PLANT SCIENCE TODAY
Vol 12(sp4): 01–18
https://doi.org/10.14719/pst.11006

eISSN 2348-1900

RESEARCH ARTICLE

Impact of tillage and weed management strategies on growth, physiology and yield of summer black gram and soil microbial populations

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Received: 31 July 2025; Accepted: 26 September 2025; Available online: Version 1.0: 08 December 2025

Cite this article: Jagruti T, Prabhasmita S, Kaushik KP, Rabiratna D, Ipsita K, Ayesha M, Rajkumari B. Impact of tillage and weed management strategies on growth, physiology and yield of summer blackgram and soil microbial populations. Plant Science Today. 2025;12(sp4):01–18. https://doi.org/10.14719/pst.11006

Abstract

A field experiment was conducted at Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India, during the summer of 2024 to evaluate the impact of different tillage and weed management practices on black gram (BG). The study was comprised of four tillage practices, namely conventional tillage (CT), zero tillage (ZT), CT with residue (R) (CT+R) and ZT with residue (ZT+R) in the main plots and three weed management practices, namely H_1 (application of pendimethalin at 750 g ha^{-1} followed by imazethapyr at 70 g ha^{-1}), H_2 (H_1+ one hand weeding) and H_3(weedy check) in sub-plots, laid out in a split plot design with three replications. Various morphological, physiological, biochemical, yield parameters and soil microbial populations were studied at different growth stages of black gram. The results revealed that CT+R recorded the most significant positive effects on growth, physiological, biochemical and yield parameters, outperforming ZT in many aspects. Weed management practices, particularly H_2, enhanced crop performance by reducing weed interference. Notably, CT+R increased the total chlorophyll content by 35 % over ZT, while H_2 increased it by 34.2 % compared to H_3. Overall, the combination of CT +R and H_2 gave the maximum seed yield (1195.67 kg ha^{-1}), whereas the lowest yield (577.7 kg ha^{-1}) was recorded under ZT with H_3. Thus, CT+R combined with H_2 is recommended for optimizing the seed yield of black gram under summer conditions of Odisha.

Keywords: crop residue application; integrated weed management; tillage-weed management interaction; *Vigna mungo* L.

Introduction

Black gram *Vigna mungo* L., Family: Fabaceae) is India's fourth most important pulse crop with 8 % of the total pulse area. India is the largest producer and consumer of black gram, accounting for over 70 % of global production. The area under black gram cultivation in India is approximately 4.5 million ha, with an annual production of around 2.8 mt (1). Black gram is highly valued for its rich nutritional profile, making it an essential component of a balanced diet. It is rich in protein, carbohydrate, fats, vitamins and amino acids, which are essential for humans and for making animal feeds (2). Additionally, it is a good source of dietary fiber, which aids in digestion and helps maintain a healthy weight. Moreover, it is rich in antioxidants, particularly phenolic compounds, which help reduce oxidative stress and lower the risk of chronic diseases like heart disease and diabetes.

As a summer crop, black gram faces various challenges, including soil management and weed competition, which significantly impact its growth and physiological and biochemical processes. One of the key agricultural practices that significantly influences these factors is tillage. Tillage is essential in preparing the soil for planting, controlling weeds and incorporating organic matter into the soil profile. Different tillage practices can directly impact the soil's physical structure, nutrient availability, moisture retention and microbial activity - all of which are critical for the growth and development of black gram plants (3).

The tillage process alters the soil environment, consequently affecting crop performance. Research has shown that reduced tillage can enhance soil microfauna populations and improve soil health (4). In relation to black gram cultivation, the choice of tillage system can shape the soil environment in ways that either support or hinder the crop's physiological processes. For instance, studies have demonstrated that implementing conservation tillage practices can improve soil organic carbon dynamics, which are essential for sustaining soil fertility and structure, thus providing a favourable growth medium for crops like black gram (5). Conversely, intensive tillage practices might lead to short-term benefits in terms of weed control but could degrade soil health and reduce the long-term productivity of black gram due to soil compaction and erosion (6).

Weed management is another crucial element that affects the growth of black gram. Effective weed control reduces competition for essential resources such as light, water and nutrients, which are fundamental to crop success. Black gram is not a very good competitor against weeds (7). Weeds can cause yield loss ranging from 41.6 % to 64.1 % (8). Early weed control is crucial to ensure proper crop growth and productivity because weeds cause severe competition with black gram during the early stages of growth, particularly between three and six weeks after sowing (9). The first 20 to 40 days after sowing (DAS) are crucial for weed competition in black gram and depending on the type and severity of weed flora, season-long weed competition has been shown to diminish black gram yield by 27 % to 64 % (10).

Weed emergence in black gram begins simultaneously with crop emergence, causing crop-weed competition from the start, reducing yields by 78 % and leading to total crop failure (11). Uncontrolled weed decreases BG grain yield by 29 % to 62 % and deplete significant soil nutrients (12, 13). Weeds negatively impact various physiological processes in crops through competition. They reduce photosynthesis by shading crops. Weeds also compete for water, resulting in reduced water uptake, lower transpiration and decreased water use efficiency in crops. They also deplete soil nutrients, leading to stunted crop growth and impairing nutrient absorption. Weeds can release chemicals that disrupt phytohormones, further hindering growth. These effects lead to increased crop respiration, reduced biomass, delayed maturation and lower yields. Hence, effective weed management is vital for maintaining crop health and performance. Various weed management strategies, such as manual weeding, mechanical weeding and herbicides, are employed to control weed population. Each method has advantages and limitations and its effectiveness can vary depending on the tillage system used. Herbicides are currently the sole solution to address the high weed infestation in conservation agriculture caused by the presence of weed seed in the upper layer of soil due to no tillage operations (14). Integrated weed management approaches, which combine multiple strategies, have been recommended as a sustainable way to manage weed populations and increase crop productivity (15).

Implementing various tillage practices can influence the incidence and growth of weeds in agricultural settings. For example, reduced tillage systems have been shown to increase weed pressure as crop residues that might otherwise be turned into the soil remain on the surface, providing a habitat for weeds (16). These dynamics underline the importance of integrating tillage management strategies with effective weed control measures to maximize the yields of black gram crops.

Moisture retention is also a vital component of soil management in black gram cultivation. Different tillage systems can profoundly affect soil moisture levels and optimizing moisture availability directly affects growth rates and yield outcomes. Studies have demonstrated that no-till practices can result in higher moisture levels during critical growth phases of crops compared to CT (17). Since black gram is sensitive to drought conditions, managing soil moisture through judicious tillage practices can significantly enhance its resilience to climatic variations and contribute to the overall yield stability of the crop.

Additionally, the biochemical processes occurring within the soil are deeply influenced by the tillage approach adopted. The microbial community, which plays a critical role in nutrient cycling and organic matter decomposition, can be affected by the intensity and type of tillage. For instance, ZT has been associated with greater stability of microbial communities, positively impacting soil health and aiding crop nutrient availability (18). Conversely, CT tends to disrupt these communities, leading to decreased nutrient availability and adversely affecting black gram growth and productivity (19).

The interaction between soil management practices, particularly tillage and the physiological processes of black gram is complex and multifaceted. Effective tillage practices not only influence physical soil properties but also shape the biological activity within the soil. Soil tillage can enhance the availability of essential nutrients, such as nitrogen, which is particularly critical for leguminous crops like black gram, which are known for their ability to fix atmospheric nitrogen (3). Research shows that differing tillage practices can lead to variations in soil nitrogen levels, significantly affecting crop growth and yield outputs (20). Conventional tillage typically involves intensive soil disturbance, which can reduce weed pressure but may lead to soil degradation. Conservation tillage, on the other hand, minimizes soil disturbance, promoting soil health but potentially increasing weed challenges. Therefore, four tillage–residue combinations were selected to represent a gradient of soil disturbance and residue retention levels commonly practised in India. This enabled the evaluation of their interactive effects with weed management on crop performance.

Pendimethalin is a pre-emergence herbicide that controls annual grasses and broadleaf weeds. Imazethapyr is a post-emergence herbicide effective against a wide spectrum of broadleaf weeds and sedges. This sequence was chosen for the experiment because it is widely recommended in pulses. The two herbicides have complementary modes of action, provide prolonged weed suppression and ensure crop safety. This combination is particularly relevant for summer black gram, where high weed pressure during the early growth stages severely limits productivity. The study was also designed in the context of the rice-black gram system, a popular conservation agriculture practice in Odisha, where weeds pose a major threat to this short-duration crop due to strong early weed competition. Therefore, pendimethalin was applied as a pre-emergence herbicide at the recommended dose to manage the initial flush of early-germinating weeds. Subsequent weed flushes were managed either through post-emergence application of imazethapyr or by one-hand weeding, allowing a logical comparison of integrated strategies against the weedy check. Both pendimethalin and imazethapyr are officially recommended for black gram, making them the most relevant and practical choices for this study. Integrating effective weed management strategies with appropriate tillage practices is the key to optimizing the growth of black gram and ensuring sustainable production.

