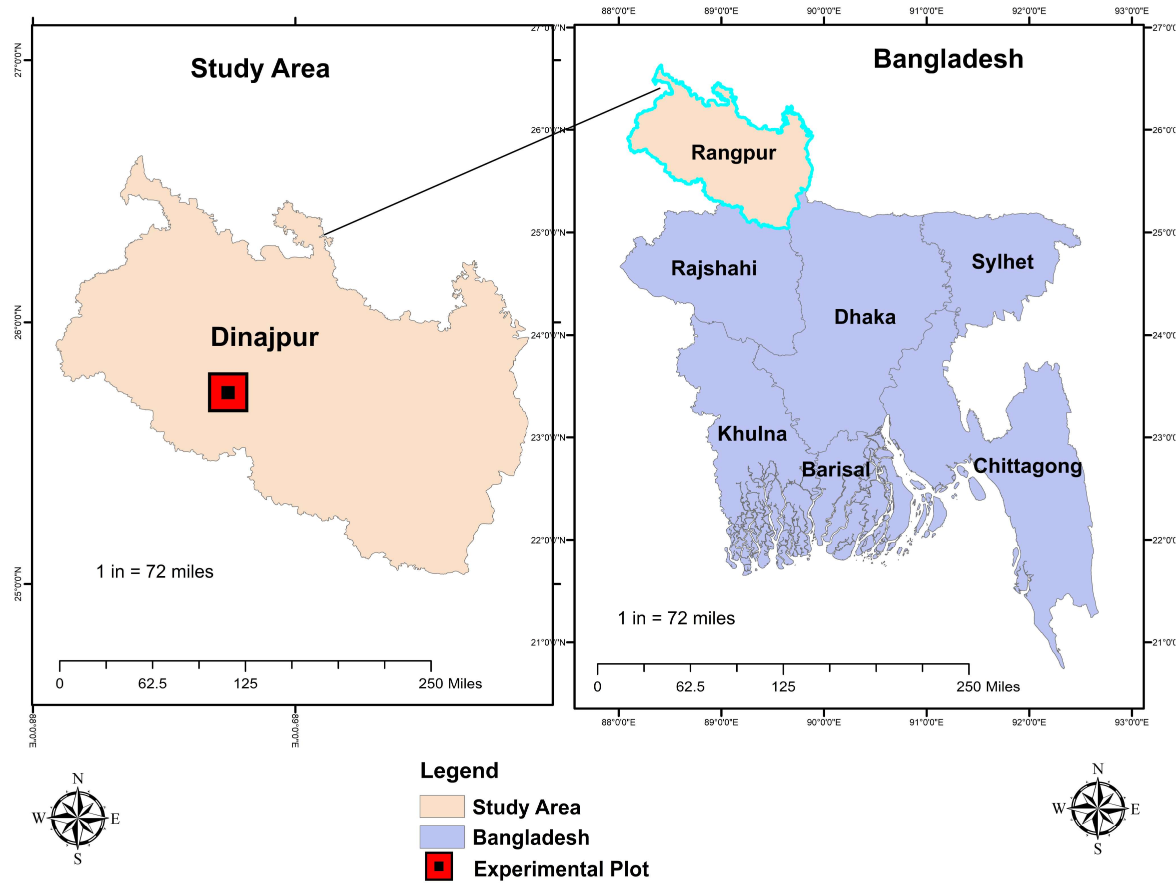

Figure 1. Location of the experimental site

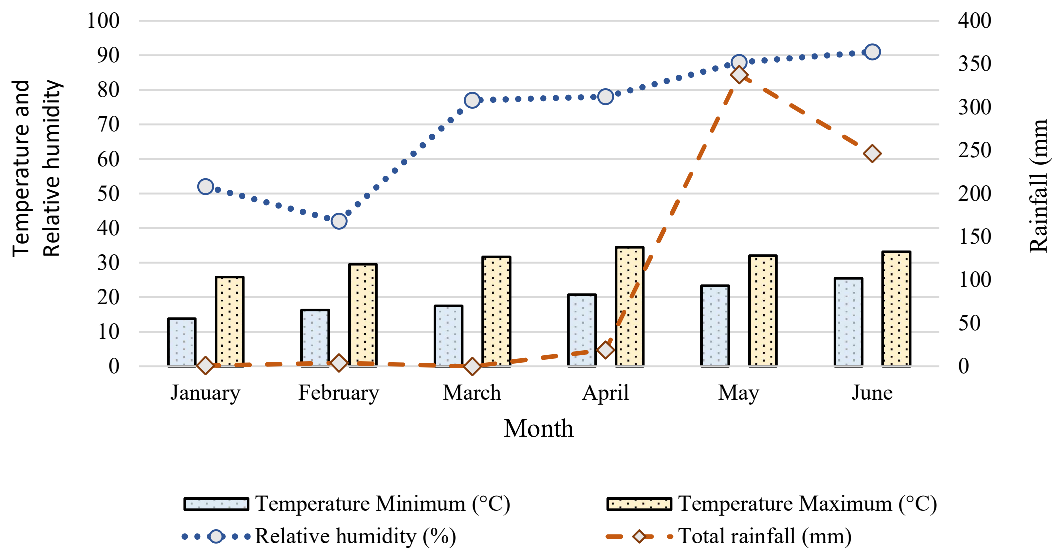

Figure 2: Meteorological data for growing season, January- June, 2022

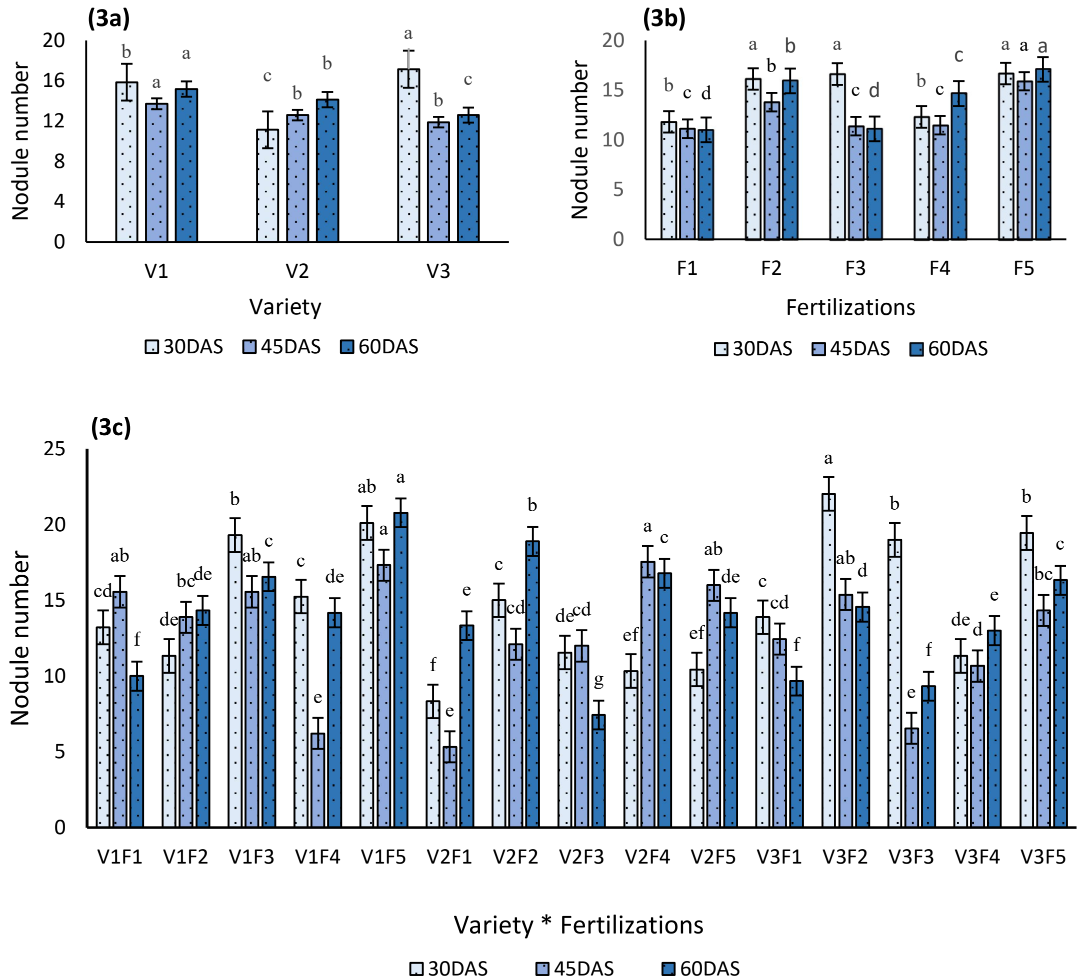

Figure 3. Effect of variety (3a), fertilization (3b), and their interaction (3c) on nodule number of blackgram at different growth stages (30, 45, and 60 DAS). Bars represent mean values for V_1 (BARI Mash-1), V_2 (BARI Mash-3), and V_3 (BARI Mash-4), and fertilization treatments F_1-F_5 (recommended fertilizer dose, poultry litter-based compost, biofertilizer treatments, and biochar). Different letters indicate significant differences among treatments at $p \leq 0.05$ according to Tukey's test.

