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

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ABSTRACT

In Bangladesh, sole dependence on inorganic fertilisers has led to declining soil organic matter, nutrient imbalance, and progressive soil health degradation. Therefore, nutrient management involving organic manures and biofertilisers 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 biofertilisers on growth, physiological attributes, and yield performance of black gram (*Vigna mungo*). The experiment was laid out in a two-factor randomised 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 fertilisers, poultry litter-based compost (PLBC), BARI biofertiliser, BINA biofertiliser, and biochar. 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 1000-seed weight, in some treatments. Among the 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 demonstrated the most effective nutrient management strategy for enhancing black gram productivity under field conditions.

How to Cite

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INTRODUCTION

Black gram (*Vigna mungo* L.) is a short-duration pulse crop belonging to the family Leguminosae. It is widely recognised as an important source of plant-based protein and essential nutrients (Nasir et al., 2022). It contains 26–28% protein and 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 (Prioty et al., 2023).

Sustainable crop production requires efficient nutrient management that maintains soil fertility while minimising environmental degradation. Excessive and imbalanced use of chemical fertilisers 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 use 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). Biofertilisers, 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, biofertilisers, and biochar offers a promising approach to improve soil health and crop productivity. Therefore, the aim of the present study was to evaluate the effects of organic manure and biofertilisers on the growth and yield of black gram.

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 (25.39°N, 88.41°E, elevation 37.58 m) (Fig. 1).

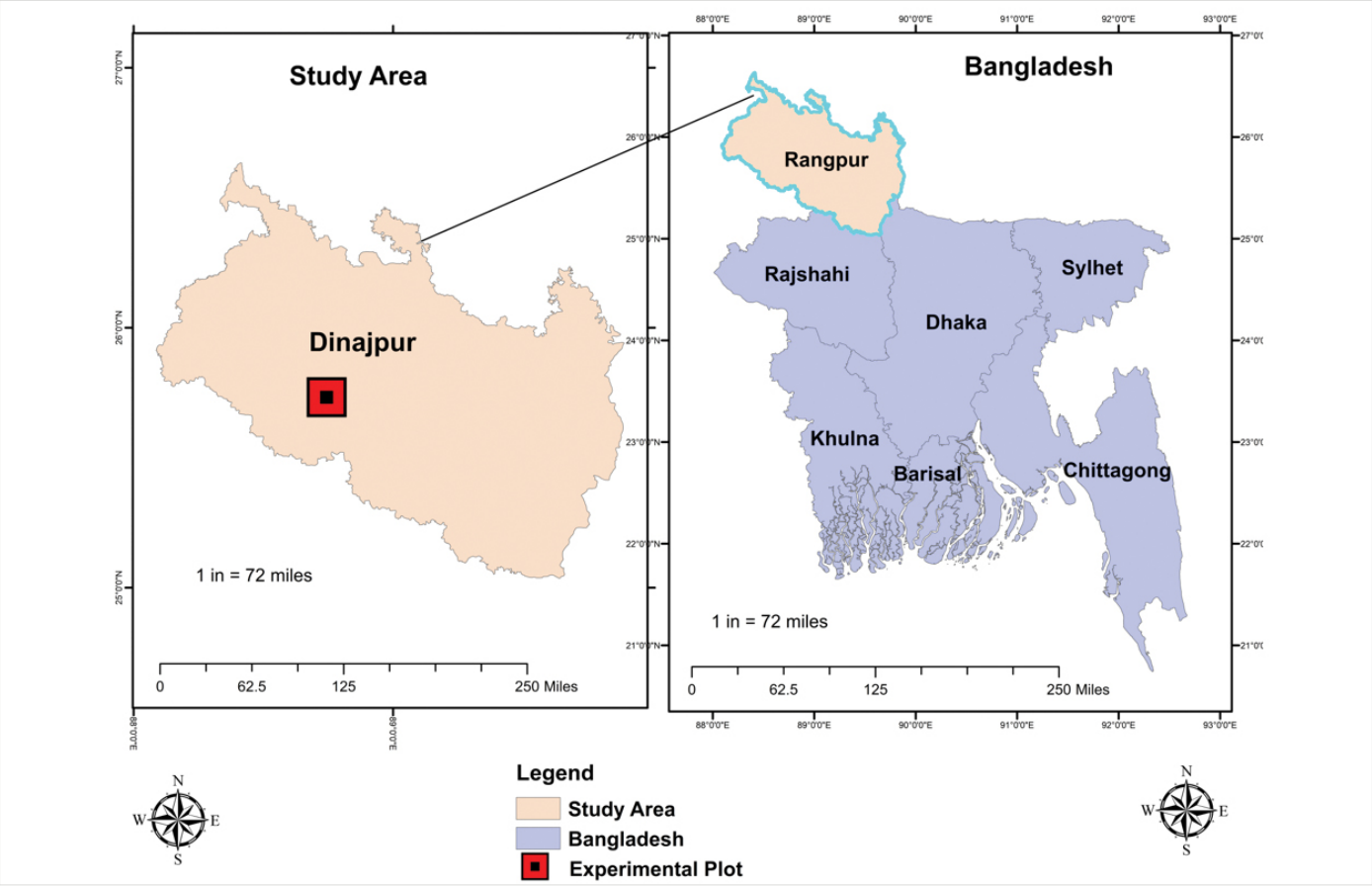


Figure 1. Location of the experimental site

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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 texture of the site was sandy loam. 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.

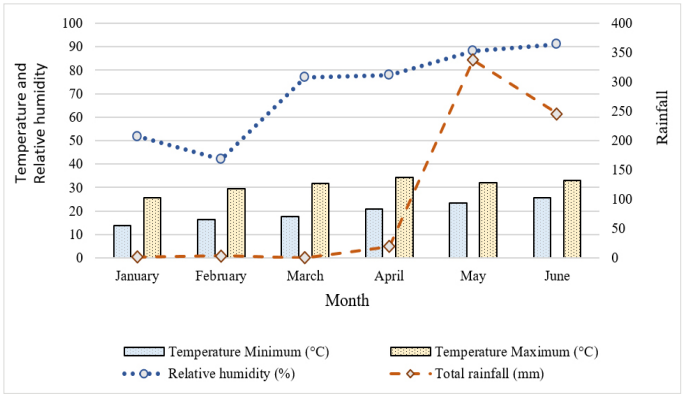


Figure 2. Meteorological data during the growing season (January-June 2022): temperature (°C), relative humidity (%), and rainfall (mm)

Physicochemical characterisation 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.

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

General characters	Description	Interpretation
Location	Crop Physiology and Ecology Field	-
Agro-Ecological Zone (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 (0.02–0.002 mm)	27.0	-
Clay (< 0.002 mm)	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/100 g soil)	5.60	Low
Total N (%)	0.07	Very low
Available P (ppm)	16.75	Medium
Exchangeable K (meq/100 g soil)	0.17	Medium low

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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. Total nitrogen (N) was measured using the Kjeldahl digestion and distillation method. Following acid digestion, available phosphorus (P) was quantified colourimetrically 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 randomised complete block design (RCBD) with three replications. The experimental unit was defined as an individual plot measuring 3 × 1 m. A total of 45 experimental plots were established. Spacing was 50 cm between blocks and 25 cm between plots. The treatments consisted of two factors. Factor A comprised five fertilisation treatments: F_1 = recommended dose of fertiliser (RDF), consisting of 40 kg ha^{-1} urea, 90 kg ha^{-1} triple superphosphate (TSP), and 40 kg ha^{-1} muriate of potash (MOP); F_2 = poultry litter-based compost at 7.5 t ha^{-1}; F_3 = Bangladesh Agricultural Research Institute, Bangladesh (BARI) biofertilizer at 85 g kg^{-1} seed; F_4 = Bangladesh Institute of Nuclear Agriculture, Bangladesh (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.

BARI and BINA biofertilisers 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.

The physicochemical characteristics of the poultry litter-based compost and biochar used in this study are presented in Table 2.

