



RESEARCH ARTICLE

Residual efficacy of biochar and organic-inorganic nutrient sources on growth efficiency and yield potential of green gram (*Vigna radiata* L.) under a wheat-green gram cropping system

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Abstract

The present investigation was carried out at the research farm of Lovely Professional University, Jalandhar, Punjab. The wheat–green gram field experiment was conducted to evaluate the residual effect of different biochar sources and nutrient management on growth and yield potential of green gram. The experiment was laid out in split plot design with three biochar sources i.e., paddy straw biochar (B1), red gram stover biochar (B2) and cotton stover biochar (B3) as main plot and four nutrient management practices as sub-plots, which were 100 % recommended dose of fertilisers (RDF) (N1), 70 % RDF + foliar spray (FS) of liquid compost (N2), 70 % RDF + FS of nano diammonium phosphate (DAP) (N3) and control (N4) with three replications. The results revealed that B3 recorded higher plant height, higher accumulation of biomass, leaf area index (LAI), chlorophyll index and yield attributes than other biochar sources. Similarly, the residual effect of 100 % RDF (N1) recorded significantly higher growth and yield attributes than other nutrient management practices. Therefore, the interaction treatment B3N1 recorded the significantly highest grain yield (21.92 q ha⁻¹) and straw yield (40.52 q ha⁻¹). However, 70 % RDF with liquid compost or nano DAP can also be used to supplement or partially substitute for synthetic fertilisers and act as a sustainable crop production system. These findings highlight the potential of biochar blended nutrient management in optimising green gram productivity while reducing dependence on synthetic fertilisers.

Keywords: biochar; nutrient management; optimising; residual effect; sustainable crop production

Introduction

Intensive cropping systems face growing challenges of soil nutrient depletion, declining organic matter and over-dependence on synthetic fertilisers, all of which threaten long-term agricultural sustainability. In cereal-legume rotations such as wheat-green gram, maintaining soil fertility across successive crops is particularly critical, as the succeeding crop receives no fresh fertiliser input and relies entirely on residual soil nutrients. Addressing these challenges requires soil amendments that can deliver sustained nutritional benefits beyond a single growing season. Biochar, a carbon (C)-rich porous material produced by pyrolysis of organic biomass under low-oxygen conditions, has emerged as a promising long-term soil amendment. With a C content of 65–90 %, it improves soil structure, enhances water and nutrient retention, increases cation exchange capacity, reduces leaching losses and stimulates beneficial microbial activity (1). Crucially, its recalcitrant aromatic structure resists rapid decomposition, enabling residual effects that persist across multiple crop cycles by positively influencing soil moisture dynamics, nutrient availability and microbial communities long after initial application (2).

These residual properties are particularly relevant for green gram (*Vigna radiata* L.), a pulse crop of major economic and nutritional significance. India, the world's largest producer and consumer of pulses, cultivates green gram over approximately 1.56 million hectares with a record production of 2.1 MT in 2022–23 (3, 4). Green gram depends on symbiotic nitrogen (N) fixation and adequate soil nutrient availability for optimal growth and yield. Residual biochar in the soil can act as a slow-release nutrient reservoir, support rhizobial activity and buffer soil pH, collectively creating a more favourable rooting environment for succeeding legume crops (5, 6).

Beyond biochar, the choice of nutrient management in the preceding crop also exerts significant residual influence on the succeeding crop. Integrated nutrient management (INM), which combines organic and inorganic nutrient sources, improves soil nutrient pools, enhances biological activity and sustains fertility across cropping seasons (7). In cereal-legume rotations, residual N from inorganic fertilisers and organic manures applied to the preceding crop has been shown to positively influence dry matter accumulation (DMA), yield attributes and overall productivity of the following legume crop (8). Emerging nutrient sources such as liquid

compost and nano diammonium phosphate (DAP), which offer high nutrient use efficiency through rapid foliar absorption, hold additional promise as partial substitutes for conventional inorganic fertilisers in such systems.

Despite growing evidence on the individual benefits of biochar and INM, information on the combined residual effects of different biochar feedstock sources and organic-inorganic nutrient combinations on succeeding green gram under a wheat-green gram cropping system remains limited. The comparative residual performance of different biochar feedstocks (paddy straw, (B1) red gram stover (B2) and cotton stover (B3)) alongside organic and inorganic nutrient sources on a zero-tillage legume crop has not been adequately studied in the Indo-Gangetic Plains agro-climatic context.

Therefore, the present investigation was carried out with the following objectives: (i) to evaluate the residual effect of three biochar sources applied to the preceding wheat crop on growth attributes, yield attributes and grain yield of succeeding green gram; (ii) to assess the residual influence of four nutrient management practices (100 % recommended dose of fertilisers (RDF), 70 % RDF + liquid compost, 70 % RDF + nano DAP and control) on green gram productivity; and (iii) to identify the best combination of biochar source and nutrient management for optimising green gram yield under a wheat-green gram cropping system with zero-tillage conditions.