This study investigates the impact of different tillage and weed management practices on the growth and physiological responses of summer black gram. By examining and understanding these effects of various tillage systems in combination with diverse weed control strategies, the research aims to identify the most effective approaches to enhance crop performance that maximize yield, improve soil health and promote sustainable agricultural practices. Despite the importance of tillage and weed management practices in black gram cultivation, there is limited research on their effects on crop growth and physiological responses, especially during the summer when environmental conditions can be challenging. With this gap in mind, the experiment was conducted with the following objectives: 1) To evaluate morphological, physiological and biochemical attributes of summer black gram under different tillage and weed management practices, 2) To assess the microbial population as influenced by different tillage and weed management practices, 3) To study the effect of different tillage and weed management practices on yield and yield attributes of summer black gram. The findings will provide valuable insights for developing sustainable agricultural practices that enhance black gram productivity and contribute to food security.

Materials and Methods

A field experiment was conducted to study the crop growth and physiological responses of summer black gram under different tillage and weed management practices at the Agronomy Main Research Farm, College of Agriculture, Odisha University of Agriculture and Technology , Bhubaneswar, during the summer of 2024. Weather parameters recorded during the period of experiment is presented in Fig. 1. The experiment comprised four tillage practices in the main plot and three weed management practices in subplots laid out in split-plot design with three replications, with individual plots measuring 7 m × 6 m. Details of the treatments are given in Table 1. The soil (0 cm-15 cm) at the experimental site was sandy loam (78.3 %, 8.6 % and 13.1 % sand, silt and clay, respectively) in texture, having a pH of 6.44 and electrical conductivity (EC) 0.30 dS m^{-1} with 0.39 % organic C, 186 kg N, 26.9 kg P_2O_5 and 123.6 kg K_2O ha^{-1}, respectively. In CT, after harvesting of the preceding crop, the plots were prepared for the next sowing by ploughing twice with a disc harrow, followed by two passes with a cultivator and levelling with a planker. In ZT plots, black gram was sown with a specially designed zero-till seed-cum-fertilizer-planter without any prior tillage operation. Rice residue at 5 t ha^{-1} was applied in plots. Black gram variety "OBG-33 (Shashi)" was sown at 20 kg ha^{-1} at a depth of 4 cm- 5 cm with row spacing of 25 cm and at an inter-row plant spacing of 10 cm apart. The recommended dose of fertilizer (20 kg N, 40 kg P_2O_5 and 20 kg K_2O ha^{-1}, respectively) was applied through urea, diammonium phosphate and muriate of potash. The herbicides were applied as per the treatments.

Morphological parameters

Different morphological parameters like plant height, number of branches per plant, number of leaves per plant, number of root nodules per plant and root length were measured from five randomly selected plants from each treatment at 20 DAS, 40 DAS and harvesting time. Then, the mean value was calculated and presented as a suitable unit.

Table 1. Details of the treatments

Sl. No.	Treatments	Symbol
	Main plot treatments	
1.	Conventional tillage	CT
2.	Zero tillage	ZT
3.	Conventional tillage + residue	CT+R
4.	Zero tillage + residue	ZT+R
	Sub plot treatments	
1.	Application of pendimethalin @750g/ha at 2 days after sowing (DAS) followed by imazethapyr @ 70g/ha at 20 DAS	H_1
2.	H_1+ one hand weeding at 30 DAS	H_2
3.	Weedy check	H_3

Physiological parameters

Physiological and biochemical parameters were recorded at 20, 30 and 40 DAS, which is the most critical period for the crop-weed competition in the case of black gram, which is between three and six weeks after sowing (9). Five randomly selected plants per replication were sampled for each observation and their mean values were used for analysis. Leaf area index (LAI) was calculated as the ratio of leaf surface (one side only) to the ground area occupied by the plant or a crop stand (21). Crop growth rate (CGR) was determined per the formula and expressed as g $m^{-2}day^{-1}$ (22).

$$CGR = W_2 - W_1 / [P \times (t_2 - t_1)] \quad \text{(Eqn.1)}$$

where, P is the ground area, W_1 and W_2 are plant dry weights at time t_1 and t_2 respectively.

Relative growth rate (RGR) was calculated and expressed as g g^{-1} day^{-1} (22).

$$RGR = (\ln W_2 - \ln W_1)/(t_2 - t_1) \quad \text{(Eqn. 2)}$$

where, W_1 and W_2 are dry weights of plant at time t_1 and t_2, respectively.

Net assimilation rate (NAR) was calculated per the following formula and expressed as g m^{-2} day^{-1} (23).

$$NAR = [(W_2 - W_1) \times (\log_e A_2 - \log_e A_1)] / [(t_2 - t_1) \times (A_2 - A_1)] \quad \text{(Eqn. 3)}$$

where, W_1 and W_2 are the dry weights of the plant at times t_1 and t_2, respectively and A_1 and A_2 are the leaf areas at times t_1 and t_2, respectively.

Dry weight of the plant samples was estimated by oven drying at 80 °C for 72 hr to reach a constant weight.

Biochemical parameters

For the estimation of leaf photosynthetic pigments like chlorophyll and carotenoid, a finely chopped 0.1 g of fresh leaf sample was incubated in 80 % (v/v) acetone in the dark for 24 hr. Optical density (OD) was then measured at 645, 663 and 480 nm using a spectrophotometer. The chlorophyll and carotenoid contents were calculated as per standard protocol and expressed as mg.g^{-1} fresh weight (FW) (24).

$$\text{Chlorophyll a} = [(12.7 \times OD_{663}) - (2.69 \times OD_{645})] \times V / (1000 \times W) \quad \text{(Eqn. 4)}$$

$$\text{Chlorophyll b} = [(22.9 \times OD_{645}) - (4.68 \times OD_{663})] \times V / (1000 \times W) \quad \text{(Eqn. 5)}$$

$$\text{Total chlorophyll} = [(20.2 \times OD_{645}) + (8.02 \times OD_{663})] \times V / (1000 \times W) \quad \text{(Eqn. 6)}$$

$$\text{Carotenoid} = [(OD_{480} + 0.114 \times OD_{663}) - (0.638 \times OD_{645})] \times V / (1000 \times W) \quad \text{(Eqn. 7)}$$

where, V is the extract volume (mL) and W is the fresh weight of the leaf (g).

Proline was estimated as per standard protocol (25). 0.25 g fresh leaves were homogenized in 5 mL 3 % sulphosalicylic acid and centrifuged at 4000 rpm. The supernatant was mixed with 5 mL glacial acetic acid and 5 mL acid ninhydrin in test tubes. The tubes were kept for 1 hr at 100 °C in a hot water bath and then vortexed with 20 mL toluene. OD value of the toluene layer was measured at 520 nm. Proline content was calculated using a standard curve and expressed as µg g^{-1} FW.