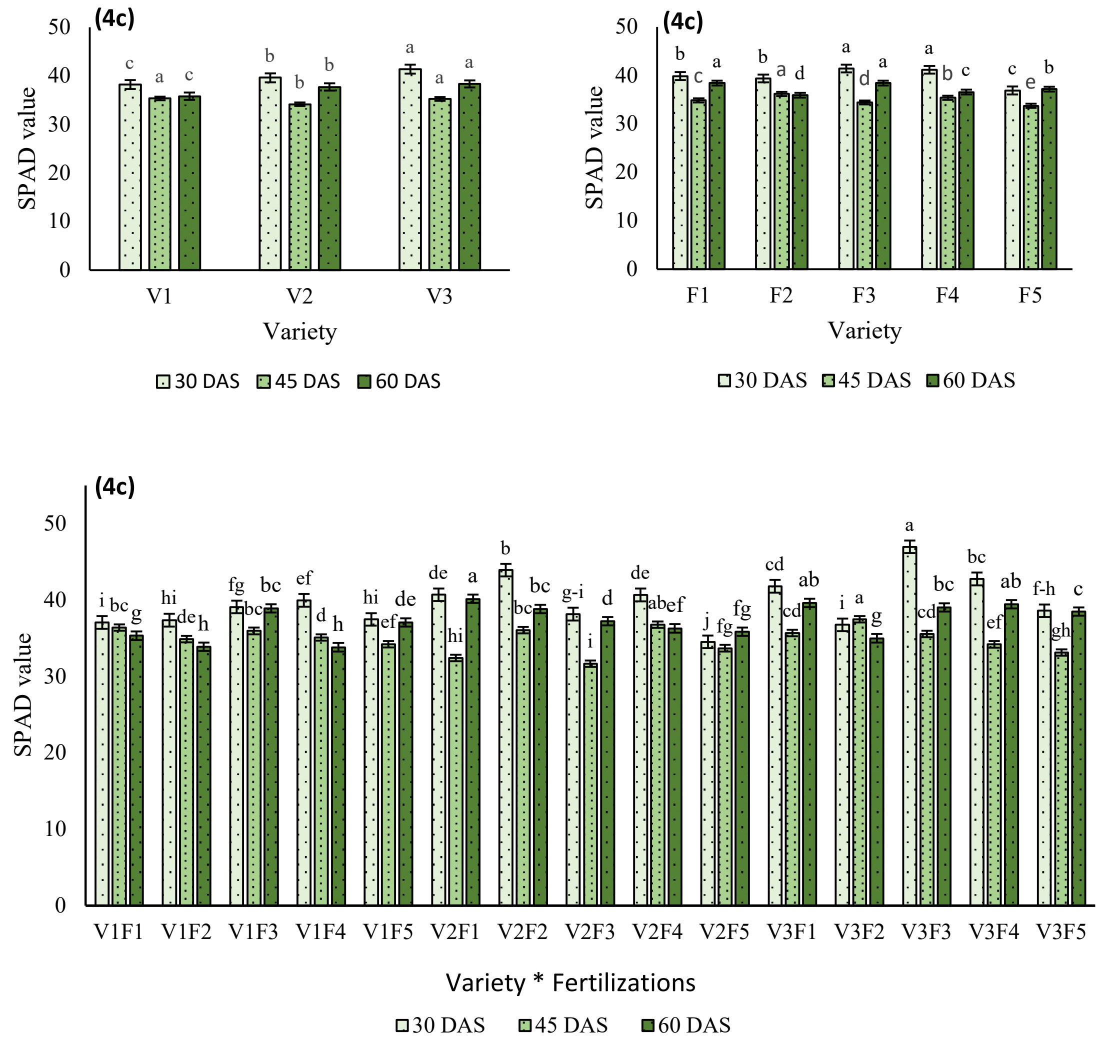

Figure 4. Effect of variety (4a), fertilization (4b), and their interaction (4c) on SPAD value of blackgram at different growth stages (30, 45, and 60 DAS). Bar charts represent mean SPAD values of three varieties (V_1-V_3), five fertilization levels (F_1-F_5), and their combined interactions (V × F) across 30, 45, and 60 days after sowing (DAS). Different letters on bars indicate statistically significant differences among treatments at $p < 0.05$ according to Tukey's test.