Materials and Methods

Description of the experimental site

The experiment was carried out at experimental farm Lovely Professional University, Jalandhar, Punjab. This field has an average elevation of 252 m above mean sea level (AMSL) and is located at 31°22'31.81" N latitude and 75°23'03.02" E longitude. Data on the weather gathered from November 2024 to July 2025 revealed significant seasonal fluctuation in temperature, humidity,

precipitation and evaporation. The highest temperature ranged from 9.79–44.90 °C and the lowest temperature ranged from 2.16–1.60 °C. The average maximum and minimum temperatures were 29.46 and 16.10 °C respectively. Relative humidity remained usually high and peaked at 98 %. Events involving rainfall were sporadic; the most daily rainfall measured was 32 mm (Fig. 1). With evaporation fluctuating between 0 and 10.5 mm, there was evidence of greater atmospheric need over the summer months. The data showed a shift from frigid winter temperatures to hot and muggy monsoon weather. The experimental site was characterised by sandy loam soil texture, comprising 75 % sand, 10.3 % silt and 14.7 % clay. The soil exhibited with pH of 7.6, electric conductivity of 0.30 dS m⁻¹ and the organic carbon (OC) content was moderate i.e. 0.34 %. Available N was low (180 kg ha⁻¹), whereas available phosphorus (P) and potassium (K) were 22 and 184 kg ha⁻¹ respectively. The field experiment was conducted using split plot design with three main factors during preceding wheat cultivation (B1, B2 and B3) which was applied at the rate of 5 t ha⁻¹ and all three biochar sources were purchased from Ekokrishi Solutions, Nandurbar, Maharashtra and four sub factors (N1: 100 % RDF through inorganic fertiliser, N2: 70 % RDF + two foliar spray (FS) of liquid compost at 30 and 60 days after sowing (DAS), N3: 70 % RDF + two FS of nano DAP at 30 and 60 DAS at the rate of 4 mL L⁻¹ (N3) having ultra-small particle size of less than 100 nm and N4: control) with three replications (Table 1). An organic liquid formulation was prepared by using kitchen waste and animal dung, with each ingredient added at 2 kg. Sixteen liters of water were added and the mixture was fermented for 30 days in an airtight container. The mixture was stirred at 5 days interval. After 30 days, the mixture was filtered through a muslin cloth, an extract collect in clean container. The preceding wheat crop was used seed rate of 100 kg ha⁻¹ of variety DBW222 were drilled at a depth of 4 cm with planting geometry of 22.5×10 cm and the RDF at the rate of 120:60:40 kg ha⁻¹ of N : P : K was followed. The full doses of P, K and 50 % of the N were applied at the time of sowing and the remaining 50 % of the N was applied in two splits, one at crown initiation stage and the other at

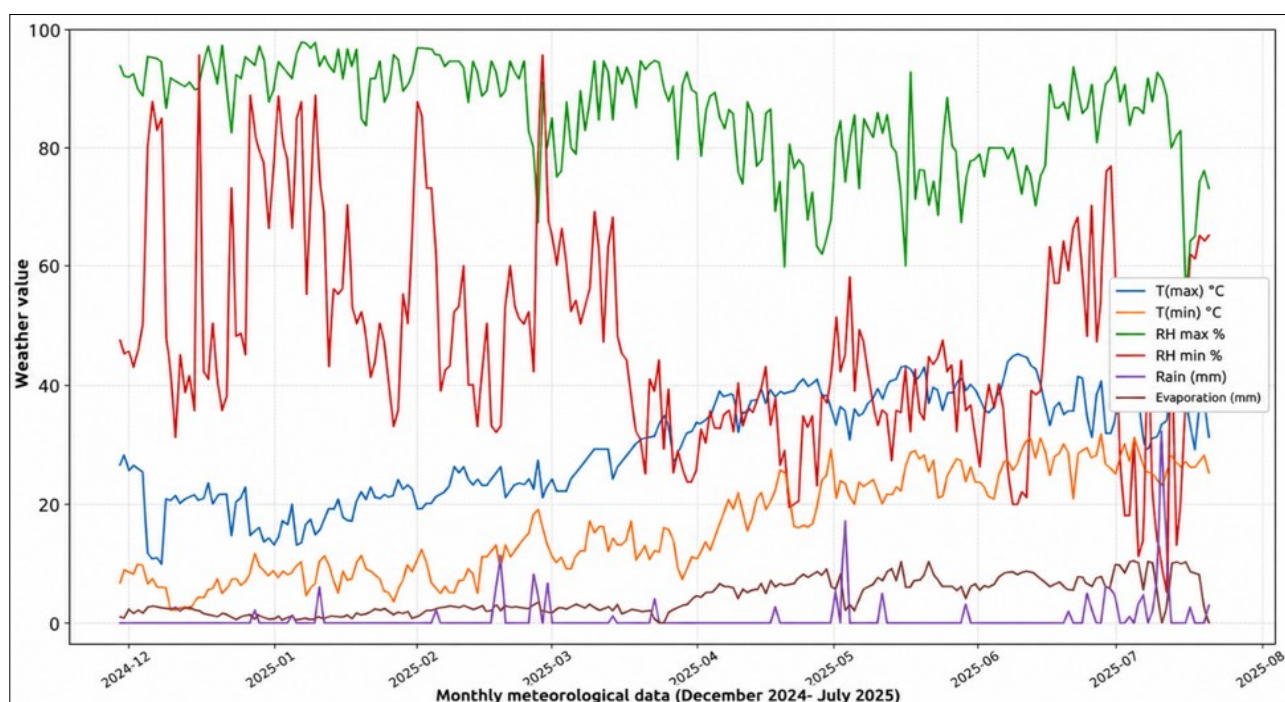


Fig. 1. Weather of the experimental site during both cropping seasons (2024–25).