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

Note: pH = Potential of hydrogen; EC = Electrical conductivity; N = Nitrogen; P = Phosphorus; K = Potassium; C:N = Carbon-to-nitrogen ratio.

Poultry litter-based compost exhibited higher nutrient contents (N, P, and K) and a lower C:N ratio, whereas biochar was characterised by higher pH, organic carbon content, and C:N ratio, indicating their complementary roles as soil amendments.

Fertilisation

During final land preparation, the recommended fertiliser treatment (F_1) was applied as a basal dose, consisting of urea, TSP, and MOP at 40, 90, and 40 kg ha^{-1}, respectively. Poultry-litter-based compost (F_2) and biochar (F_5) were applied to the respective plots at rates of 7.5 and 5.0 t ha^{-1}, respectively. All treatments were applied by broadcasting and thoroughly incorporated into the soil during final land preparation.

Seed inoculations and sowing of seeds

For each plot, 9 g black gram seed was required, based on the recommended seed rate of 30 kg ha^{-1}. Seeds were weighed and packed into 45 individual polythene bags.

Seeds for the plots designated for inoculation with BARI (F_3) and BINA (F_4) biofertilisers (18 packets in total, six per variety: BARI Mash-1, BARI Mash-3, and BARI Mash-4) were treated prior to sowing. The seeds were first soaked in molasses, after which 0.77 g biofertiliser 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. 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 was 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 DAS and subsequently at 15-day intervals. From each plot, three plants were randomly selected and carefully uprooted. 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 per plant was recorded. Fresh weights of shoots and roots were measured immediately using an electronic balance, and samples were 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.

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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 per plant was counted, and pod length was measured on ten randomly selected pods per plant, 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 analysed using Statistix 10 (Analytical Software, Tallahassee, USA). Since independent destructive sampling was performed at 30, 45, and 60 DAS, data from each sampling date were analysed separately. A two-factor factorial analysis of variance (ANOVA) based on a randomised complete block design (RCBD) was performed using the model:

$$Y_{ijk} = \mu + B_i + V_j + F_k + (VF)_{jk} + \varepsilon_{ijk},$$

where *B* is the block (replication) effect, *V* the fixed effect of variety, *F* the fixed effect of the fertiliser treatment, *(VF)* their interaction, and *ε* the random error. Blocks were included to account for field variability. Before ANOVA, the normality of residuals was assessed using the Shapiro-Wilk test, while homogeneity of variances was assessed using Levene's test, 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, fertilisation, and their interaction at all growth stages. Among the varieties, V_3 produced the tallest plants at 30 DAS and at harvest, whereas V_2 recorded the greatest plant height at 45 DAS and 60 DAS. Fertilisation treatments also showed significant variation, where F_2 resulted in greater plant height at early stages, while F_3 exhibited higher values at later stages, and the lowest plant height at final harvest was recorded under F_5. The interaction effect showed pronounced differences among treatment combinations, with the tallest plants observed in V_3F_1 and V_2F_2, followed by V_3F_3 and V_3F_4, whereas the lowest plant height was recorded in V_2F_4 (Table 3).

Leaf number

Leaf number was also significantly influenced by variety and interaction effects at all growth stages, while fertilisation showed significant variation at all stages except 45 DAS. Among the varieties, V_1 consistently produced the highest number of leaves, recording 49.88 leaves at final harvest, followed by V_3 and V_2. Fertilisation treatments indicated that F_2 produced the highest leaf number at final harvest, followed by F_1, while comparatively lower values were recorded under F_4 and F_5. The interaction effect revealed that V_1F_4 and V_1F_2 produced the highest leaf numbers, followed by V_1F_1 and V_3F_2, whereas the lowest leaf number was observed in V_2F_4. 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).

Branch number

Branches per plant was significantly influenced ($p \leq 0.05$) by variety, fertilisation, 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 and 60 DAS, whereas V_2 recorded the highest values at 45 DAS and V_3 at final harvest, although the varietal effect at final harvest was not significant. Fertilisation F_1 produced the highest number of branches at 30 DAS, F_3 at 45 DAS, F_2 at 60 DAS and final harvest. The interaction effect showed that V_1F_3 produced the highest number of branches at 30 DAS, V_2F_1 and V_3F_3 at 45 DAS, V_3F_2 at 60 DAS, and V_2F_2 at final harvest, whereas the lowest values were recorded in V_1F_4 and V_2F_5 at 30 DAS, V_3F_5 at 45 DAS, V_2F_1 at 60 DAS, and V_2F_3 at final harvest (Table 4).

Root length

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

Nodule number

Nodule number per plant was significantly ($p \leq 0.05$) affected by variety, fertilisation, 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, whereas V_1 was superior at 45 and 60 DAS; V_2 consistently recorded lower values (11.13-14.13). Fertilisation markedly influenced nodulation, with F_5 and F_2 producing higher nodule numbers, while F_1 and F_3 resulted in lower values. 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 per plant (V_1F_5 at 60 DAS), whereas V_2F_3 showed the lowest value (7.44). Overall, both varietal differences and fertilisation regimes markedly influenced nodulation dynamics in black gram.

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Table 3. Effect of varieties and fertilisations on plant height and leaf number of black gram at different sampling intervals (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	12.35^{c}	22.52^{b}	33.89^{c}	39.17^{b}	6.24^{a}	16.24^{a}	40.89^{a}	49.88^{a}
V_2	12.74^{b}	23.56^{a}	36.07^{a}	39.09^{b}	5.51^{c}	13.79^{b}	36.58^{b}	46.13^{c}
V_3	14.40^{a}	22.56^{b}	35.44^{b}	42.07^{a}	5.91^{b}	14.16^{b}	36.45^{b}	47.39^{b}
Level of significance	*	*	*	*	*	*	*	*
Fertilizations								
F_1	13.42^{b}	23.85^{b}	34.72^{b}	40.88^{b}	6.17^{a}	16.11^{a}	39.07^{b}	48.74^{b}
F_2	14.24^{a}	24.22^{a}	34.39^{c}	40.53^{c}	5.43^{b}	15.15^{a}	42.18^{a}	50.21^{a}
F_3	13.01^{c}	22.13^{d}	37.62^{a}	41.56^{a}	6.18^{a}	14.18^{a}	34.92^{c}	45.11^{e}
F_4	13.46^{b}	21.71^{e}	34.68^{b}	40.04^{d}	6.07^{a}	13.87^{a}	35.01^{c}	48.03^{c}
F_5	11.69^{d}	22.48^{c}	34.24^{c}	37.55^{e}	5.57^{b}	14.33^{a}	38.67^{b}	46.90^{d}
Level of significance	*	*	*	*	*	NS	*	*
Interactions between Variety and Fertilizations								
V_1F_1	12.87^{c-e}	23.95^{c}	32.63^{j}	38.68^{h}	6.43^{b-d}	15.00^{a-d}	39.56^{c}	50.58^{bc}
V_1F_2	13.31^{b-d}	22.68^{ef}	31.49^{k}	36.48^{k}	5.67^{b-g}	16.11^{a-d}	42.7^{6ab}	51.71^{b}
V_1F_3	12.79^{de}	21.78^{h}	34.25^{g}	40.23^{g}	8.22^{a}	20.64^{a}	37.41^{d}	44.11^{i}
V_1F_4	11.72^{gh}	22.49^{fg}	34.71^{f}	42.27^{d}	5.56^{c-g}	13.00^{b-d}	43.6^{a}	53.67^{a}
V_1F_5	11.08^{h}	21.67^{h}	36.35^{d}	38.19^{i}	5.32^{e-g}	16.44^{a-d}	41.11^{bc}	49.31^{de}
V_2F_1	12.10^{fg}	24.69^{b}	33.35^{i}	37.52^{j}	5.76^{b-f}	17.33^{a-c}	41.98^{ab}	48.04^{fg}
V_2F_2	13.89^{b}	26.19^{a}	39.09^{b}	43.45^{b}	5.11^{fg}	15.11^{a-d}	41.18^{bc}	48.67^{ef}
V_2F_3	12.7^{d-f}	23.31^{d}	38.17^{c}	41.16^{f}	5.56^{c-g}	11.11^{cd}	36.66^{de}	45.64^{h}
V_2F_4	13.49^{bc}	21.32^{i}	35.94^{e}	35.00^{m}	6.22^{b-e}	11.06^{cd}	27.99^{h}	40.97^{j}
V_2F_5	11.53^{gh}	22.29^{g}	33.78^{h}	38.31^{i}	4.89^{fg}	14.33^{a-d}	35.08^{ef}	47.31^{g}
V_3F_1	15.30^{a}	22.91^{e}	38.16^{c}	46.43^{a}	6.33^{b-d}	16.00^{a-d}	35.68^{de}	47.59^{fg}
V_3F_2	15.52^{a}	23.77^{c}	32.59^{j}	41.65^{e}	5.50^{d-g}	14.22^{b-d}	42.61^{ab}	50.24^{cd}
V_3F_3	13.54^{bc}	21.28^{i}	40.45^{a}	43.29^{b}	4.78^{g}	10.78^{d}	30.69^{g}	45.59^{h}
V_3F_4	15.16^{a}	21.33^{i}	33.39^{hi}	42.85^{c}	6.44^{bc}	17.56^{ab}	33.44^{f}	49.45^{c-e}
V_3F_5	12.48^{ef}	23.48^{d}	32.59^{j}	36.14^{l}	6.50^{b}	12.22^{b-d}	39.83^{c}	44.09^{i}
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 biofertiliser; F_4 = BINA biofertiliser; F_5 = Biochar 5 t ha^{-1}. V_1 = BARI Mash-1; V_2 = BARI Mash-3; V_3 = BARI Mash-4.