Protein content was determined following a standardized protocol (26). 1 g of fresh leaves was homogenized in 10 mL of 10 %

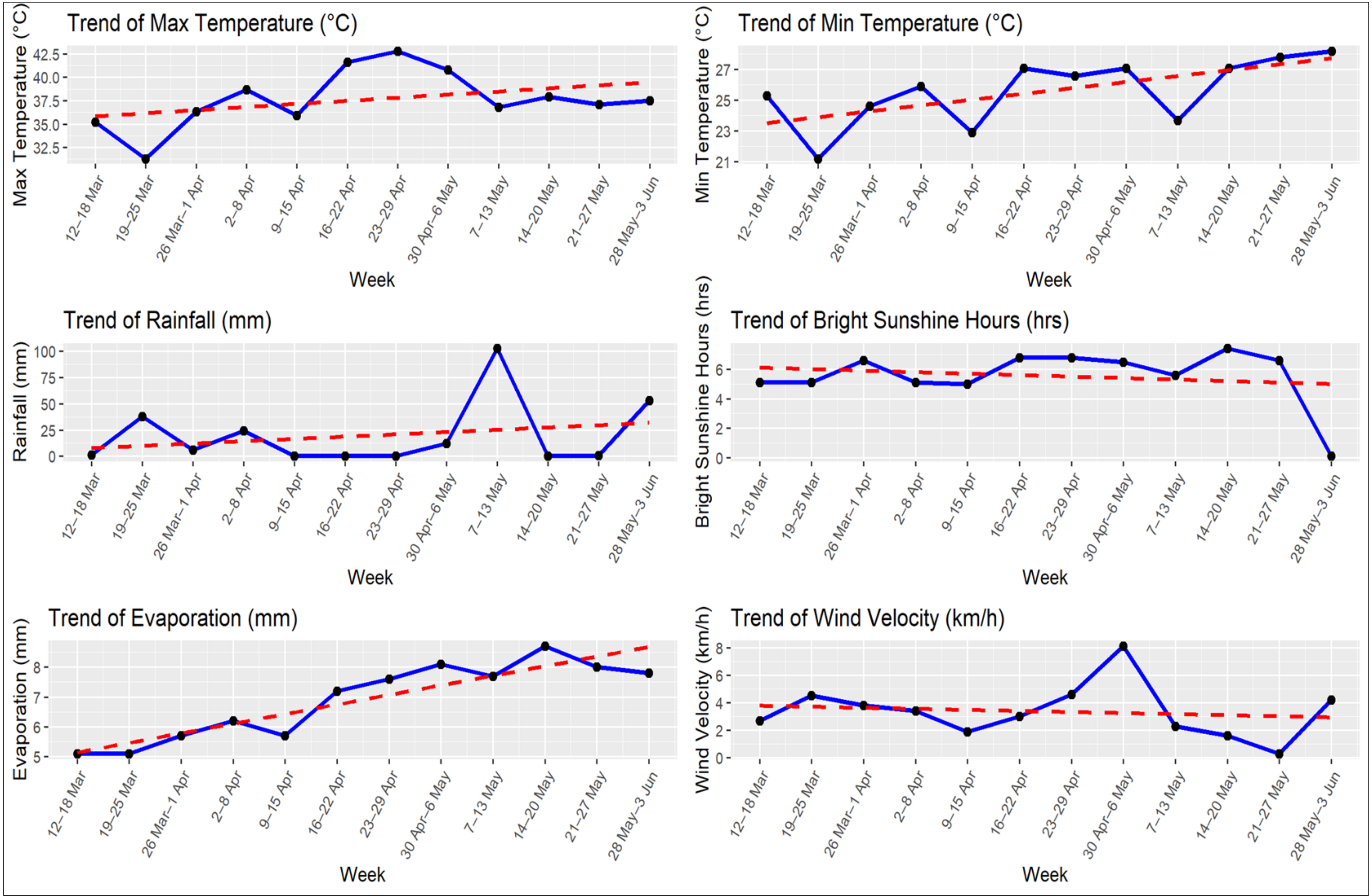

Fig. 1. Trend of the weather parameters throughout the crop growing cycle.

trichloroacetic acid and centrifuged at 5000 rpm for 10 min. After discarding the supernatant, 10 mL of 1N NaOH was added to the residue and centrifuged at 10000 rpm for 10 minutes. 0.2 mL of the clear supernatant was taken and diluted to 2 mL with distilled water. 10 mL of alkaline copper reagent was added and incubated for 10 min. Further, 1 mL of diluted Folin–Ciocalteu reagent was added and the mixture was incubated in the dark at room temperature for 30 min until a blue color developed. Absorbance was measured at 660 nm. Protein concentration was calculated from the standard curve prepared with bovine serum albumin and expressed as mg g^{-1} FW.

For the estimation of nitrate reductase (NR) activity, 200 mg fresh leaf discs were submerged in a reaction mixture (2 mL phosphate buffer, 1.6 mL 25 % n-propanol, 3 mL 0.2M KNO_3, 1 mL EDTA, 2.4 mL water and 1 mL NADH) and incubated in the dark at 27 °C for 1 hr with shaking. The reaction was stopped with 4 mL sulphanilamide and 4 mL 0.02 % NED solution. After 20 min, the absorbance was measured at 540 nm. Nitrate reductase activity was calculated using the standard curve data and expressed as µmol NO_2^- produced g^{-1} FW hr^{-1}.

Yield attributes and yield

The observations pertaining to yield attributes and yield were taken from five randomly selected plants at harvest. The mean value was calculated and presented.

Soil microbial population

Microbial population data were recorded at three stages: before sowing (initial), 40 DAS and at harvest. Since no plots were established before sowing, soil samples were collected from five random spots of the experimental field and the mean value of these counts was taken as the initial microbial population. Similarly, for recording microbial population at 40 DAS and at harvest, soil samples were collected from five random spots from each plot and the mean value of these counts was presented.

The standard serial plate count method quantified the microbial population (bacteria, fungi and actinomycetes). Nutrient agar was used for bacteria, potato dextrose agar for fungi and actinomycetes isolation agar for actinomycetes. Soil samples were serially diluted in sterile normal saline solution and inoculated onto the media using the spread plate technique. The plates were incubated at 28±2 °C for the required period (24 hr for bacteria, 48 hr for fungi and 5 days for actinomycetes). Colony-forming units (CFU) per gram FW of the soil were counted post-incubation.

Statistical analysis

All the data recorded in pre- and postharvest studies were compiled in appropriate tables. They were subjected to statistical analysis per the procedure prescribed for split plot design to obtain the analysis of Variance table (27). The treatment variations were tested for significance by F-test. The standard error of mean SE(m) ± and critical difference (CD) at 5 % probability level were calculated as per the formulae to interpret the result (28).

Results and Discussions

The experimental findings are presented with relevant tables and figures. Then those are interpreted in the context of previous research findings, highlighting the key factors contributing to plant growth, development and productivity variations.

Effect of tillage and weed management on morphological parameters of black gram

Plant height

Plant height increased progressively until harvest under all treatments (Table 2). Tillage practices had no significant effect at 20 DAS but showed clear differences thereafter. At 40 DAS, CT+R (33.1 cm) recorded the maximum height, followed by ZT+R (30.4 cm) and CT (30.1 cm), while ZT (28.1 cm) was the lowest. A similar trend was observed at harvest, with CT+R (53.2 cm) > ZT+R (47.1 cm) > CT (44.4 cm) > ZT (42.7 cm). This increase in plant height under CT+R could be attributed to its improvement of the soil's physical, biological and chemical properties, such as reducing compaction, enhancing soil-seed contact, improving aeration and promoting root growth. Additionally, mulch improves soil quality by breaking up clay and allowing better water and air movement. Adding residue as mulch increased the plant height in CT and ZT compared to CT and ZT without mulch. Similar result was also found in chickpea (29). CT reduced weed competition by lowering weed populations, which allowed crops to absorb more moisture and nutrients from deeper soil layers, ultimately contributing to increased plant height. Plant height is often reduced in ZT due to compacted soil layers, which limit root growth and nutrient uptake. Additionally, slower decomposition of crop residues in ZT can reduce early nutrient availability, affecting plant growth. This result was corroborated by a previous investigation (30).

Table 2. Effect of tillage and weed management on plant height and number of branches per plant at different growth stages of black gram

TREATMENTS	Plant height (cm)			Number of branches per plant		Root length	
	20 DAS	40 DAS	At harvest	20DAS	40 DAS	20DAS	40 DAS
Tillage Practices (T)							
CT	17.4	30.1	44.4	2.1	3.8	8.2	12.9
ZT	16.0	28.1	42.7	1.9	3.2	6.9	9.2
CT+R	18.3	33.1	53.2	2.4	5.1	10.0	14.6
ZT+R	16.8	30.4	47.1	2.3	4.6	9.3	12.6
SEm (±)	0.65	0.89	1.90	0.04	0.14	0.25	0.54
CD (p=0.05)	NS	3.09	6.58	0.14	0.48	0.86	1.86
Weed Management (H)							
H_1	18.0	29.4	48.0	2.2	4.7	9.2	13.6
H_2	18.3	32.5	47.9	2.3	5.0	9.9	12.8
H_3	14.9	29.3	44.6	1.8	2.7	6.7	10.6
SEm (±)	0.28	0.82	0.91	0.05	0.12	0.21	0.30
CD (p=0.05)	0.87	2.40	2.66	0.16	0.34	0.63	0.88
Interaction	NS	NS	S	NS	NS	S	S

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g ha^{-1}; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

There was a significant effect of weed management on plant height at all stages. H_2 resulted in the maximum plant height at 20 (18.3 cm) and 40 DAS (32.5 cm), while at harvest, H_1 (48.0 cm) and H_2 (47.9 cm) were comparable and significantly higher than H_3 (44.6 cm). A similar result was reported in another experiment (31). This increase in height can be explained by effective weed management, reducing weed density and dry matter, which in turn decreased competition for resources like nutrients, moisture, sunlight and space, giving the crop better growth conditions than the weedy check.