T(max): maximum temperature; T(min): minimum temperature; RH max: maximum relative humidity; RH min: minimum relative humidity.

Table 1. Treatment details of the application of biochar sources and nutrient management impact on succeeding green gram under wheat-green gram cropping system

Treatment	Treatment combination	Green gram crop cultivation details
B1N1	Paddy biochar + 100 % RDF	Green gram variety Vishwas Mahi was grown after wheat to study residual effects of biochar and nutrient sources. It was sown under zero tillage at 30 × 10 cm spacing without applying fertilisers.
B1N2	Paddy biochar + 70 % RDF + liquid compost	
B1N3	Paddy biochar + 70 % RDF + nano DAP	
B1N4	Paddy biochar + control	
B2N1	Red gram biochar + 100 % RDF	
B2N2	Red gram biochar + 70 % RDF + liquid compost	
B2N3	Red gram biochar + 70 % RDF + nano DAP	
B2N4	Red gram biochar + control	
B3N1	Cotton biochar + 100 % RDF	
B3N2	Cotton biochar + 70 % RDF + liquid compost	
B3N3	Cotton biochar + 70 % RDF + nano DAP	
B3N4	Cotton biochar + control	

RDF: recommended dose of fertiliser; DAP: diammonium phosphate.

tillering stage. The same treatment layout was retained for the succeeding green gram crop for assessing the residual effect of biochar and nutrient sources applied to previous wheat. The green gram variety Vishwas Mahi was cultivated with 30 × 10 cm and sown under zero tillage after wheat harvesting along with no application of fertiliser doses, to all treatment plots.

Statistical analysis

Fisher's analysis of variance technique was employed to analyse and interpret the data following the guidelines (9). A significance level of $p = 0.05$ was utilised for both *F*-tests and *t*-tests. Critical differences were computed whenever the *F*-tests yielded significant results. OPSTAT online software version 6.8 was used to test the least significant difference (LSD) between the treatment means.

Results and Discussion

Effect of biochar sources growth and development of green gram

The mean values of the growth attributes showed significant differences among treatments, influenced by the residual effects of the biochar sources during 2025–26 (Table 2). At harvest, the significantly greatest plant height and DMA were recorded in B3 (56.24 cm) (25.14 g), followed by B2 (54.71 cm) (24.52 g) which was statistically at par with B3 and B1 (52.86 cm) (21.82 g) showed the significantly lowest value of plant height and DMA. The application of B3 increased plant height and DMA by 6.40 and 15.17 % compared to B1. Plant height and DMA were significantly increased by the imposed treatments at all stages of crop growth. It might be attributed to the residual effect of biochar providing better growing conditions to crop by continuous supply of nutrients and improvement of soil properties. The variation in growth parameters was considered to be due to variation in the availability of major nutrients. Increase in the effective microorganisms in the soils increases the mineralisation. This was supported by earlier study (6). Biochar's effectiveness fades over time, its residual effects demonstrate its potential as a long-term strategy for optimising nutrient management and reducing fertiliser inputs (10). The amount of chlorophyll in the leaf is an indicator of the plant's photosynthetic efficiency, which has a direct impact on crop growth and yield. Chlorophyll not only depends on light exposure but also depends on proper nutrient presence. Significantly higher reading of

chlorophyll index was observed in B3 (41.84), followed by B2 (41.53). The significantly lowest chlorophyll index was noticed under B1 (41.22). Chlorophyll index increased in B3 application by 1.50 and 0.74 % over B1 and B2. Biochar's porous structure provides habitat for soil microbes, boosting microbial activity and organic matter mineralisation. This enhances nutrient availability and supports sustainable nutrient cycling, promoting efficient nutrient use in wheat-based cropping systems (11). Among the three sources of biochar, B3 showed the significantly highest value of leaf area index (LAI) i.e. (4.37) followed by B2 (4.11) and B1 (4.02). At the same time, biochar can reduce the leaching of soil nitrate-nitrogen, improve the soil's nitrate carrying capacity and reduce the soil nitrate reductase activity, soil denitrification intensity and soil nitrogen oxide flux, so as to slow down the loss of soil nitrate-nitrogen, thereby maintaining the nitrogen use efficiency (NUE) of crops and promoting the increase of plant biomass (12, 13).