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Table 4. Effect of varieties and fertilisation on number of branches and root length (cm) of black gram at different sampling intervals (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	2.79^{a}	4.27^{b}	7.18^{a}	7.45^{a}	11.38^{a}	12.02^{b}	20.02^{a}
V_2	2.47^{b}	4.52^{a}	6.82^{b}	7.50^{a}	11.04^{a}	12.69^{a}	20.16^{a}
V_3	2.62^{ab}	4.04^{c}	7.07^{a}	7.52^{a}	11.43^{a}	13.11^{a}	20.35^{a}
Level of significance	*	*	*	NS	NS	*	NS
Fertilizations							
F_1	2.85^{a}	4.56^{ab}	6.37^{c}	6.88^{c}	11.21^{ab}	12.59^{b}	22.17^{a}
F_2	2.70^{ab}	4.26^{bc}	8.67^{a}	9.00^{a}	11.71^{a}	13.66^{a}	20.20^{bc}
F_3	2.74^{ab}	4.74^{a}	6.708^{b}	7.04^{bc}	11.44^{ab}	12.39^{b}	17.99^{d}
F_4	2.52^{ab}	3.96^{cd}	6.68^{b}	7.15^{bc}	11.03^{b}	12.00^{b}	19.84^{c}
F_5	2.33^{b}	3.87^{d}	6.63^{bc}	7.37^{b}	11.04^{b}	12.41^{b}	20.68^{b}
Level of significance	*	*	*	*	*	*	*
Interactions between Variety and Fertilizations							
V_1F_1	2.56^{bc}	3.89^{d-f}	7.10^{b-d}	7.25^{b-e}	10.92^{b-d}	11.43^{d}	21.55^{b}
V_1F_2	3.22^{ab}	4.44^{b-e}	7.44^{bc}	7.55^{bc}	11.50^{a-c}	12.50^{b-d}	19.23^{d-f}
V_1F_3	3.56^{a}	5.11^{ab}	7.56^{b}	7.78^{b}	11.31^{a-d}	12.03^{cd}	18.21^{fg}
V_1F_4	2.22^{c}	4.22^{c-f}	7.25^{bc}	7.56^{bc}	11.56^{a-c}	12.15^{b-d}	19.61^{c-e}
V_1F_5	2.43^{bc}	3.67^{fg}	6.56^{de}	7.11^{b-e}	11.62^{a-c}	11.99^{cd}	21.52^{b}
V_2F_1	2.78^{a-c}	5.22^{a}	5.55^{f}	6.77^{c-e}	12.09^{ab}	13.70^{a-c}	21.29^{b}
V_2F_2	2.33^{bc}	4.56^{a-d}	9.11^{a}	9.78^{a}	12.16^{ab}	13.87^{ab}	20.35^{b-d}
V_2F_3	2.33^{bc}	3.89^{d-f}	6.56^{de}	6.56^{e}	10.43^{cd}	12.64^{b-d}	17.19^{g}
V_2F_4	2.67^{a-c}	4.11^{d-f}	6.33^{e}	6.78^{c-e}	10.59^{cd}	11.73^{d}	20.83^{bc}
V_2F_5	2.22^{c}	4.83^{a-c}	6.56^{de}	7.62^{b}	9.90d	11.54^{d}	21.13^{b}
V_3F_1	3.22^{ab}	4.55^{a-d}	6.44^{de}	6.63^{de}	10.62^{cd}	12.65^{b-d}	23.68^{a}
V_3F_2	2.56^{bc}	3.78^{e-g}	9.45^{a}	9.68^{a}	11.46^{a-c}	14.60^{a}	21.03^{b}
V_3F_3	2.33^{bc}	5.22^{a}	6.22^{e}	6.78^{c-e}	12.57^{a}	12.49^{b-d}	18.56^{ef}
V_3F_4	2.67^{a-c}	3.56^{fg}	6.44^{de}	7.11^{b-e}	10.93^{b-d}	12.12^{b-d}	19.09^{d-f}
V_3F_5	2.32^{bc}	3.11^{g}	6.78^{c-e}	7.39^{b-d}	11.59^{a-c}	13.69^{a-c}	19.40^{d-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 biofertiliser; F_4 = BINA biofertiliser; F_5 = Biochar 5 t ha^{-1}. V_1 = BARI Mash-1; V_2 = BARI Mash-3; V_3 = BARI Mash-4.

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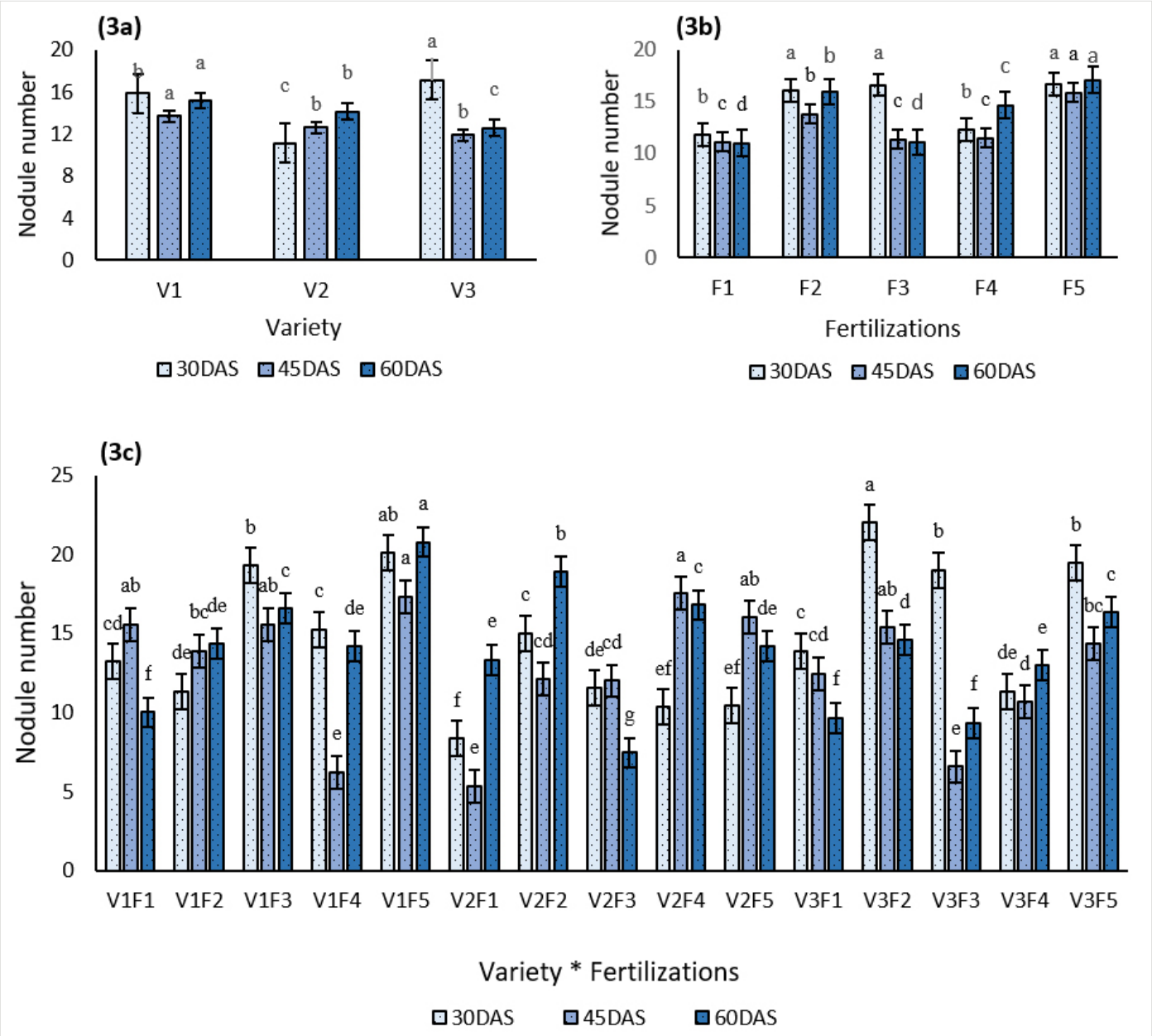