Number of branches per plant

The number of branches per plant increased to 40 DAS (Table 2). Tillage practices had a significant effect at both 20 and 40 DAS. At 20 DAS, the highest number of branches was recorded under CT+R (2.4), which was at par with ZT+R (2.3), followed by CT (2.1), while ZT (1.9) was lowest. A similar trend was observed at 40 DAS, with CT+R (5.1) > ZT+R (4.6) > CT (3.8) > ZT (3.3). Superiority of CT+R over ZT could be attributed to improved soil physical properties, which enhanced nutrient and water uptake from deeper soil layers, promoting better growth and branching. Additionally, the early growth stage is critical for branching and the balanced availability of growth factors provided by tillage practices helped to reduce crop-weed competition, further supporting branch development.

Weed management significantly influenced the number of branches per plant. At 20 DAS, H_2 (2.3) recorded the maximum, which was comparable to H_1 (2.2), while H_3 (1.8) was the lowest. At 40 DAS, the highest number of branches was again observed in H_2 (5.0), followed by H_1 (4.7), with the minimum in the weedy check (2.7). Weed control reduced weed density, minimizing competition between crops and weeds for essential resources during the critical branching period. As a result, plants were able to utilize nutrients and moisture more efficiently, promoting better growth. Similar findings were reported in other studies (12, 32).

Number of leaves per plant

The number of leaves increased progressively up to harvest (Fig. 2). Tillage practices had no significant effect at 20 DAS, but differences became evident later. At 40 DAS, CT+R (40.1) recorded the maximum leaf number, followed by ZT+R (37.1), CT (33.7) and ZT (30.5). A similar trend was observed at harvest, with CT+R (53.2) > ZT+R (47.9) > CT (47.1) > ZT (45.1). This was due to better moisture retention and improved soil health from crop residue. Residue mulching helps reduce evaporation, leading to better water availability to the plants. Residue also provides organic matter that enhances soil fertility, promoting better nutrient uptake. Poor performance of ZT without residue cover may be due to soil compaction and poor water retention, which limits root growth and nutrient availability.

Weed management practices significantly impacted the number of leaves per plant at all stages. H_2 recorded the maximum number of leaves in black gram at 20 DAS (9.1), 40 DAS (41.8) and harvest (50.3), while the minimum was observed in H_3 (7.9, 29.4 and 44.7, respectively). The superiority of H_2 can be attributed to better weed control, which helped the plant to uptake nutrients for leaf production. On the other hand, weeds compete with the crops for nutrients, water and other resources thereby reducing the number of leaves in weedy check.

Number of nodules per plant

The number of nodules increased up to 40 DAS (Fig. 3). At 20 DAS, CT+R (17.77/plant) recorded the maximum, followed by CT (14.1), ZT+R (13.42) and ZT (7.5). Among weed management practices, H_2 (16.38) produced the highest nodules, followed by H_1 (14.23), while H_3 (9.03) was lowest. At 40 DAS, CT+R (30.14) again recorded the highest, followed by ZT+R (22.67), CT (18.03) and ZT (14.36). Similarly, H_2 (26.51) was superior to H_1 (21.81) and H_3 (15.55). A significant interaction was observed at 40 DAS (Table 3), with the maximum nodules under CT+R–H_2 (38.2), followed by CT+R–H_1 (33.30) and ZT+R–H_2 (28.30), while ZT–H_3 (12.0) recorded the minimum.

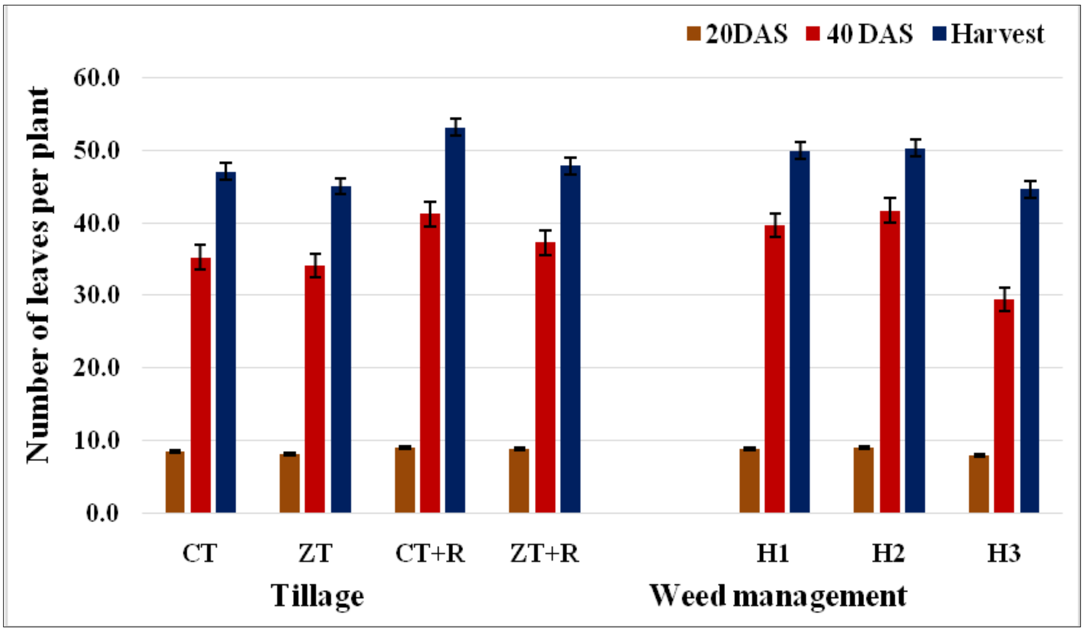

Fig. 2. Effect of tillage and weed management on the number of leaves per plant at various growth stages of black gram.

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

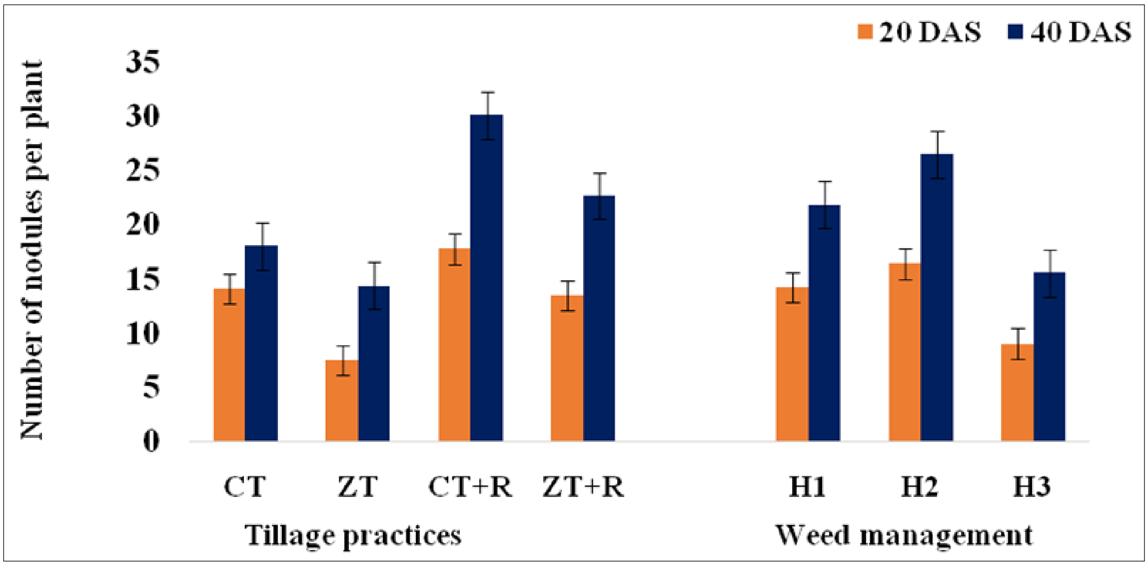

Fig. 3. Effect of tillage and weed management on the number of nodules per plant at various growth stages of black gram.