Nutrient management effect on growth and development of green gram

Residual effect of nutrient management significantly influenced on growth parameter of green gram during 2025–26 (Table 2). Significantly, the greatest plant height and DMA were recorded in N1 (58.66 cm) (26.95 g), followed by N2 (55.64 cm) (25.83 g) which was on par with N3 (55.16 cm) (24.20 g) and the significantly lowest plant height and DMA were recorded in N4 (48.94 cm) (18.33 g). Similarly residual effect of applying 100 % RDF resulted in an increase in plant height by 5.42 %, 6.35 % and 19.88 % compared to 70 % RDF with 2 FS of liquid compost, 70 % RDF with 2 FS of nano DAP and the control respectively. Higher organic nutrition in the preceding crop improved residual nutrients for moong, enhancing carbohydrate-to-protein conversion. This promoted protoplasm and cell wall development, increasing cell size, plant height and DMA. Similar findings in succeeding in crop due to application of higher doses of organic applied to previous crop have been reported in earlier studies (14, 15). A similar trend was observed for LAI. The significantly greatest LAI (4.67) was recorded under N1, followed by N2 (4.22) which was statistically on par with N3 (4.06) and significantly lower values were recorded in N4 (3.70) respectively. The residual effect of soybean row patterns with nutrient combinations enhanced succeeding fodder oat and reduced dependency on synthetic fertilisers while sustaining productivity (16). The chlorophyll index observed under the N1 was 11.53 %

higher than N4. Application of RDF, liquid compost and nano DAP, which allow for rapid and efficient absorption through plant surfaces, stomata, or roots, resulting in improved nutrient use efficiency compared to conventional granular fertilisers. The nutrient released by manure and fertiliser towards the post-anthesis stage in succeeding crop wheat. Thus, the nutrients were available to develop the site of photosynthesis, thereby aiding yield development of the crop. Additionally, synergistic application of both organic and inorganic fertilisers may provide a sufficient level of nutrition which takes part in biosynthesis of chlorophyll (17).

Interaction effect on growth and development of green gram

The interaction between the residual effect of application of biochar sources and nutrient management sources had a positive impact on the growth attributes of green gram (Table 2). The significantly highest plant height was recorded in B3N1 (60.46 cm), which was statistically at par with B2N1 (58.97 cm) and followed by B1N1 (56.56 cm), B3N2 (56.31 cm) and B3N3 (56.09 cm) indicating that these combinations promoted superior vegetative growth followed by B2N2 (55.66 cm) and B1N2 (54.96 cm) suggesting a consistent positive response to intermediate nutrient levels across different biochar treatments. On the other hand, the lowest plant height was observed in B1N4 (45.22 cm), which was significantly lower than all other treatment combinations. Biochar adsorbs nutrients like ammonium and phosphate, reducing leaching and altering nutrient availability. Initially, it may immobilise nutrients, but over time, it functions as a slow-release source and microbial substrate, explaining delayed yield benefits in later crops (18). A similar trend followed in DMA. The maximum DMA was recorded under the treatment combination B3N1 (27.12 g), which was statistically at par with B2N1 (26.93 g), B1N1 (26.82 g), B3N2 (26.52 g), B3N3 (26.40 g),

B2N2 (25.78 g), B1N2 (25.18 g) and B2N3 (24.89 g). These treatment combinations demonstrated superior vegetative growth which leads to greater biomass production as evidenced by higher DMA. This was followed by B1N3 (21.30 g), which also exhibited appreciable performance, suggesting a favourable response to moderate nutrient levels across various biochar treatments. Conversely, the significantly lowest DMA was recorded in B1N4 (14.00 g). These values were significantly lower than those of the other treatment combinations. Biochar alters soil microbial communities and enzyme activities, with lasting effects that influence nutrient mineralisation. Increased microbial biomass and shifts toward P-mineralising or N-immobilising microbes have been observed month to year after application (19). The highest chlorophyll index was recorded under B3N1 (43.26), which was statistically at par with B2N1 (43.09), indicating that these combinations were most effective in enhancing chlorophyll content. Other treatment combinations, such as B1N1 (42.96), B3N2 (42.55), B3N3 (42.43), B2N2 (42.21), B1N2 (42.14), B2N3 (41.97) and B1N3 (41.80), also showed relatively higher chlorophyll index values, though slightly lower than the top-performing treatments. Combined biochar and organic amendments offer synergistic residual benefits: biochar enhances nutrient retention and reduces leaching, while labile nutrients from compost or manure support soil biological activity, leading to improved wheat growth in durum wheat and rice-wheat systems (1). In contrast, the lowest chlorophyll content was observed in B1N4 (37.99), which was closely similar to B2N4 (38.85) and B3N4 (39.11). Under LAI, significantly highest value was observed in B3N1 (4.71) which was on par with B2N1 (4.68), B1N1 (4.62), B3N2 (4.54) and B3N3 (4.45). But on the other hand, significantly lowest LAI was found in treatment combination B1N4 (3.59) which was closely related to B2N4 (3.75)

Table 2. Residual effect of biochar sources and nutrient management on growth attributes of green gram wheat-green gram cropping system during 2024–25