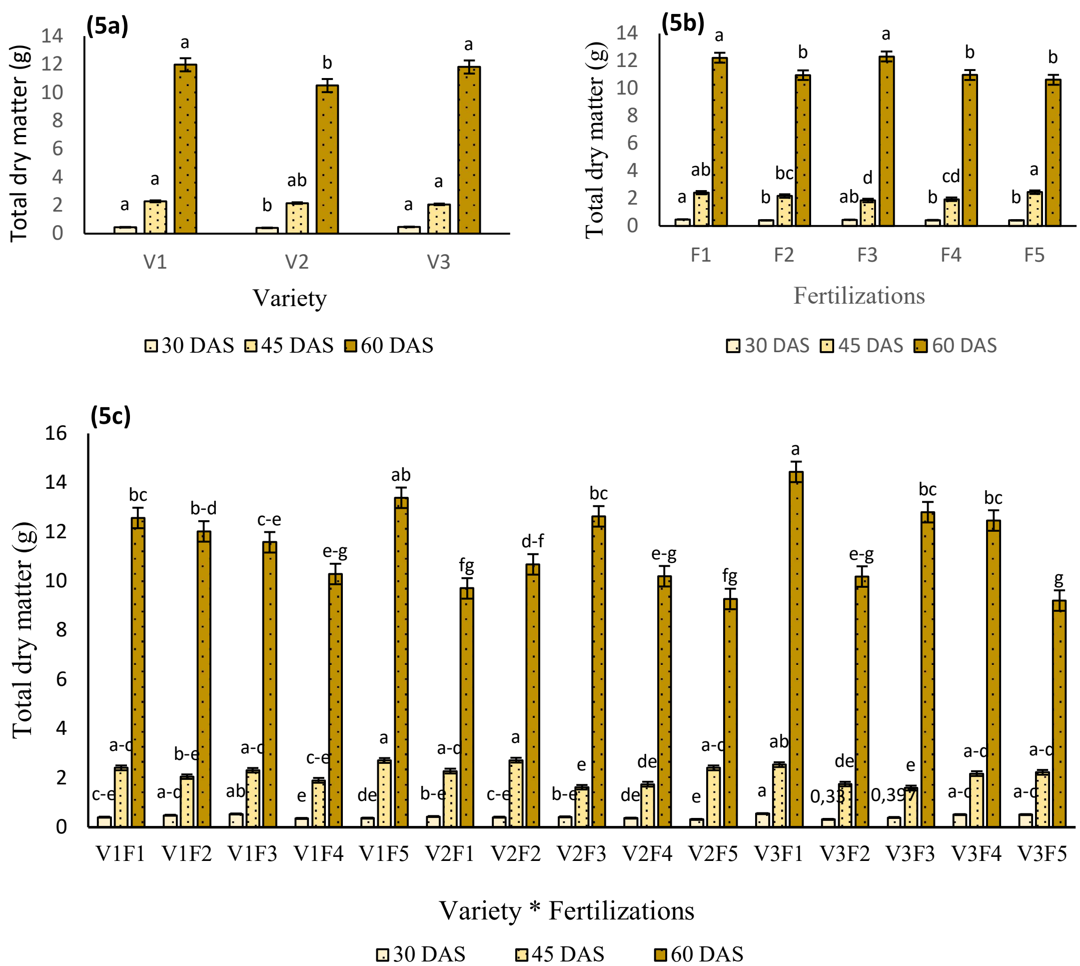

Figure 5. Effect of variety (5a), fertilization (5b), and their interaction (5c) on total dry matter accumulation of black gram at different growth stages (30, 45, and 60 DAS). Bar charts represent mean total dry matter (g plant^{-1}) of three varieties (V_1-V_3), five fertilization treatments (F_1-F_5), and their combined interactions (V × F) across 30, 45, and 60 days after sowing (DAS). Different letters on the bars indicate statistically significant differences among treatments at $p < 0.05$ according to Tukey's test.