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g ha^{-1}; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

Table 3. Interaction effect of tillage and weed management on the number of nodules per plant in black gram at 20 DAS and 40 DAS

Treatments	20 DAS			40 DAS		
	H_1	H_2	H_3	H_1	H_2	H_3
CT	14.90	15.20	12.20	18.30	22.20	13.60
ZT	8.80	7.30	6.40	13.72	17.35	12.00
CT+R	18.40	27.60	7.30	33.30	38.20	18.80
ZT+R	14.80	15.40	10.20	21.92	28.30	17.80
	SEm (±)	CD (p=0.05)		SEm (±)	CD (p=0.05)	
T within H	0.712	2.173		1.905	5.814	
H within T	0.756	2.206		2.025	5.911	

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

The higher number of nodules under CT+R may be attributed to improved soil aeration from tillage, which enhances root growth and favors the activity of nitrogen-fixing bacteria such as *Rhizobium*. Residue incorporation further improves soil moisture, nutrient cycling and microbial activity, creating favourable conditions for nodule initiation. Mulch also moderates soil temperature and promotes a stable environment for nodulation. In contrast, ZT often results in compacted soil with higher bulk density, reducing root length, aeration and nutrient availability, thereby limiting rhizobial infection and nodule formation.

Weed management by pre and post-emergence herbicides, especially at the critical crop weed competition period, helps to increase the production and root nodulation of black gram. Among weed management practices, a larger number of nodules were found under weed control treatments, indicating that pendimethalin and imazethapyr had no adverse effects on nodulation and may have even promoted nodule initiation. Similar findings were reported in earlier studies (33). In contrast, the reduction in nodule number under weedy check may be attributed to increased competition with crops, which suppressed growth. This observation is reported in previous studies (34).

Root length

Data presented in Table 2 revealed that root length increased from 20 DAS to 40 DAS. At 20 DAS, among tillage and residue management practices, CT+R recorded the highest root length (10 cm), followed by ZT+R (9.35 cm), CT (8.23 cm) and ZT (6.89 cm), respectively. In contrast, the highest root length was observed in H_2 (9.96 cm), which is at par with H_1 (9.17 cm) and the lowest root length was recorded in the weedy check (6.73 cm). The interaction was found to be significant. At 40 DAS, the highest root length was observed in CT+R (14.59 cm), followed by CT (12.96 cm), which is at par with ZT+R (12.62 cm). The lowest root length was observed in the zero-tillage plot (9.25 cm).

The application of crop residue mulch led to a reduction in the bulk density of soil compared to treatments without mulch. This reduction can be attributed to increased earthworm activity, improved soil porosity and the presence of relatively higher levels of organic matter in the mulched treatments. Higher soil moisture storage contributed to better root growth than the no-mulch treatment. No tillage with residue mulching can be practiced for maintaining better soil physical health, root growth without any significant reduction in crop productivity compared to CT. This result was supported by (35). Whereas, ZT significantly reduced root length due to higher bulk density in 0 cm-15 cm layer, preventing roots from extending down the profile. This may be due to the fact that whenever root meets a compact layer, its length decreases. This result was corroborated by the findings of another study (36).

Different weed management practices had a significant impact on root length. Higher root length was observed in H_1 (13.61 cm), followed by H_2 (12.82 cm) and the weedy check (10.63 cm), respectively. The interaction effect was found to be significant. Shorter root length under weedy check compared to other weed control practices may be due to competition from weeds for essential resources like nutrients, water and light. Weeds restrict the root growth of the crop by dominating these resources, while herbicide application eliminates weeds, allowing the crop roots to grow freely and access nutrients effectively.

Effect of tillage and weed management on physiological parameters of black gram

Crop growth rate

Table 4 shows that CGR was significantly influenced by both tillage and weed management practices. During 20–40 DAS, CT+R recorded the highest CGR, exceeding ZT+R, CT and ZT by 15.99 %, 51.11 % and 76.05 %, respectively. Weed management treatments revealed that H_2 achieved the maximum CGR, while H_3 recorded a 50.58 % reduction compared to H_2. From 40 DAS to harvest, CT+R again registered the highest CGR (5.43 g m^{-2} day^{-1}), followed by ZT+R (4.92 g m^{-2} day^{-1}), which was at par with CT (4.80 g m^{-2} day^{-1}), while ZT (4.33 g m^{-2} day^{-1}) recorded the lowest. Among weed management practices, H_2 produced the highest CGR (5.72 g m^{-2} day^{-1}), followed by H_1 (5.32 g m^{-2} day^{-1}), whereas H_3 recorded the lowest (3.57 g m^{-2} day^{-1}). The interaction effect of tillage and weed management was also significant.

Relative growth rate

Table 4 shows that RGR was significantly influenced by tillage and weed management at 20–40 DAS. CT+R (0.110 g $g^{-1}day^{-1}$) recorded the highest RGR, followed by ZT+R (0.107), CT (0.097) and ZT (0.090). Among weed management practices, H_1 and H_2 (0.108) were higher than H_3 (0.087). From 40 DAS to harvest, no clear trend was observed.

Net assimilation rate

At 20-40 DAS, NAR was highest under CT+R (0.97 g m^{-2} day^{-1}), followed by ZT+R (0.90 g m^{-2} day^{-1}) and CT (0.84 g m^{-2} day^{-1}), while ZT (0.78 g m^{-2} day^{-1}) recorded the lowest (Fig. 4). Among weed management practices, H_2 recorded the maximum NAR (0.97 g m^{-2} day^{-1}), followed by H_1 (0.92 g m^{-2} day^{-1}), with the minimum in H_3 (0.73 g m^{-2} day^{-1}). A similar trend was observed at 40 DAS–harvest.

Leaf area index

Various tillage practices and weed control methods significantly influenced LAI (Fig. 5). At 20 DAS, CT+R recorded the highest LAI, exceeding ZT+R, CT and ZT by 9.2 %, 25.10 % and 49.55 %, respectively. Among weed management practices, H_2recorded 6.7 % and 73.07 % higher LAI than H_1 and H_3, respectively. Similarly, at 40 DAS, CT+R recorded the maximum LAI, surpassing ZT+R, CT and ZT by 6.79 %, 12.30 % and 20.94 %, respectively. Weed management

Table 4. Effect of tillage and weed management on crop growth rate and relative growth rate at different growth stages of black gram

TREATMENTS	Crop growth rate (g m² day⁻¹)		Relative growth rate (g g⁻¹ day⁻¹)	
	20-40 DAS	40 DAS-Harvest	20-40 DAS	40 DAS-Harvest
Tillage Practices (T)				
CT	3.60	4.80	0.097	0.035
ZT	3.09	4.33	0.090	0.038
CT+R	5.44	5.43	0.110	0.028
ZT+R	4.69	4.92	0.107	0.029
SEm (±)	0.079	0.88	0.003	0.001
CD(p=0.05)	0.272	0.305	0.010	0.003
Weed Management (H)				
H_1	4.90	5.32	0.108	0.030
H_2	5.16	5.72	0.108	0.030
H_3	2.55	3.57	0.087	0.037
SEm (±)	0.085	0.089	0.003	0.001
CD (*p*=0.05)	0.249	0.261	0.009	0.003
Interaction	S	S	S	S

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g ha^{-1}; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (*p* = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

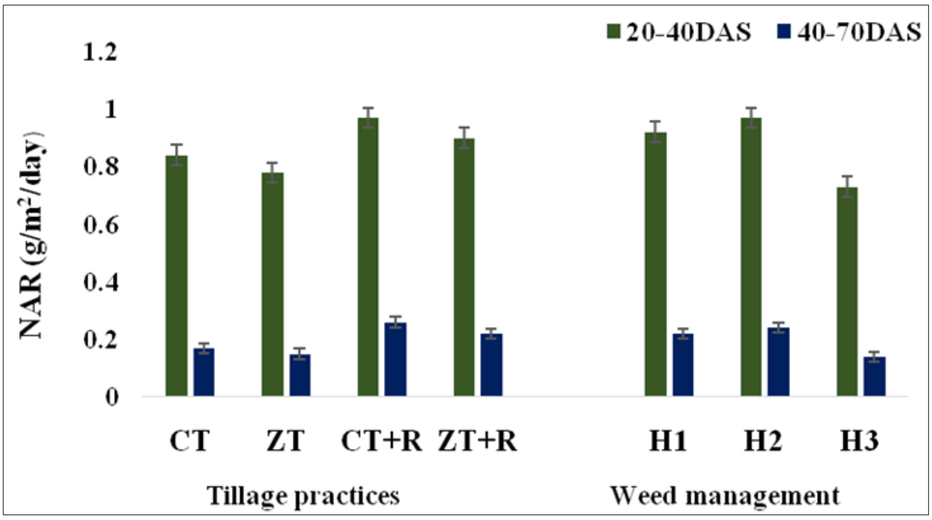

Fig. 4. Effect of tillage and weed management on net assimilation rate at various growth stages of black gram.