Treatments	Plant height (cm)	DMA (g)	LAI	SPAD
Biochar sources				
B1-Paddy straw biochar	52.86 ± 5.16	21.82 ± 5.71	4.02 ± 0.44	41.22 ± 2.21
B2-Red gram stover biochar	54.71 ± 3.93	24.52 ± 2.82	4.11 ± 0.40	41.53 ± 1.85
B3-Cotton stover biochar	56.24 ± 3.42	25.14 ± 3.10	4.37 ± 0.41	41.84 ± 1.86
SEm (±)	0.46	0.38	0.05	0.06
CD ($p = 0.05$)	1.80	1.51	0.21	0.24
Nutrient management				
N1-100 % RDF	58.66 ± 1.97	26.95 ± 0.15	4.67 ± 0.05	43.10 ± 0.15
N2-70 % RDF + FS liquid compost	55.64 ± 0.67	25.83 ± 0.67	4.22 ± 0.28	42.30 ± 0.22
N3-70 % RDF + FS nano DAP	55.16 ± 0.81	24.20 ± 2.62	4.06 ± 0.34	42.07 ± 0.33
N4-control	48.94 ± 3.47	18.33 ± 3.75	3.70 ± 0.10	38.65 ± 0.59
SEm (±)	0.44	0.55	0.085	0.09
C.D. ($p = 0.05$)	1.33	1.62	0.252	0.27
Interaction				
B1N1	56.56 ± 0.50	26.82 ± 1.07	4.62 ± 0.25	42.96 ± 0.44
B1N2	54.96 ± 0.58	25.18 ± 1.42	4.03 ± 0.11	42.14 ± 0.31
B1N3	54.68 ± 0.50	21.30 ± 1.00	3.84 ± 0.13	41.80 ± 0.41
B1N4	45.22 ± 2.53	14.00 ± 0.70	3.59 ± 0.08	37.99 ± 0.08
B2N1	58.97 ± 0.93	26.93 ± 0.83	4.68 ± 0.18	43.09 ± 0.05
B2N2	55.66 ± 0.49	25.78 ± 0.58	4.10 ± 0.19	42.21 ± 0.28
B2N3	54.71 ± 0.47	24.89 ± 1.43	3.91 ± 0.20	41.97 ± 0.33
B2N4	49.49 ± 1.66	20.47 ± 2.02	3.75 ± 0.43	38.85 ± 0.18
B3N1	60.46 ± 1.24	27.12 ± 1.53	4.71 ± 0.27	43.26 ± 0.26
B3N2	56.31 ± 0.88	26.52 ± 1.68	4.54 ± 0.25	42.55 ± 0.43
B3N3	56.09 ± 0.23	26.40 ± 1.63	4.45 ± 0.33	42.43 ± 0.11
B3N4	52.10 ± 2.96	20.51 ± 3.05	3.77 ± 0.23	39.11 ± 0.26
SEm (±)	0.82	0.90	0.14	0.15
CD ($p = 0.05$)	2.42	2.69	0.41	0.44

DMA: dry matter accumulation; LAI: leaf area index; SPAD: soil plant analysis development.

and B3N4 (3.77). In rice-wheat systems, biochar reduces N leaching and nitrous oxide (N_2O) emissions, enhancing fertiliser N retention and subsequent wheat N recovery, especially with optimised N application. Effects vary with biochar feedstock and pyrolysis temperature, which affect surface chemistry and nutrient sorption (20).

Biochar sources effect on yield attributes and the yield of green gram

The test weight values observed with residual effect of cotton and B2 were found to be closely related and generally higher compared to those recorded with B1 (Table 3). Among the treatments, the significantly highest test weight was recorded in B3 (46.82 g), followed by B2 (46.28 g), while the lowest value was observed under B1. In this study, the most significant results were observed with a fresh biochar application at a dose of 5 t ha^{-1} . Meanwhile, a 10 t ha^{-1} biochar application significantly enhanced growth in one-season-old biochar, whereas the optimum result for two-season-old biochar was achieved (10). The mean values of the yield parameters demonstrated that different biochar sources had significant impacts on succeeding green gram. The significantly highest grain and straw yield was recorded in B3 (18.57 q ha^{-1}) (37.80 q ha^{-1}), which was statistically on par with B2 (17.32 q ha^{-1}) (37.15 q ha^{-1}). The significantly lowest grain and straw yield was recorded in B1 (16.75 q ha^{-1}) (35.00 q ha^{-1}). The use of B3 resulted in a 7.20 and 10.84 % increase in grain yield and 1.75 and 8 % increase in straw yield as compared to red gram and B1 respectively. Biochar's stable aromatic structure resists decomposition, enhancing long-term soil organic carbon (SOC) storage and influencing SOC dynamics, aggregate stability, water retention and nutrient buffering, thereby benefiting soil quality and crop performance over years to decades (21). The B3 increased number of pods per plant over B2 and B1 by 3.67 and 5.39 %. In drought-prone environments, residual improvements in soil water retention after biochar application have supported greater root proliferation and drought resilience in subsequent wheat seasons, enhancing yields under water stress. Long-term successive applications further amplified these effects (19). The significantly highest number of numbers of grain per pod was recorded under B3 (9.42 no.), followed by B2 (8.42 no.). The lowest number of grains per spike was recorded in B1 (8.08 no.). The B3 increased number of grains per pod over B2 and paddy stover biochar by 11.87 and 16.49 %. Biochar's porous structure and low bulk density enhance soil porosity, reduce compaction and improve water retention, promoting root growth and water availability, especially in coarse or drought-prone soils, with lasting effects observed in long-term field trials (22).