Figure 3. Effect of variety (3a), fertilization (3b), and their interaction (3c) on nodule number of black gram at different growth stages (30, 45, and 60 DAS). Bars represent mean values for V_1 (BARI Mash-1), V_2 (BARI Mash-3), and V_3 (BARI Mash-4), and fertilization treatments F_1-F_5 (F_1 = recommended dose of fertilizer, F_2 = poultry litter-based compost, F_3 = Bangladesh Agricultural Research Institute). Different letters indicate significant differences among treatments at $p \leq 0.05$ according to Tukey's test.

Physiological traits

SPAD Value

The graphical analysis of SPAD values at 30, 45, and 60 DAS (Fig. 4) revealed significant ($p < 0.05$) variation among varieties, fertilisation treatments, and their interactions, indicating strong temporal and treatment-dependent responses across growth stages. Among varieties, V_3 consistently exhibited the highest SPAD values, followed by V_2, whereas V_1 recorded the lowest values. Fertilisation also significantly influenced chlorophyll content, with higher SPAD values observed under F_3 and F_4 at 30 DAS, F_2 at 45 DAS, and F_1 as well as F_3 at 60 DAS, while F_5 consistently produced the lowest readings for all three varieties. Interaction effects were pronounced, with the highest SPAD values recorded in V_3F_3 at 30 DAS, V_2F_2 at 30 DAS, and V_3F_2 at 45 DAS, whereas the lowest values were observed in V_2F_3 at 45 DAS and V_1F_4 at 60 DAS, indicating strong variety × fertilisation interactions affecting chlorophyll accumulation and leaf physiological status.

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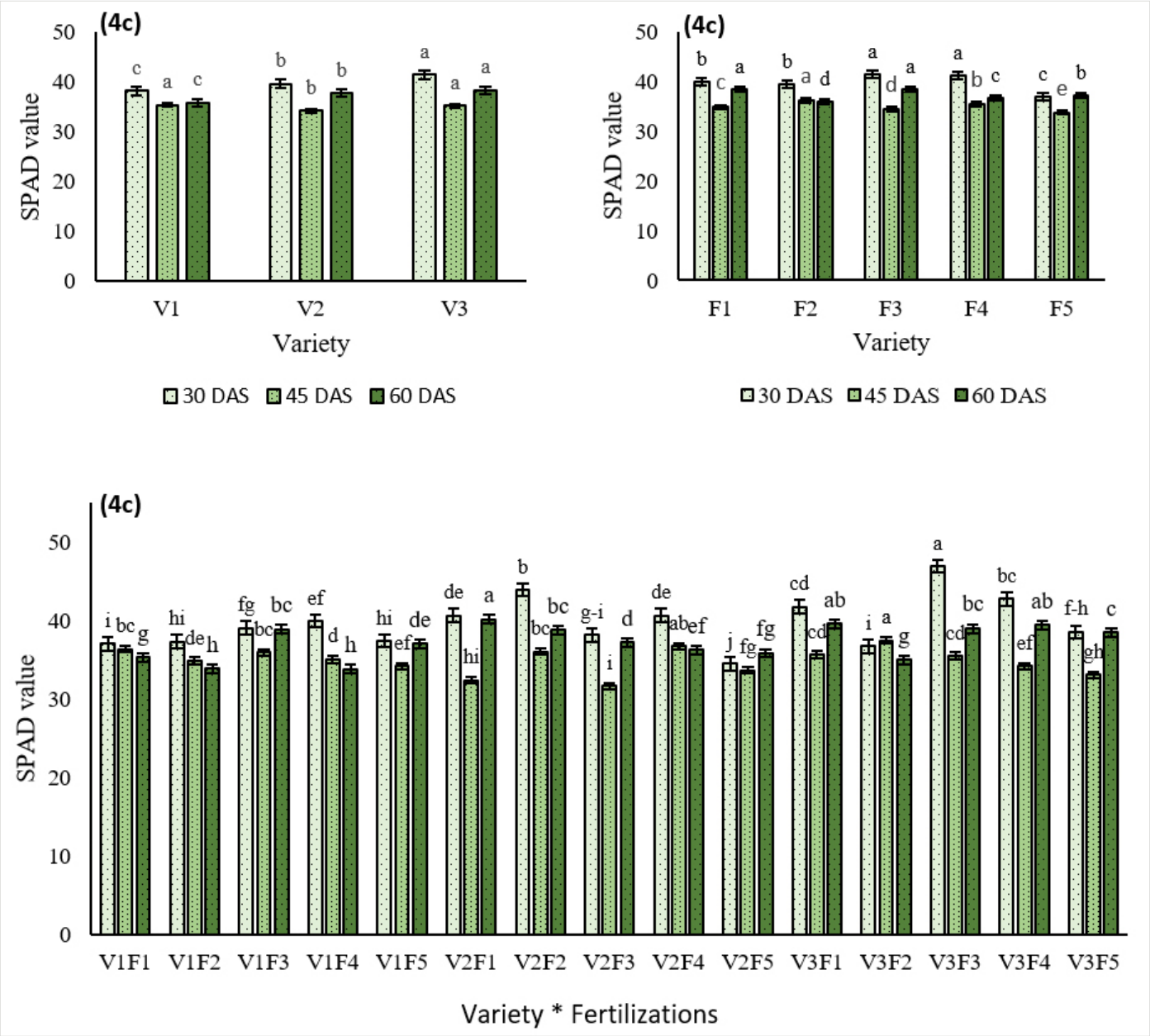


Figure 4. Effect of variety (4a), fertilization (4b), and their interaction (4c) on SPAD value of blackgram at different growth stages (30, 45, and 60 DAS). Bar charts represent mean SPAD values of three varieties (V_1 = BARI Mash-1, V_2 = BARI Mash-3, V_3 = BARI Mash-4), five fertilization levels (F_1 = recommended dose of fertilizer, F_2 = poultry litter-based compost, F_3 = Bangladesh Agricultural Research Institute biofertilizer, F_4 = Bangladesh Institute of Nuclear Agriculture biofertilizer, and F_5 = biochar), 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.