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (*p* = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

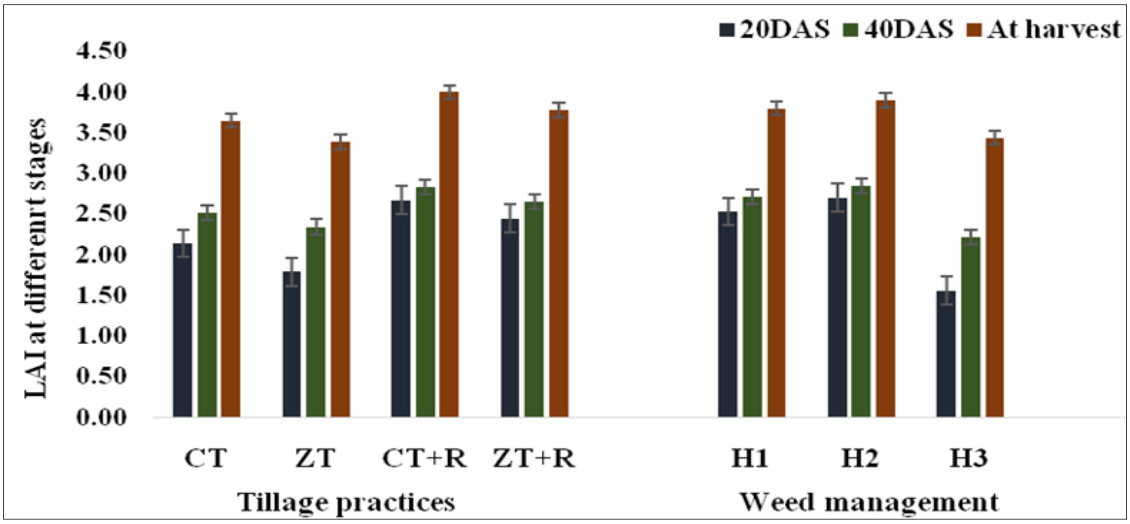

Fig. 5. Effect of tillage and weed management on LAI at various growth stages of black gram.

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (*p* = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

also showed significant effects, with H_2 (similar to H_1) recording 28.05 % higher LAI than H_3. At harvest, tillage practices did not differ significantly, whereas weed management remained significant, with H_2 (at par with H_1) showing 13.37 % higher LAI than H_3.

The superior performance of CT+R can be attributed to enhanced soil aeration, improved root penetration and better moisture retention. These conditions resulted in vigorous plant growth and more leaf development, thus resulting in a higher LAI. Residue application in CT+R and ZT+R further improved aeration, water infiltration and nutrient availability, leading to higher CGR, RGR, NAR and LAI. In contrast, ZT limited these parameters with minimal soil disturbance. Similarly, the highest CGR, RGR, NAR and LAI values under H_2 resulted from reduced crop-weed competition for light, space, water and nutrients. These outcomes align closely with the findings of (37).

Root, stem and leaf dry weight

Table 5 presents the effect of tillage and weed management practices on the dry matter partitioning of black gram. Root dry weight was the maximum under CT+R, with increases of 57.32 %, 30.54 % and 48.39 % over ZT at 20 DAS, 40 DAS and harvest, respectively. Among weed management practices, H_2 recorded the highest root dry weight, exceeding H_3 by 55.45 %, 81.40 % and 48.41 % at the corresponding stages.

Stem dry matter increased progressively with crop growth. CT+R recorded the highest stem dry matter, with percentage increases of 38.43 %, 78.89 % and 47.16 % over ZT at 20 DAS, 40 DAS and harvest, respectively. Similarly, H_2 outperformed H_3 with increases of 38.18 %, 105.56 % and 70.31 % at 20 DAS, 40 DAS and harvest, respectively.

Leaf dry matter also increased steadily up to harvest. Data recorded at 20 DAS, 40 DAS and at harvest indicated that CT+R contributed higher leaf dry matter, i.e. 9.6 g m^{-2}, 43.55 g m^{-2} and 115.62 g m^{-2}, respectively, which were 30.92 %, 58.94 % and 39.8 % increased over ZT in the respective growth stages. Under weed management, H_2 recorded the highest leaf dry matter (9.63, 72.34 and 119.20 g m^{-2}), 46.79 %, 94.50 % and 75.13 % higher than H_3 at the respective stages. A significant interaction was observed at 40 DAS (Table 6), with the maximum leaf dry weight under CT+R–H_2 (83.80 g m^{-2}), followed by CT+R–H_1 (80.48 g m^{-2}) and ZT+R–H_2 (76.12 g m^{-2}), while ZT-H_3 (16.72 g m^{-2}) recorded the minimum. At harvest, the maximum was noted under CT+R–H_2 (130.08 g m^{-2}), closely followed

Table 5. Effect of tillage and weed management on dry matter accumulation at different growth stages of black gram

TREATMENTS	Dry weight of plant part (g m^{-2})								
	20 DAS			40 DAS			Harvest		
	Root dry weight	Stem dry weight	Leaf dry weight	Root dry weight	Stem dry weight	Leaf dry weight	Root Dry weight	Stem dry weight	Leaf dry weight
Tillage Practices (T)									
CT	2.54	3.32	8.02	15.68	31.22	52.22	27.28	131.01	96.96
ZT	2.32	2.81	7.34	14.44	26.68	45.20	23.10	119.09	82.70
CT+R	3.65	3.89	9.61	18.85	47.73	74.46	34.28	169.31	115.62
ZT+R	2.95	3.61	8.79	16.72	37.88	68.27	31.84	144.76	108.92
SEm (±)	0.04	0.09	0.26	0.444	1.086	1.531	0.94	3.72	1.712
CD (p=0.05)	0.13	0.30	0.90	1.538	3.759	5.297	3.24	12.88	5.922
Weed Management (H)									
H_1	2.97	3.58	9.13	18.82	41.79	69.00	31.80	154.63	115.88
H_2	3.42	3.80	9.63	19.61	44.30	72.34	33.20	169.18	119.20
H_3	2.20	2.75	6.56	10.81	21.55	38.77	22.37	99.32	68.06
SEm (±)	0.06	0.09	0.23	0.47	1.00	1.605	0.50	2.47	2.183
CD (p=0.05)	0.17	0.27	0.68	1.38	2.918	4.683	3.24	7.20	6.372
Interaction	S	NS	NS	NS	NS	S	S	NS	S

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g ha^{-1}; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (*p* = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

Table 6. Interaction effect of tillage and weed management on leaf dry weight (g.m[2]) of black gram at 40 DAS and at harvest

Treatments	40 DAS			At Harvest		
	H_1	H_2	H_3	H_1	H_2	H_3
CT	60.08	69.96	26.61	108.73	110.04	72.10
ZT	59.40	59.48	16.72	104.06	108.73	35.30
CT+R	80.48	83.80	59.09	128.29	130.08	88.48
ZT+R	76.04	76.12	52.64	122.44	127.95	76.38
	SEm (±)	CD (p=0.05)		SEm (±)	CD (p=0.05)	
T within H	3.035	9.275		3.955	11.943	
H within T	3.209	9.366		4.367	12.744	

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

by ZT+R–H_2 (127.95 g m^{-2}) and CT+R–H_1 (128 29 g m^{-2}), whereas ZT-H_3 (35.30 g m^{-2}) recorded the minimum.

Lower dry matter accumulation under ZT as compared to CT may be due to soil compaction at the plow layer in the early years of ZT, which restricts root and plant development. Previous studies also confirm that CT supports better crop growth and yield than ZT (38). Higher dry matter production with residue incorporation might be due to the fact that the organic supplements from the crop residue improved the soil organic carbon and soil health, resulting in higher plant growth. Similar results were reported in another study (39).

The poor performance of unweeded control compared to weed-free plots highlights the negative effect of weed competition. Weed-free plots produced the higher dry matter, showing the importance of weed control in maximizing growth. Pre-emergence application of pendimethalin followed by imazethapyr with one hand weeding resulted in significantly higher dry matter. This indicates effective weed suppression and a favorable crop environment, which enhanced photosynthesis and translocation of assimilates from source to sink. The reduction in weed competition also improved nutrient uptake, resulting in taller plants with greater leaf area and higher dry matter production. These findings are in close agreement with earlier reports (30, 40).