https://doi.org/10.5513/SUTS4224

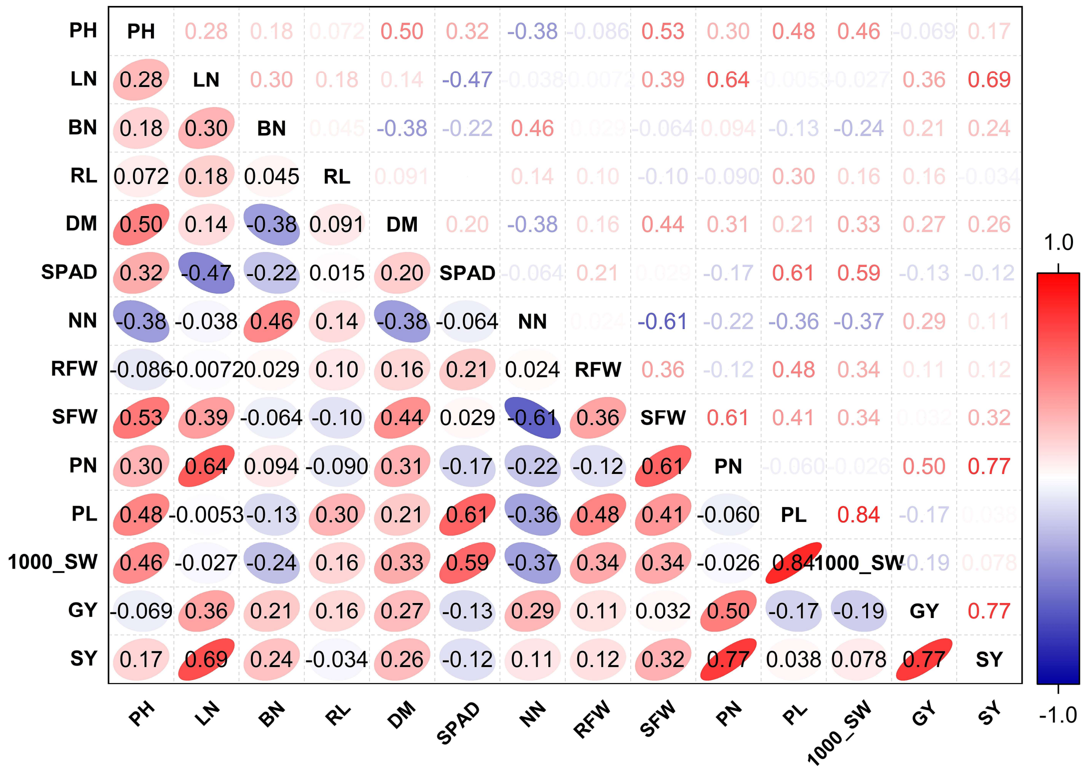

Figure 6. Correlation matrix showing the relationships among agronomic, physiological, and yield-related traits. Here, PH = plant height, SY = straw yield, LN = leaf number, GY = grain yield, BN = branch number, PN = pod number, RL = root length, DM = dry matter, PL = pod length, SPAD = SPAD value, NN = nodule number, RFW = root fresh weight, SFW = shoot fresh weight, and 1000_SW = 1000-seed weight.