Biomass accumulation

Root fresh weight

Root fresh weight was significantly influenced ($p \leq 0.05$) by variety, fertilisation, and their interaction at all growth stages (Table 5). Among varieties, V_3 recorded the highest root fresh weight at 30 DAS and 60 DAS, whereas V_2 showed the lowest values. Fertilisation treatments F_2 and F_3 produced higher root fresh weight at 30 DAS, while F_1, F_2, and F_5 recorded comparatively higher values at 60 DAS, with F_4 showing the lowest. Interaction effects indicated that V_2F_2 and V_3F_3 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.

Shoot fresh weight

Shoot fresh weight varied significantly ($p \leq 0.05$) among treatments. V_3 produced the highest shoot biomass at 60 DAS, whereas V_2 recorded the lowest. Fertilisation F_1 resulted in the highest shoot fresh weight across stages, particularly at 60 DAS, while F_4 showed the lowest values. Interaction effects revealed that V_3F_3 and V_3F_1 produced the maximum shoot biomass, whereas V_2F_4 and V_2F_5 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, fertilisation treatments, and their interactions.

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

Treatment	Root fresh weight (g) at			Shoot fresh weight (g) at		
Variety	30DAS	45DAS	60DAS	30DAS	45DAS	60DAS
V_1	0.26^{b}	0.62^{a}	2.06^{b}	1.94^{a}	7.83^{a}	51.00^{b}
V_2	0.25^{b}	0.54^{b}	1.88^{c}	1.62^{b}	7.76^{a}	47.54^{c}
V_3	0.33^{a}	0.55^{b}	2.31^{a}	1.86^{a}	6.93^{b}	52.23^{a}
Level of significance	*	*	*	*	*	*
Fertilizations						
F_1	0.22^{c}	0.61^{a}	2.23^{a}	2.15^{a}	8.87^{a}	53.53^{a}
F_2	0.35^{a}	0.62^{a}	2.21^{a}	1.78^{b}	7.23^{b}	52.20^{b}
F_3	0.34^{a}	0.58^{b}	2.01^{b}	1.75^{b}	7.34^{b}	53.39^{ab}
F_4	0.24^{b}	0.52^{c}	1.74^{c}	1.69^{b}	6.21^{c}	47.24^{c}
F_5	0.26^{b}	0.51^{c}	2.22^{a}	1.65^{b}	7.88^{b}	44.90^{d}
Level of significance	*	*	*	*	*	*
Interactions between Variety and Fertilizations						
V_1F_1	0.22^{d}	0.66^{bc}	2.44^{c}	1.87^{cd}	9.61^{a}	52.78^{cd}
V_1F_2	0.22^{d}	0.52^{fg}	2.21^{d}	1.88^{cd}	6.16^{e}	55.53^{b}
V_1F_3	0.37^{b}	0.65^{bc}	1.62^{g}	2.46^{b}	8.39^{a-d}	48.34^{ef}
V_1F_4	0.29^{c}	0.68^{ab}	1.63^{g}	1.43^{e}	5.85^{e}	53.89^{bc}
V_1F_5	0.22^{d}	0.58^{de}	2.38^{c}	2.08^{c}	9.15^{ab}	44.46^{gh}
V_2F_1	0.21^{de}	0.61^{cd}	2.15^{de}	1.82^{cd}	8.53^{a-c}	51.42^{cd}
V_2F_2	0.47^{a}	0.72^{a}	2.26^{d}	1.63^{de}	9.59^{a}	50.32^{de}
V_2F_3	0.19^{de}	0.55^{ef}	1.82^{f}	1.40^{e}	6.68^{de}	52.11^{cd}
V_2F_4	0.24^{d}	0.39^{h}	1.77^{f}	1.78^{d}	6.54^{e}	41.13^{i}
V_2F_5	0.16^{e}	0.41^{h}	1.42^{h}	1.44^{e}	7.45^{b-e}	42.71^{hi}
V_3F_1	0.23^{d}	0.55^{ef}	2.10^{e}	2.75^{a}	8.45^{a-d}	56.39^{b}
V_3F_2	0.36^{b}	0.61^{cd}	2.15^{de}	1.82^{cd}	5.96^{e}	50.75^{de}
V_3F_3	0.47^{a}	0.55^{ef}	2.61^{b}	1.38^{e}	6.96^{c-e}	59.72^{a}
V_3F_4	0.20^{de}	0.49^{g}	1.82^{f}	1.88^{cd}	6.24^{e}	46.73^{fg}
V_3F_5	0.40^{b}	0.54^{e-g}	2.86^{a}	1.45^{e}	7.04^{c-e}	47.53^{f}
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 biofertiliser; F_4 = BINA biofertiliser; F_5 = Biochar 5 t ha^{-1}. V_1 = BARI Mash-1; V_2 = BARI Mash-3; V_3 = BARI Mash-4.

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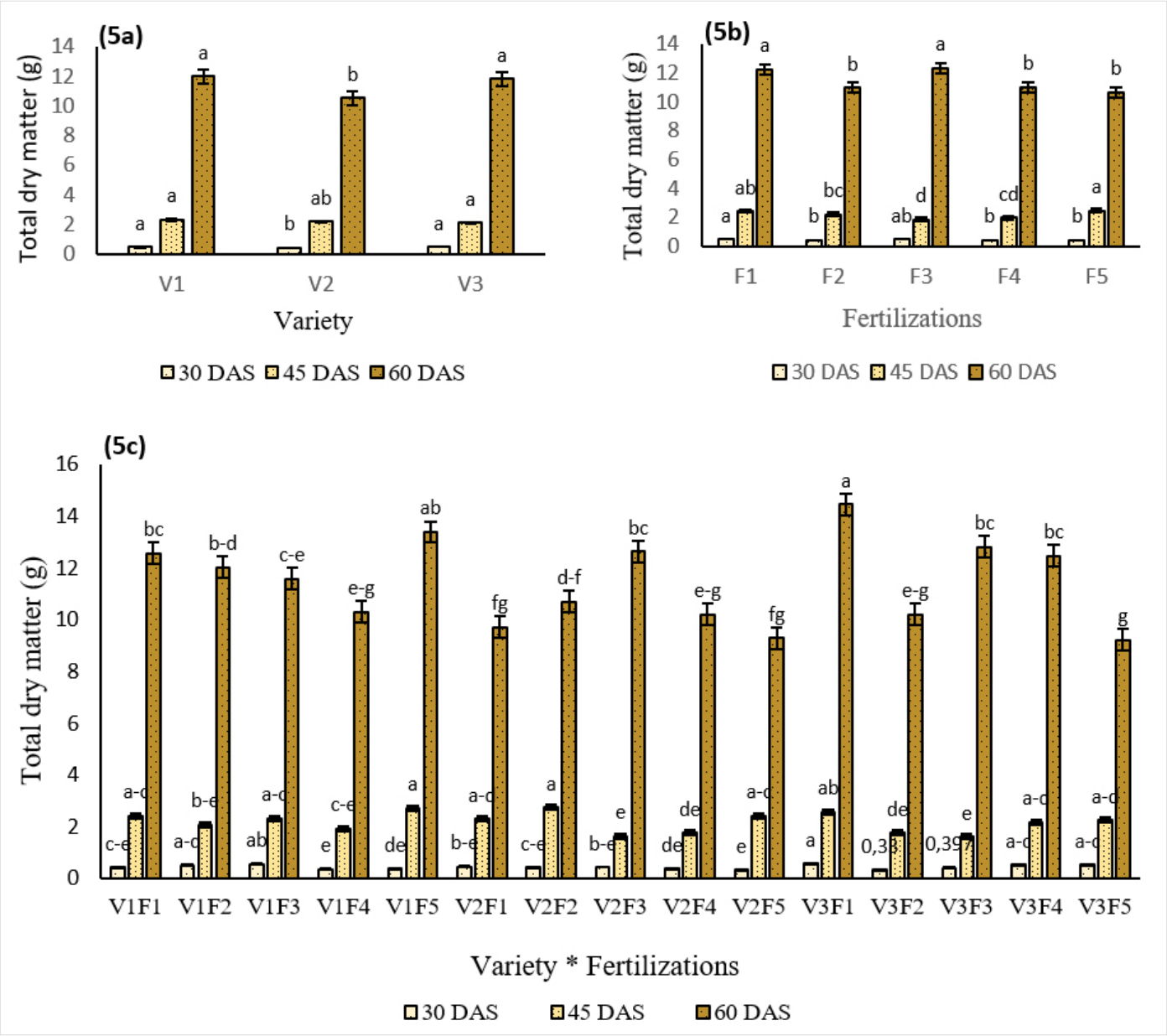