Effect of tillage and weed management on biochemical parameters of black gram

Chlorophyll and carotenoid content

Chlorophyll-a, chlorophyll-b and total chlorophyll content at different crop stages were estimated, analysed and presented in Table 7. From the data, it was revealed that there was an increase in chlorophyll content up to 40 DAS under all treatments. CT+R consistently recorded the highest values, followed by ZT+R, CT and ZT. At 40 DAS, the maximum chlorophyll-a was obtained in CT+R (2.00 mg/g FW), while the lowest was in ZT (1.46 mg/g FW). Among weed management practices, H_2 (1.94 mg/g FW) recorded the highest chlorophyll-a, followed by H_1, with H_3 showing the minimum (1.42 mg/g FW).

Chlorophyll-b also increased with crop growth. At 20 DAS, CT+R (0.76 mg g^{-1} FW) and H_2 (0.70 mg g^{-1} FW) showed the maximum values. Similar trends were observed at later stages, with CT+R and H2 remaining superior, while ZT and H_3 recorded the minimum chlorophyll-b.

At 40 DAS, CT+R (2.97 mg/g FW) recorded the highest total chlorophyll content, followed by ZT+R (2.64 mg g^{-1} FW), CT (2.35 mg g^{-1} FW) and ZT (2.20 mg/g FW). Weed management showed significant differences, with H_2 (2.82 mg g^{-1} FW) superior to H_1 (2.70 mg g^{-1} FW) and H_3 (2.10 mg g^{-1} FW). A significant interaction was noted (Table 8), with CT+R–H_2 (3.53 mg g^{-1} FW) producing the highest and ZT–H_3 (1.84 mg g^{-1} FW) the lowest total chlorophyll.

Carotenoid content followed a similar trend (Fig. 6). At 40 DAS, CT+R (0.099 mg g^{-1} FW) recorded the maximum, while ZT (0.075 mg g^{-1} FW) was the lowest. Among weed management treatments, H_2 (0.094 mg g^{-1} FW) produced the highest carotenoids, followed by H_1 (0.092 mg g^{-1} FW), with H_3 (0.060 mg g^{-1} FW) showing the minimum.

Residue cover in both CT and ZT increased the leaf chlorophyll content as compared to CT and ZT without residue. This may be due to moisture retention and better supply of nutrients like nitrogen essential for chlorophyll production. In addition, residues

Table 7. Effect of tillage and weed management on chlorophyll-a, chlorophyll-b and total chlorophyll content

TREATMENTS	Chlorophyll-a (mg g^{-1} FW)			Chlorophyll-b (mg g^{-1} FW)			Total chlorophyll content (mg g^{-1} FW)		
	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS	20 DAS	30 DAS	40 DAS
Tillage Practices (T)									
CT	1.08	1.18	1.54	0.57	0.72	0.76	1.67	1.92	2.35
ZT	1.05	1.13	1.44	0.56	0.67	0.67	1.62	1.80	2.20
CT+R	1.24	1.28	2.07	0.76	0.87	0.87	2.04	2.15	2.97
ZT+R	1.15	1.23	1.83	0.64	0.77	0.80	1.79	2.00	2.64
SEm (±)	0.035	0.036	0.049	0.025	0.023	0.031	0.053	0.030	0.077
CD (p=0.05)	0.12	NS	0.170	0.085	0.052	0.106	0.182	0.105	0.267
Weed Management (H)									
H_1	1.16	1.23	1.77	0.65	0.78	0.81	1.85	2.02	2.70
H_2	1.19	1.26	1.97	0.70	0.84	0.85	1.92	2.10	2.82
H_3	1.04	1.12	1.41	0.54	0.65	0.65	1.60	1.78	2.10
SEm (±)	0.034	0.02	0.034	0.020	0.015	0.018	0.049	0.046	0.032
CD (p=0.05)	0.099	0.07	0.098	0.060	0.044	0.053	0.143	0.135	0.094
Interaction	NS	NS	S	S	NS	NS	NS	NS	S

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

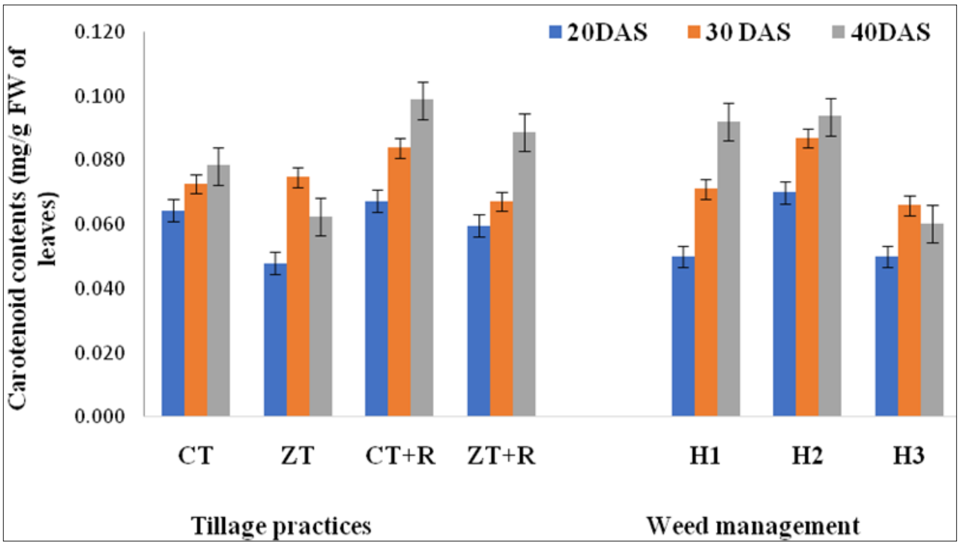

Fig. 6. Effect of tillage and weed management on carotenoid content of leaves at various growth stages.

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

Table 8. Interaction effect of tillage and weed management on total chlorophyll content (mg g^{-1} FW) of black gram leaves at 40 DAS

TREATMENTS	H_1	H_2	H_3
L	2.45	2.48	2.12
ZT	2.36	2.40	1.84
CT+R	3.04	3.53	2.36
ZT+R	2.95	2.88	2.10
	SEm (±)	CD (p = 0.05)	
T within H	0.093	0.307	
H within T	0.065	0.188	

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g ha^{-1} followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

on the soil surface create a favourable microclimate by moderating soil temperature, conserving soil moisture and reducing evaporative losses. These conditions improve root activity, enhance nutrient uptake efficiency and maintain leaf water status, collectively supporting higher chlorophyll synthesis and stability. Residue cover can also reduce soil surface radiation load, indirectly protecting chlorophyll molecules from photodegradation. CT produced more chlorophyll than ZT, which is likely due to the fact that compact soil in the case of ZT negatively influences the leaf chlorophyll content. The findings of the current study are consistent with previous data demonstrating the advantage of CT over ZT (41). Chlorophyll contains nitrogen atoms in its structure, which are essential for its synthesis.

Weeds in the weedy check plots compete with crops for nutrients, including nitrogen, limiting the plant's ability to synthesize chlorophyll. The higher chlorophyll content in treatment H_2may be attributed to better nitrogen availability and uptake. Herbicides and hand weeding suppressed weed growth, reducing competition for light, nutrients and water in crops, allowing crops to absorb more nitrogen and promoting increased chlorophyll production. Moreover, reduced weed competition also improves canopy light distribution and gas exchange, enhancing photosynthetic activity and chlorophyll maintenance. This resulted in greener, more photosynthetically active plants with better overall growth.