Nutrient management effect

There was significant difference in various yields attributing characters of green gram with respect to nutrient combinations applied to preceding wheat crops (Table 3). The residual effect of nutrient combinations on the number of grains per pod and number of pod per plant was recorded the significantly highest under N1 (11.11 no.) (40.11 no.) due to the balanced supply of macronutrients through NPK promoted optimal vegetative and reproductive growth, resulting in improved spike development and grain setting and was followed by N2 (9.00 no.) (37.89 no.) which was statistically at par with N3 (8.11 no.) (36.78 no.) and the significantly lowest values for number of grains per pod and number of pod per plant of green gram was recorded in N4 (6.33 no.) (30.89 no.). Among the

nutrient management approaches evaluated, foliar application of plant-based NPK extracts led to the highest yields, with nano-NPK and homemade NPK sprays performing slightly lower (23). Similar findings of residual effect of 100 % RDF + organic fertilisers applied to previous kharif rice crop recorded significantly higher yield attributes, seed and stover yields and economic of succeeding broad bean (24). Under different nutrient management practices, all nutrient combinations resulted in nearly similar test weight compared to those of the control (N4). The test weight observed under the N1 treatment (100 % RDF) was 8.22 % higher compared to the N4 treatment (control). The plant extract may contain higher levels of micronutrients, which boost nutrient efficiency within the plant's metabolic processes. A similar result was found previously (25–27). Significantly, the highest grain and straw yield was recorded in N1 (20.17 and 40.17 q ha^{-1}), followed by N2 (17.51 and 37.51 q ha^{-1}) which was statistically on par with N3 (17.36 and 36.51 q ha^{-1}) and the lowest grain and straw yield was recorded in N4. The integrated application of mineral and organic NPK inputs enhances soil N availability and stimulates the activity of soil enzymes involved in organic matter formation. This, in turn, improves soil fertility, promotes aggregate formation and positively influences wheat yield (28). The use of 100 % RDF using inorganic sources gave the best growth and yield. Close behind this was liquid compost and nano DAP spray which are bio-stimulants and help in the sustainability of agriculture (29). Among the nutrient sources, the application of 70 % RDF combined with two foliar applications of plant extract resulted in significantly improved growth and yield attributes (30).

Interaction effect

The yield and yield parameter showed positive influence on interaction between the residual effect of different biochar and nutrient sources (Table 3). A gradual decrease in the number of grains per pod and number of pods per plant were observed with the reduction in N levels from N2 to N3 under each biochar treatment, along with the application of liquid compost and nano DAP but the results were comparable between them. The lowest grain number per pod and pod number per plant was recorded in treatment B1N4 (6.00 no.) (30.56 no.). Recent field studies, including Mediterranean and long-term wheat rotations, show that biochar applied in earlier seasons enhances later wheat yields, spike density and grain weight-especially when combined with compost or NPK-by improving soil chemical and biological properties over time (1). The maximum test weight (48.32 g) was observed under the B3N1 treatment, which was significantly higher than all other treatment combinations. This was followed by B2N1 and B1N1, which also recorded comparatively higher values and were within a similar range, although they differed statistically. The minimum test weight was recorded under the B1N4 (43.71 g) treatment. Wheat-maize rotations are globally widespread, particularly in regions with variable water supplies and soil types. These systems benefit from biochar and nutrient interventions as follows: De-ashed biochar-based slow-release fertilisers (BSRFs) improve NUE, raising wheat and maize grain yields by up to 12 and 21 % respectively, while allowing for reductions in synthetic N application by approximately 25 % (31). Among the different treatment combinations, the highest grain yield was obtained under B3N1 (21.92 q ha^{-1}), which was statistically at par with B2N1. This indicates that these treatments favoured better reproductive growth of the crops which contributed to yield increment. The treatments

Table 3. Residual effect of biochar sources and nutrient management on yield attributes and yield of green gram under wheat-green gram cropping system during 2024–25