Figure 5. Effect of variety (5a), fertilisation (5b), and their interaction (5c) on total dry matter accumulation of black gram at different growth stages (30, 45, and 60 DAS). Bar charts represent mean total dry matter (g per plant) of three varieties (V_1 = BARI Mash-1, V_2 = BARI Mash-3, V_3 = BARI Mash-4), five fertilization treatments (F_1 = recommended dose of fertilizer, F_2 = poultry litter-based compost, F_3 = Bangladesh Agricultural Research Institute biofertilizer, F_4 = Bangladesh Institute of Nuclear Agriculture biofertilizer, and F_5 = biochar), 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.

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, while V_1 recorded the maximum biomass at 45 and 60 DAS, closely followed by V_3 at 60 DAS; V_2 consistently showed lower values across stages. Fertilisation significantly affected biomass production, where F_1 and F_3 resulted in higher dry matter at 30 DAS, F_5 showed the highest accumulation at 45 DAS, and F_3 recorded the maximum at 60 DAS, whereas F_2, F_4, and F_5 generally remained lower at later stages. Interaction effects indicated marked variability, with the highest total dry matter recorded in V_3F_1 at 30 DAS and 60 DAS, while V_2F_2 showed superior performance at 45 DAS. In contrast, the lowest values were observed in V_2F_5 at 60 DAS and V_3F_3 at 45 DAS, indicating strong genotype × fertilisation interactions in biomass accumulation.

Yield and yield-contributing characters

All yield and yield-related traits were influenced ($p \leq 0.05$) by variety, fertilisation, 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, whereas V_3 recorded the lowest. In contrast, V_3 exhibited the longest pods, followed by V_2, while V_1 had the shortest pods. Among fertilisation treatments, F_2 resulted in the highest pod number, while F_5 showed the lowest. Pod length was the greatest under F_1. Interaction effects indicated that V_1F_2 produced the maximum pod number, whereas V_3F_1 recorded the longest pods (Table 6).

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Table 6. Effect of variety, fertilisation, 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	46.33^{a}	4.84^{c}	41.07^{c}	2.00^{a}	4.21^{a}
V_2	37.77^{b}	4.95^{b}	43.26^{b}	1.77^{b}	3.42^{c}
V_3	37.45^{b}	5.35^{a}	46.69^{a}	1.53^{c}	3.61^{b}
Level of significance	*	*	*	*	*
Fertilizations					
F_1	44.16^{a}	5.25^{a}	45.68^{a}	1.74^{c}	3.76^{b}
F_2	45.56^{a}	4.99^{bc}	43.19^{c}	2.11^{a}	4.31^{a}
F_3	41.42^{b}	4.99^{bc}	42.87^{d}	1.65^{d}	3.52^{e}
F_4	38.39^{c}	4.97^{c}	45.01^{b}	1.41^{e}	3.61^{c}
F_5	33.04^{d}	5.03^{b}	41.64^{e}	1.93^{b}	3.55^{d}
Level of significance	*	*	*	*	*
Interactions between Variety and Fertilizations					
V_1F_1	46.33^{bc}	4.96^{fg}	42.30^{g}	2.03^{e}	4.34^{d}
V_1F_2	57.30^{a}	4.84^{i}	42.22^{g}	2.56^{a}	5.03^{a}
V_1F_3	45.87^{bc}	4.74^{j}	38.42^{j}	1.70^{g}	3.65^{h}
V_1F_4	47.87^{b}	4.82^{i}	41.32^{h}	1.26^{j}	3.87^{f}
V_1F_5	34.27^{f}	4.86^{hi}	41.10^{h}	2.46^{b}	4.17^{e}
V_2F_1	43.00^{b-d}	5.26^{d}	46.08^{d}	1.64^{gh}	3.76^{g}
V_2F_2	45.50^{bc}	5.02^{f}	44.68^{e}	2.35^{c}	4.49^{c}
V_2F_3	36.63^{ef}	4.80^{ij}	42.58^{g}	1.33^{j}	2.78^{k}
V_2F_4	25.83^{g}	4.74^{j}	43.46^{f}	1.30^{j}	2.37^{l}
V_2F_5	37.87^{d-f}	4.93^{gh}	39.53^{i}	2.22^{d}	3.72^{g}
V_3F_1	43.13^{b-d}	5.53^{a}	48.66^{b}	1.55^{h}	3.19^{j}
V_3F_2	33.87^{f}	5.12^{e}	42.67^{g}	1.43^{i}	3.39^{i}
V_3F_3	41.77^{c-e}	5.44^{b}	47.60^{c}	1.913^{f}	4.12^{e}
V_3F_4	41.47^{c-e}	5.34^{c}	50.27^{a}	1.66^{g}	4.59^{b}
V_3F_5	27.00^{g}	5.30^{cd}	44.29^{e}	1.12^{k}	2.76^{k}
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 biofertiliser; F_4 = BINA biofertiliser; F_5 = Biochar 5 t ha^{-1}. V_1 = BARI Mash-1; V_2 = BARI Mash-3; V_3 = BARI Mash-4

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1000-seed weight

1000-seed weight differed across treatments. V_3 recorded the highest value, followed by V_2, while V_1 showed the lowest. Among fertilisation treatments, F_1 produced the highest seed weight, whereas F_5 recorded the lowest. The interaction effect revealed that V_3F_4 produced the maximum 1000-seed weight, followed by V_3F_1 (Table 6).

Grain yield

Grain yield was influenced by all factors. V_1 produced the highest grain yield, followed by V_2, whereas V_3 recorded the lowest. Among fertilisation treatments, F_2 resulted in the highest grain yield, while F_4 showed the lowest. Interaction effects indicated that V_1F_2 produced the maximum grain yield, whereas V_3F_5 recorded the lowest (Table 6).

Straw yield

Straw yield was also affected by all treatments. V_1 recorded the highest straw yield, followed by V_3, while V_2 showed the lowest. Among fertilisation treatments, F_2 produced the highest straw yield, whereas F_4 recorded comparatively lower values. Interaction effects revealed that V_1F_2 produced the maximum straw yield, while V_2F_4 showed the minimum (Table 6). Top of FormBottom of Form

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), pod length (PL), and 1000-seed weight (1000_SW), indicating that vigorous vegetative growth contributed positively to reproductive performance. Leaf number (LN) exhibited strong positive correlations with pod number (PN) and straw yield (SY), suggesting the importance of leaf development in biomass production and yield enhancement. SPAD value was positively correlated with PL and 1000_SW, reflecting the role of chlorophyll content in seed development and assimilate accumulation. PN showed strong positive relationships with grain yield, identifying it as a key determinant of productivity. Additionally, PL had the highest positive correlation with 1000_SW, indicating that longer pods contributed to better seed weight. GY was strongly associated with SY, implying that treatments promoting vegetative biomass also enhanced economic yield. In contrast, nodule number (NN) showed negative correlations with shoot fresh weight (SFW) and 1000_SW.