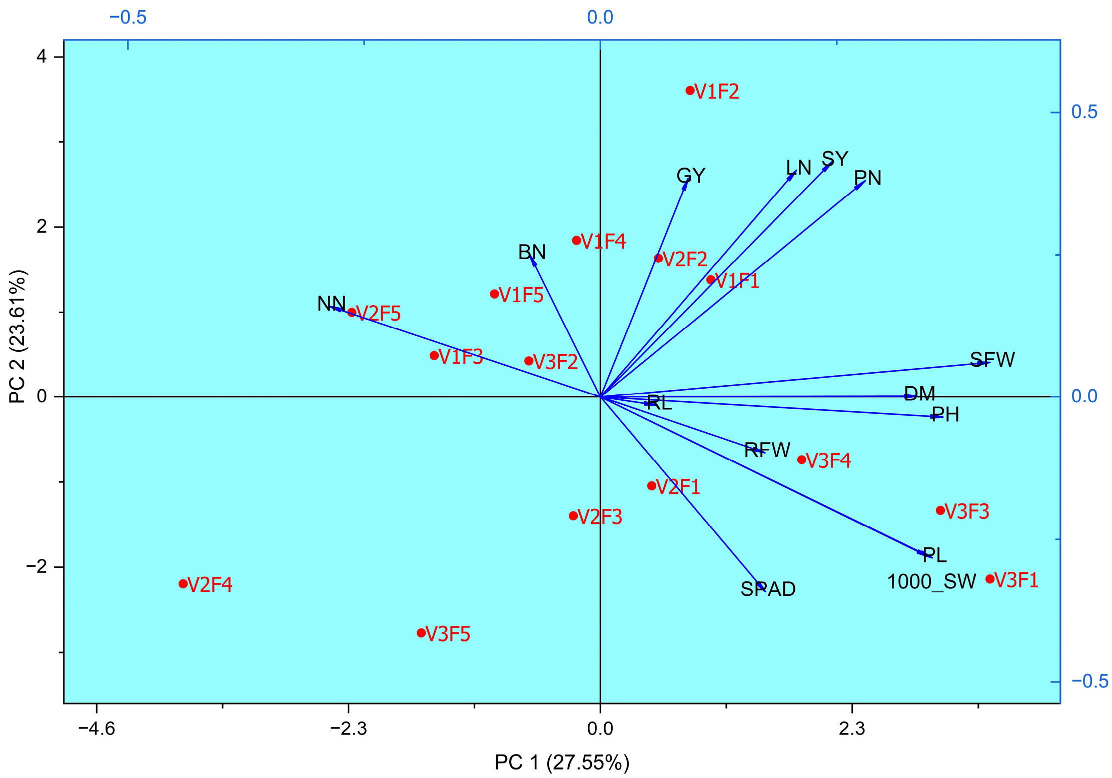

Figure 7. Principal component analysis (PCA) biplot showing the relationships among treatment combinations (TCs) and agronomic, physiological, and yield-related traits. Each point represents the mean value of a treatment combination (TC), while the vectors represent the measured variables and indicate their direction and magnitude of contribution to the principal components, as well as their correlations with each other.