Treatment details	No. of grains pod ⁻¹	No. of pods plant ⁻¹	Test weight (g)	Grain yield (q ha ⁻¹)	Stover yield (q ha ⁻¹)
Biochar sources					
B1-Paddy straw biochar	8.08 ± 1.97	35.58 ± 3.75	45.90 ± 1.63	16.75 ± 1.90	35.00 ± 4.98
B2-Red gram stover biochar	8.42 ± 1.97	36.17 ± 3.85	46.28 ± 1.47	17.32 ± 2.46	37.15 ± 2.42
B3-Cotton stover biochar	9.42 ± 2.08	37.50 ± 4.28	46.82 ± 1.49	18.57 ± 2.24	37.80 ± 2.36
SEm(±)	0.22	0.35	0.04	0.32	0.44
CD (<i>p</i> = 0.05)	0.86	1.38	0.14	1.27	1.72
Nutrient management					
N1-100 % RDF	11.11 ± 0.51	40.11 ± 0.62	47.92 ± 0.38	20.17 ± 1.78	40.17 ± 0.35
N2-70 % RDF + liquid compost	9.00 ± 0.88	37.89 ± 1.42	46.86 ± 0.41	17.51 ± 0.15	37.51 ± 0.50
N3-70 % RDF + nano DAP	8.11 ± 1.07	36.78 ± 1.57	46.28 ± 0.55	17.36 ± 0.11	36.51 ± 1.48
N4-control	6.33 ± 0.33	30.89 ± 0.33	44.28 ± 0.54	15.15 ± 0.80	32.40 ± 3.67
SEm (±)	0.48	0.46	0.05	0.35	0.51
CD (<i>p</i> = 0.05)	1.44	1.37	0.16	1.04	1.50
Interaction					
B1N1	10.67 ± 1.53	39.56 ± 1.39	47.57 ± 0.10	18.36 ± 1.25	39.83 ± 1.08
B1N2	8.33 ± 1.15	36.67 ± 1.20	46.50 ± 0.38	17.41 ± 1.21	37.09 ± 1.94
B1N3	7.33 ± 1.15	35.56 ± 2.72	45.82 ± 0.31	17.24 ± 0.72	34.92 ± 1.49
B1N4	6.00 ± 1.00	30.56 ± 1.35	43.71 ± 0.14	14.00 ± 0.70	28.17 ± 0.20
B2N1	11.00 ± 1.00	40.00 ± 1.45	47.88 ± 0.07	20.24 ± 1.06	40.16 ± 0.79
B2N2	8.67 ± 1.53	37.56 ± 1.65	46.78 ± 0.39	17.43 ± 0.63	37.39 ± 1.75
B2N3	7.67 ± 1.53	36.22 ± 1.50	46.12 ± 0.15	17.39 ± 0.93	36.76 ± 1.60
B2N4	6.33 ± 1.53	30.89 ± 2.59	44.36 ± 0.14	14.23 ± 0.93	34.28 ± 1.11
B3N1	11.67 ± 1.53	40.78 ± 0.77	48.32 ± 0.21	21.92 ± 1.69	40.52 ± 1.03
B3N2	10.00 ± 1.00	39.44 ± 2.88	47.30 ± 0.39	17.69 ± 0.86	38.07 ± 2.43
B3N3	9.33 ± 1.53	38.55 ± 2.34	46.89 ± 0.15	17.46 ± 0.66	37.86 ± 2.43
B3N4	6.67 ± 1.53	31.22 ± 1.95	44.78 ± 0.30	17.22 ± 1.09	34.75 ± 1.49
SEm (±)	0.76	0.78	0.09	0.62	0.88
C.D. (<i>p</i> = 0.05)	2.25	2.31	0.26	1.83	2.60

RDF: recommended dose of fertiliser; DAP: diammomium phosphate.

B1N1, B3N2, B3N3, B2N2 and B1N2, B2N3 and B1N3 recorded comparatively lower yields but still reflected a positive response to moderate nutrient levels under different biochar treatments. In contrast, the lowest grain and straw yields were recorded under the B1N4 treatment. Studies and meta-analyses show biochar combined with mineral fertiliser enhances yields more than biochar alone, as it improves fertiliser use efficiency through reduced leaching and better nutrient retention, with residual benefits increasing when integrated into optimised fertiliser programs (32). The treatment combination for straw yield, B3N1 showed significantly highest value (40.52 q ha⁻¹) which was statistically at par with B2N1 (40.16 q ha⁻¹), B1N1 (39.83 q ha⁻¹), B3N2 (38.07 q ha⁻¹) and B3N3 (37.86 q ha⁻¹). On the other hand, significantly lowest straw yield was noticed under treatment combination B1N4 (28.17 q ha⁻¹). The residual biochar alone or combined with different levels of K application increased yield of succeeding maize. Residual biochar increased availability of N, P, K, calcium (Ca) and sodium (Na) in the soil (33).

Correlation studies

Correlation analysis revealed significant positive associations among growth and yield parameters (Fig. 2). Plant height exhibited strong positive correlations with SPAD (*r* = 0.944), DMA (*r* = 0.931) and grain yield (*r* = 0.929). Test weight showed the strongest correlation with number of pods per plant (*r* = 0.986) and grains per pod (*r* = 0.967), indicating that yield improvement was strongly influenced by these yield attributes.