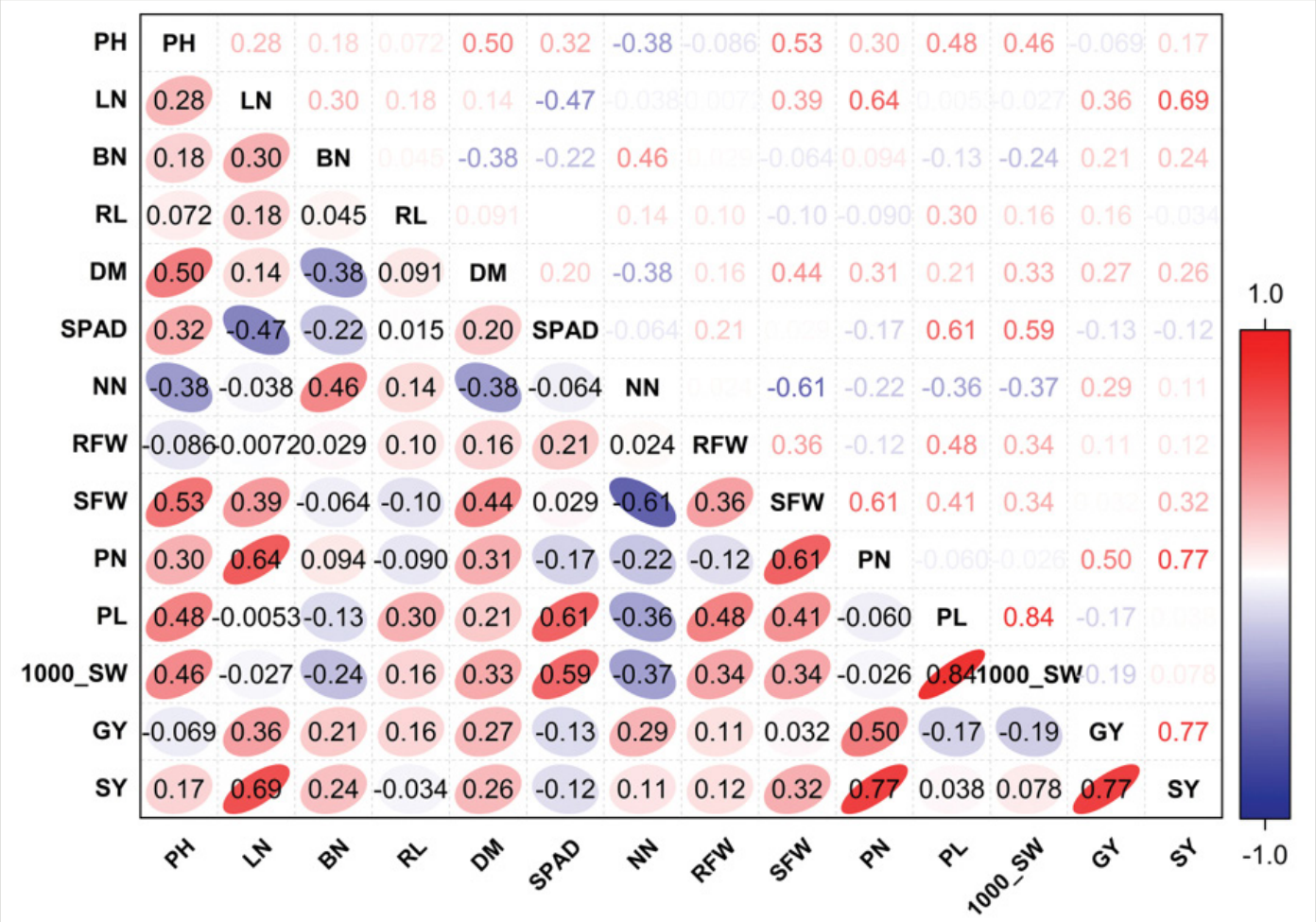


Figure 6. Correlation matrix showing the relationships among agricultural, physiological, and yield-related traits. Abbreviations: PH = plant height, SY = straw yield, LN = leaf number, GY = grain yield, BN = branch number, PN = pod number, RL = root length, DM = dry matter, PL = pod length, SPAD = SPAD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

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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 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, straw yield, leaf number, pod number, plant height, dry matter, and shoot fresh weight, whereas PC2 was primarily associated with pod length, SPAD value, and 1000-seed weight. Nodule number and branch number 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 summarised 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 favourable 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.

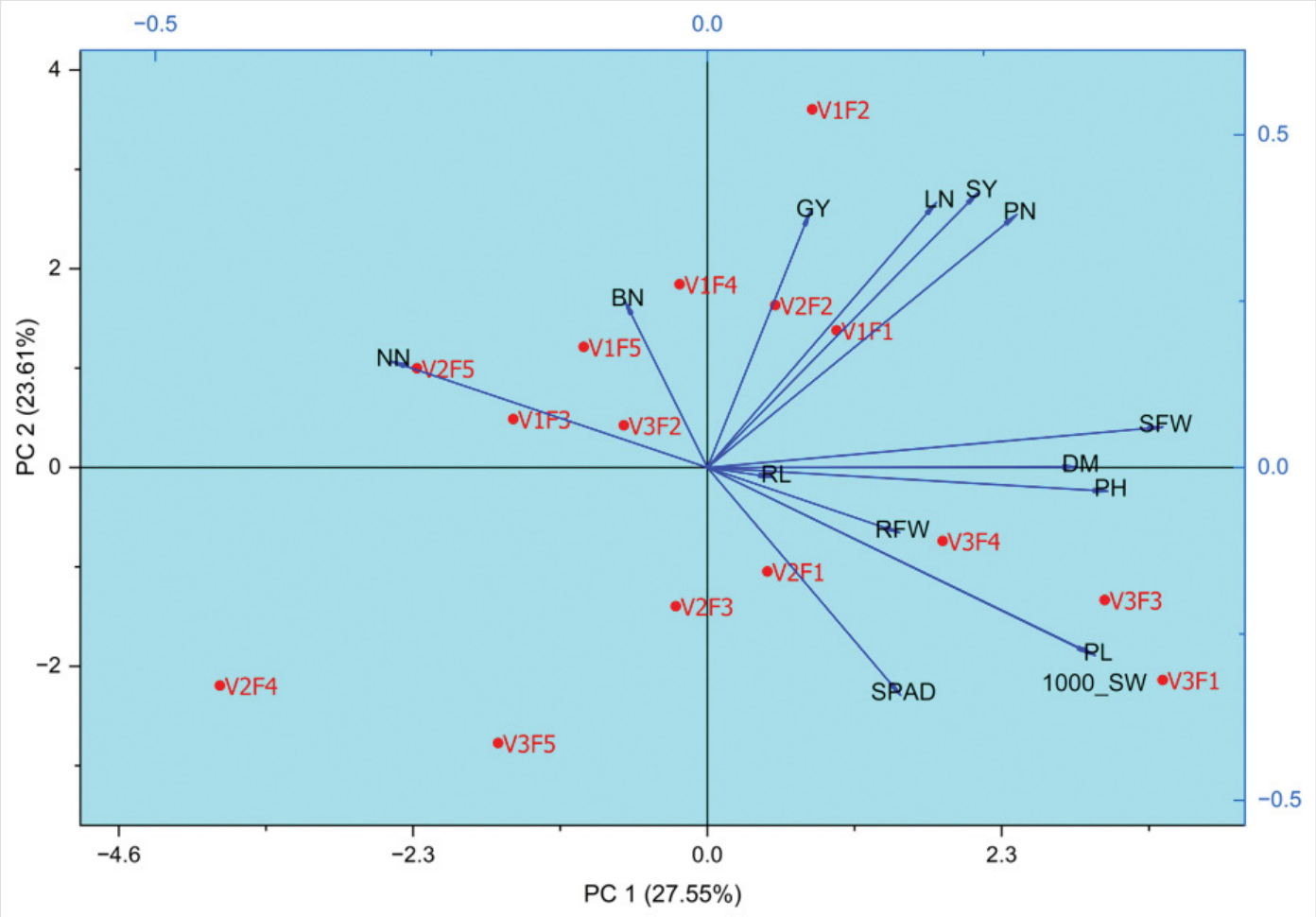


Figure 7. Principal component analysis (PCA) biplot showing the relationships among treatment combinations and agricultural, physiological, and yield-related traits. Each point represents the mean value of a treatment combination (TC), while the vectors represent the measured variables and indicate their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