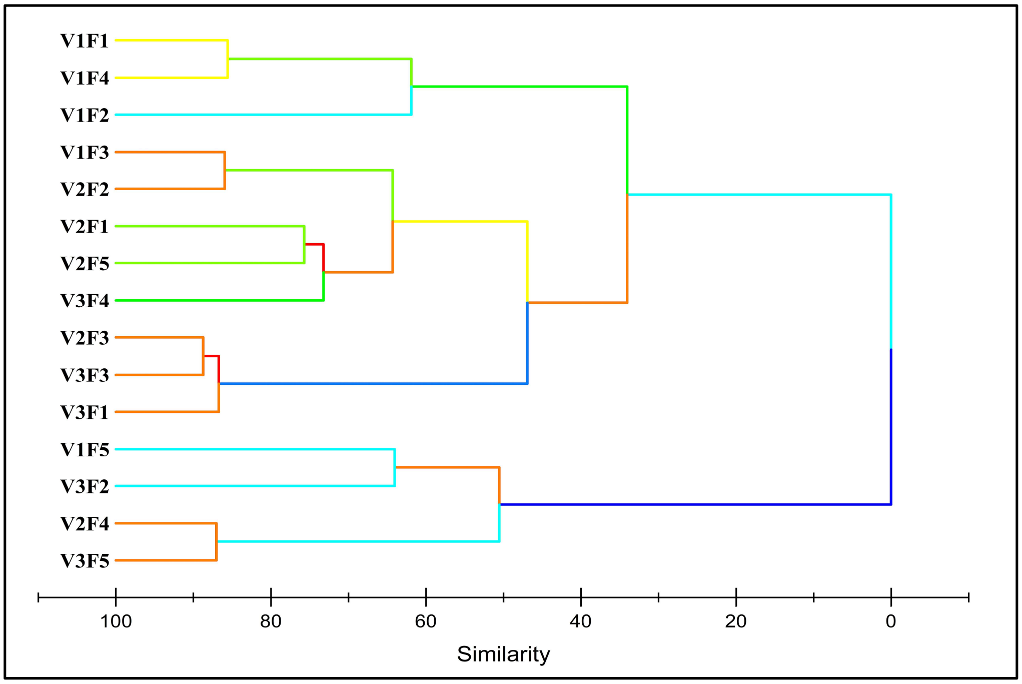

Figure 8. Cluster dendrogram showing the grouping pattern and similarity among treatment combinations based on agronomic, physiological, and yield-related traits.

Supplementary Table S1. Mean values of the measured traits for the 15 treatment combinations used in the multivariate analyses.

TC	PH	LN	BN	RL	DM	SPAD	NN	RFW	SFW	PN	PL	1000_SW	GY	SY
V_1F_1	38.68	50.58	7.25	21.55	12.56	35.33	10	2.44	52.78	46.33	4.96	42.3	2.03	4.34
V_1F_2	36.48	51.71	7.55	19.23	12.02	33.9	14.33	2.21	55.53	57.3	4.84	42.22	2.56	5.03
V_1F_3	40.23	44.11	7.78	18.21	11.58	38.93	16.56	1.62	48.34	45.87	4.74	38.42	1.7	3.65
V_1F_4	42.27	53.67	7.56	19.61	10.29	33.83	14.18	1.63	53.89	47.87	4.82	41.32	1.26	3.87
V_1F_5	38.19	49.31	7.11	21.52	13.38	37.07	20.78	2.38	44.46	34.27	4.86	41.1	2.46	4.17
V_2F_1	37.52	48.04	6.77	21.29	9.71	40.17	13.33	2.15	51.42	43	5.26	46.08	1.64	3.76
V_2F_2	43.45	48.67	9.78	20.35	10.68	38.83	18.89	2.26	50.32	45.5	5.02	44.68	2.35	4.49
V_2F_3	41.16	45.64	6.56	17.19	12.63	37.23	7.44	1.82	52.11	36.63	4.8	42.58	1.33	2.78
V_2F_4	35	40.97	6.78	20.83	10.2	36.3	16.79	1.77	41.13	25.83	4.74	43.46	1.30	2.37
V_2F_5	38.31	47.31	7.62	21.13	9.28	35.87	14.18	1.42	42.71	37.87	4.93	39.53	2.22	3.72
V_3F_1	46.43	47.59	6.63	23.68	14.44	39.63	9.67	2.1	56.39	43.13	5.53	48.66	1.55	3.197
V_3F_2	41.65	50.24	9.68	21.03	10.19	35	14.56	2.15	50.75	33.87	5.12	42.67	1.43	3.39
V_3F_3	43.29	45.59	6.78	18.56	12.8	39.03	9.33	2.61	59.72	41.77	5.44	47.6	1.913	4.12
V_3F_4	42.85	49.45	7.11	19.09	12.46	39.47	13	1.82	46.73	41.47	5.34	50.27	1.66	4.59
V_3F_5	36.14	44.09	7.39	19.4	9.21	38.51	16.33	2.86	47.53	27	5.3	44.29	1.12	2.76

Abbreviations: TC = treatment combination; PH = plant height (cm); SY = straw yield (t ha^{-1}); LN = leaf number; GY = grain yield (t ha^{-1}); BN = number of branches; PN = pod number; RL = root length (cm); DM = dry matter (g); PL = pod length (cm); SPAD = SPAD value; NN = nodule number; RFW = root fresh weight (g); SFW = shoot fresh weight (g); 1000_SW = 1000-seed weight (g).