Conclusion

Residual biochar and nutrient management applied to preceding

wheat significantly influenced growth dynamics, yield attributes and productivity of succeeding green gram. Cotton stover biochar (B3) outperformed other sources, increasing chlorophyll index by 0.74–1.49 % and test weight by 1.16–2.01 % over red gram stover (B2) and paddy straw biochar (B1). Among nutrient treatments, 100 % recommended dose of fertilisers (RDF) recorded the highest growth and yield, while 70 % RDF with liquid compost enhanced grain yield by 13.18 % and straw yield by 6.62 %, with liquid compost and nano diammomium phosphate (DAP) functioning as effective bio-stimulants supporting sustainable production. The treatment combination of B3 with 100 % RDF proved most effective, achieving maximum grain yield of 21.92 q ha⁻¹ and straw yield of 40.52 q ha⁻¹. Importantly, replacing the 30 % inorganic fertiliser deficit with liquid compost or nano DAP spray is a practical and sustainable alternative for optimising green gram yield under the wheat-green gram cropping system. Future research should explore residual biochar effects across multiple crop cycles, varying application rates and pyrolysis temperatures and alternative bio-stimulants such as seaweed extract and humic acid, alongside investigations into soil microbial diversity, enzyme activity and carbon (C) sequestration potential.

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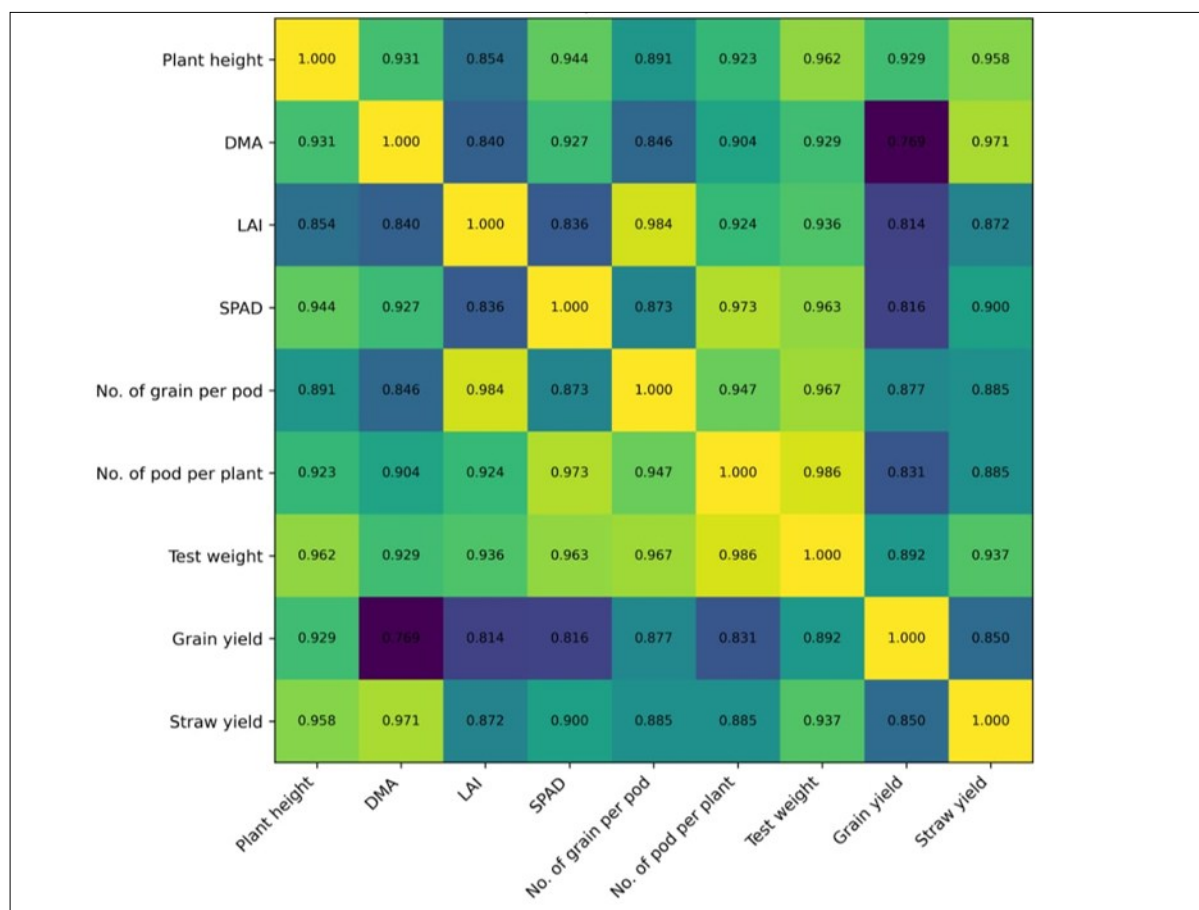


Fig. 2. Relationship between growth, yield parameters and yield of green gram under wheat-green gram cropping system during 2024–25.

DMA: dry matter accumulation; LAI: leaf area index; SPAD: soil plant analysis development.

Authors' contributions

VDJ carried out conceptualisation, methodology, investigation, data curation and writing-original draft. SK carried out supervision, visualisation, validation, writing-original draft and editing. VDJ and SK are participated in the formal analysis, writing review and editing. Both authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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