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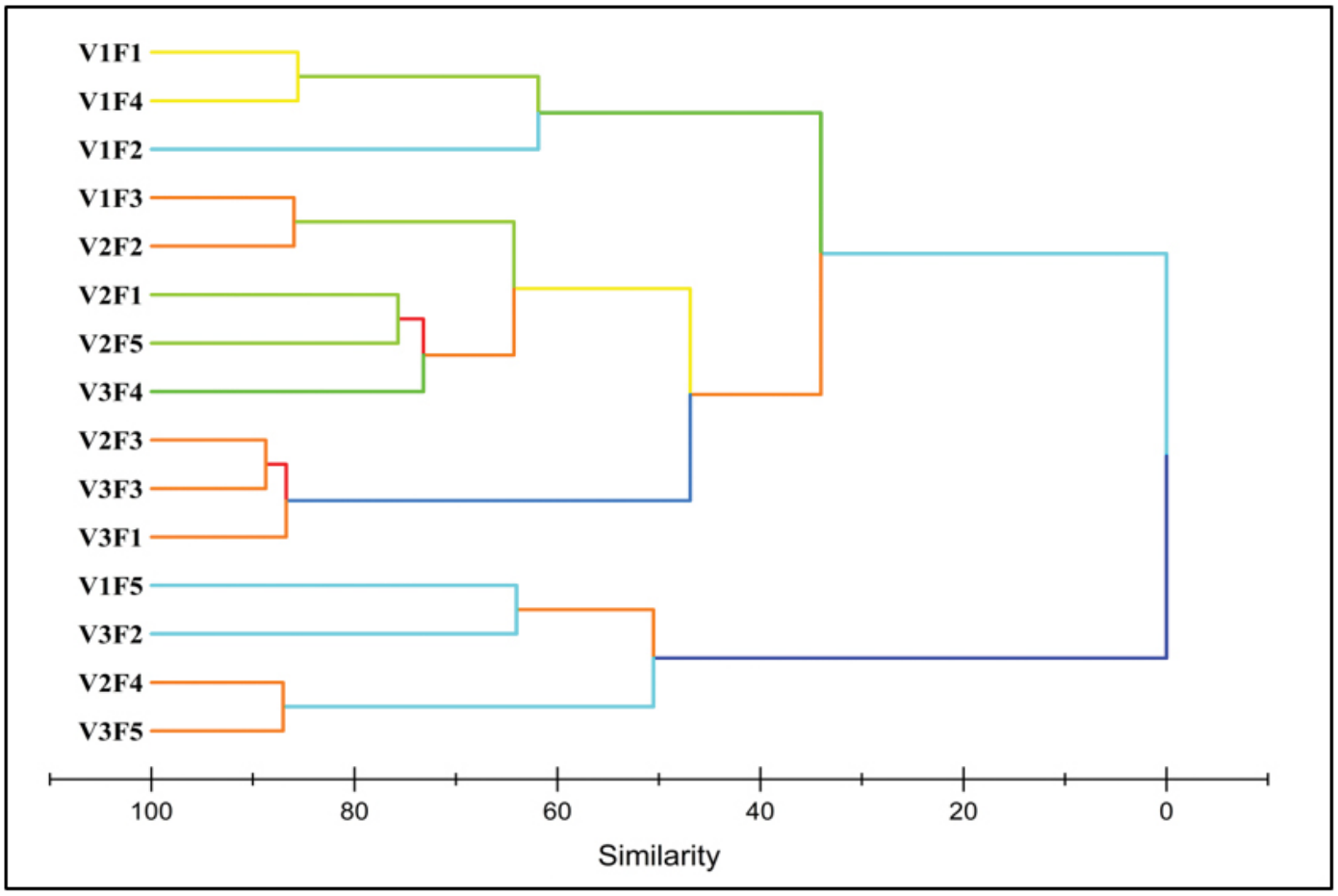


Figure 8. Cluster dendrogram showing the grouping pattern and similarity among treatment combinations (variety V x fertiliser treatment F) based on agricultural, physiological, and yield-related traits.

DISCUSSION

Growth attributes

The observed variation in plant height, leaf number, branch formation, and root length among varieties and fertilisation treatments reflects differential genetic potential and nutrient-use efficiency under varying soil nutrient regimes. Poultry litter-based compost significantly enhanced early plant height, likely due to improved nutrient mineralisation 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, biofertiliser 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. Enhanced branching under PLBC may be attributed to improved nitrogen availability and optimised assimilate partitioning, thereby increasing sink sites for reproductive development, similar to results reported by Liu et al. (2025). Root length was predominantly influenced by fertilisation, 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 favourable microbial habitat, collectively enhancing biological nitrogen fixation (Chang et al., 2025; Tian et al., 2025).

Physiological traits

The significant increase in SPAD values under biofertiliser 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 maximised under the recommended fertiliser 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

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physiological activity. Total dry matter accumulation was highest under biofertiliser 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 vigour 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). 1000-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 maximised 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 the BARI mash-1 variety produced favourable 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.

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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.

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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.

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SAŽETAK

Organska gnojiva i biognojiva poboljšavaju rast i prinos crnog graha

U Bangladešu je isključiva primjena mineralnih gnojiva dovela do smanjenja sadržaja organske tvari u tlu, neravnoteže hraniva i postupne degradacije zdravlja tla. Stoga je upravljanje hranivima koje uključuje primjenu organskih gnojiva i biognojiva ključno za obnovu plodnosti tla i održavanje dugoročne produktivnosti usjeva u intenzivnim poljoprivrednim sustavima. U tom je kontekstu od veljače do lipnja 2022. godine proveden poljski pokus radi procjene učinaka organskih gnojiva i biognojiva na rast, fiziološka svojstva i prinos crnog graha (*Vigna mungo* L.). Pokus je postavljen prema dvofaktorskom randomiziranom potpunom bloknom rasporedu s tri ponavljanja. Faktor A obuhvatio je tri sorte (BARI mash-1, BARI mash-3 i BARI mash-4), dok je faktor B uključivao pet tretmana upravljanja hranivima: preporučenu dozu gnojiva (PDG), kompost na bazi peradarskog gnoja (KBPG) u količini od 7,5 t ha^{-1}, biognojivo BARI, biognojivo BINA i biougljen u količini od 5 t ha^{-1}. Utvrđeni su značajni učinci sorte, načina upravljanja hranivima i njihove interakcije na većinu mjerenih pokazatelja, pri čemu se statistička značajnost razlikovala među svojstvima i fazama rasta. Primjena KBPG-a znatno je poboljšala pokazatelje rasta i prinosa, uključujući visinu biljaka, grananje, razvoj korijena, broj mahuna, prinos zrna, prinos slame, vrijednost SPAD indeksa i masu tisuću sjemenki, u pojedinim tretmanima. Među sortama, BARI mash-1 ostvarila je najbolji rezultat i najveći prinos zrna, dok je BARI mash-4 pokazala najslabiji rezultat. Interakcija čimbenika pokazala je najveći prinos sorte BARI mash-1 pri primjeni KBPG-a, dok je najmanji prinos utvrđen kod sorte BARI mash-4 pri primjeni biougljena. Ukupno gledano, primjena KBPG-a u količini od 7,5 t ha^{-1} pokazala se najučinkovitijom strategijom upravljanja hranivima za povećanje produktivnosti crnog graha u poljskim uvjetima.

Ključne riječi: *Vigna mungo*, organsko gnojivo, kompost od peradarskog gnoja, održiva poljoprivreda, plodnost tla

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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_2F1	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); V_1 = BARI Mash-1; V_2 = BARI Mash-3; V_3 = BARI Mash-4; F_1 = recommended dose of fertilizer (RDF); F_2 = poultry litter-based compost; F_3 = Bangladesh Agricultural Research Institute (BARI) biofertilizer; F_4 = Bangladesh Institute of Nuclear Agriculture (BINA) biofertilizer; and F_5 = biochar

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