Leaf soluble protein content

Tillage practices significantly influenced leaf soluble protein (Table 9). Protein content increased from 20 to 30 DAS and declined by 40 DAS. At 20 DAS, the highest value was in CT+R (6.5 mg g^1 FW), followed by ZT+R (5.84 mg g^1 FW), CT (5.30 mg g^1 FW) and ZT (4.92

Table 9. Effect of tillage and weed management on leaf soluble protein and proline content of leaves

TREATMENTS	Leaf soluble protein content (mg g^{-1} FW)			Proline content (µg g^{-1} FW)		
	20 DAS	30 DAS	40 DAS	30 DAS	20 DAS	40 DAS
Tillage Practices (T)						
CT	5.30	13.08	8.47	104.87	146.14	105.61
ZT	4.92	9.15	8.05	120.17	153.00	117.20
CT+R	6.51	18.06	12.24	88.59	101.38	96.63
ZT+R	5.84	17.74	9.60	98.31	136.70	99.11
SEm (±)	0.112	0.257	0.250	3.555	3.643	2.310
CD (p=0.05)	0.388	0.891	0.866	12.300	12.606	7.992
Weed Management (H)						
H_1	6.13	16.11	11.00	98.49	125.73	96.72
H_2	6.33	17.94	12.54	94.10	113.18	94.24
H_3	4.47	9.48	5.43	116.36	164.01	122.96
SEm (±)	0.153	0.385	0.388	2.713	2.336	1.908
CD (p=0.05)	0.447	1.125	1.128	7.917	6.818	5.569
Interaction	NS	S	S	S	S	S

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

mg g^{-1} FW). Higher protein under CT+R over ZT may be due to enhanced nutrient cycling and microbial activity. Residue retention as mulch in CT and ZT added organic matter to the soil, increasing soil moisture and nutrient availability. Tillage also aerates the soil, promoting root growth and nutrient uptake. ZT often slows down the decomposition of plant residues because of the absence of soil disturbance, leading to reduced aeration and lower microbial activity. This decomposition delay reduces nutrient mineralization rate, especially nitrogen, which is essential for protein synthesis in plants. With less nitrogen availability, plants under ZT might have synthesized less protein. Conversely, in CT+R, tillage improved the soil aeration, allowing the microbes to decompose organic matter more quickly, releasing nitrogen and other nutrients into the soil for plant uptake, thus boosting leaf soluble protein.

Among weed management, at 20 DAS, the maximum value was obtained in H_2(6.33 mg g^{-1}FW), which was statistically similar to H_1 and the lowest value was obtained in the weedy check (4.47 mg g^{-1}FW). A similar trend was observed at 30 DAS and 40 DAS, with protein content declining at 40 DAS compared to 30 DAS. The interaction among different treatments was significant at 30 DAS and 40 DAS (Table 10). At 30 DAS, CT+R-H_2 (23.83 mg g^{-1} FW) recorded the highest, while ZT-H_3 (8.83 mg g^{-1} FW) recorded the lowest protein content. Lower protein in weedy plots was attributed to crop–weed competition.

The increase in leaf soluble protein content in black gram up to 30 DAS, followed by a decrease at 40 DAS, can be explained by the growth and physiological stages of the plant. During the early stages of plant growth (up to 30 DAS), black gram plants experience rapid cell division and expansion. This is the phase where the plants actively synthesize proteins necessary for their growth and development, photosynthesis and other metabolic activities. After 30 DAS, the plants transit from the vegetative stage to the reproductive stage. During this phase, the plant's metabolic focus shifts from vegetative growth to reproductive development, such as flower and pod formation. Energy and nutrients, including nitrogen, are reallocated from the leaves to reproductive organs like flowers and pods. This reduction in nutrient availability for the leaves led to a decrease in soluble protein content around 40 DAS.

Proline content

Proline content in black gram leaves increased up to 30 DAS and declined by 40 DAS (Table 9). At 20 DAS, ZT recorded the highest proline content (120.17 µg g^{-1} FW), followed by CT (104.86 µg g^{-1} FW), while CT+R was the lowest (88.59 µg g^{-1} FW). Among weed management, the maximum was under H_3 (116.36 µg g^{-1} FW) and the minimum under H_2 (94.10 µg g^{-1} FW). At 30 DAS, ZT again showed the highest proline (153.00 µg g^{-1} FW), followed by CT (146.14 µg g^{-1} FW) and ZT+R (123.53 µg g^{-1} FW), while CT+R (101.38 µg g^{-1} FW) recorded the lowest. Weedy check had the highest proline (164.01 µg g^{-1} FW), followed by H_1 (118.78 µg g^{-1} FW) and H_2 (110.24 µg g^{-1} FW). At 40 DAS, proline content followed the trend: ZT (117.20 µg g^{-1} FW) > CT (105.61 µg g^{-1} FW) > ZT+R (99.11 µg g^{-1} FW) > CT+R (96.63 µg/g FW). Among weed management, the highest proline content was recorded from H_3 (122.96 µg g^{-1} FW), followed by H_1(96.72 µg g^{-1} FW) and H_2(94.24 µg g^{-1} FW). Interaction effects were significant at all stages (Table 11). At 30 DAS, the highest proline was in ZT-H_3 (191.75 µg g^{-1} FW), followed by CT-H_3 (146.14 µg g^{-1} FW), while the lowest was in CT+R-H_2 (82.14 µg g^{-1} FW), at par with CT+R-H_1 (82.00 µg g^{-1} FW). A similar trend was observed at 40 DAS, where ZT-H_3 recorded 69.32 % higher proline than CT+R-H_2.

Proline is a stress-responsive molecule that is produced in plants under stress to protect them by maintaining redox homeostasis and scavenging free radicals. Increased proline level in plants correlated with enhanced stress caused by weed and herbicide application in soil. The lower proline content in plants grown under CT+R compared to ZT may be attributed to differences in soil conditions, plant stress levels and moisture availability. Adding residue as mulch in the case of CT and ZT improved the water and nutrient availability, reducing stress and lowering proline accumulation. The reduction in proline content in the mulched plot was also reported earlier (42). ZT without residue might have experienced stress due to harder soils or nutrient availability issues, leading to nutrient stratification, where nutrients are concentrated

Table 10. Interaction effects of tillage practices and weed management on protein content in leaf (mg.g^{-1} FW) at 30 DAS and 40 DAS

Treatments	30 DAS			40 DAS		
	H_1	H_2	H_3	H_1	H_2	H_3
CT	13.03	16.66	9.57	9.08	10.86	5.46
ZT	9.21	9.42	8.83	10.67	10.36	3.13
CT+R	20.63	23.83	9.73	11.89	18.07	7.43
ZT+R	21.56	21.86	9.80	12.33	10.88	5.59
	SEm (±)	CD(p = 0.05)		SEm (±)	CD(p=0.05)	
T within H	0.680	2 .037		0.679	2.031	
H within T	0.771	2.249		0.773	2.256	

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

Table 11. Interaction effects of tillage practices and weed management on Proline content in leaf (µg.g^{-1} FW) at 30 DAS and 40 DAS

TREATMENTS	30 DAS			40 DAS		
	H_1	H_2	H_3	H_1	H_2	H_3
CT	132.00	124.13	182.30	99.47	95.92	121.45
ZT	135.24	132.00	191.75	101.24	100.53	149.82
CT+R	82.00	82.14	140.00	92.02	88.48	109.40
ZT+R	153.67	114.45	142.00	94.15	92.02	111.17
	SEm (±)	CD(p=0.05)		SEm (±)	CD(p=0.05)	
T within H	5.275	16.759		3.879	12.065	
H within T	3.816	11.138		3.816	11.138	

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

near the soil surface compared to the more aerated soil in CT systems. This might have led to nutrient stress in plants, particularly if roots were not well-developed, further increasing proline accumulation as a stress response.

The higher proline levels in weedy checks reflect the crop's attempt to mitigate the stress caused by weed competition, whereas herbicide-treated crops experienced less stress, leading to lower proline production. In a weedy check, weeds compete with the crops for essential resources, which induces stress in the crops, triggering physiological responses such as increased proline production. Proline helps plants maintain osmotic balance and stabilizes proteins and membranes during stress. Proline accumulation is a biochemical marker of stress severity in the short term. In the long term, sustained accumulation reflects an adaptive strategy that protects cellular structures and maintains osmotic balance under prolonged stress. Therefore, higher proline levels may signal greater stress in ZT and weedy checks and reflect the crop's attempt to adapt physiologically to less favourable soil and competitive environments.

The herbicides applied in the soil were absorbed by the plants, which persisted for 16-28 days, causing stress inside the cell. The residual effect of herbicides decreased in soil over time and as a result, proline content decreased at 40 DAS. The present finding was supported by the previous research (43). The decrease in proline content in weedy check at 40 DAS may be attributed to the plant's adaptation to the competitive conditions. After overcoming the critical period of crop weed competition, the crop efficiently reallocated resources, leading to a decreased reliance on proline.

Nitrate reductase (NR) activity in leaves

NR activity in leaves at 30 DAS and 40 DAS was depicted in Fig. 7. At 30 DAS, NR activity was significantly highest in CT+R (2.64 µmol NO_2^- produced g^{-1} FW hr^{-1}), followed by ZT+R (2.52 µmol NO_2^- produced g^{-1} FW hr^{-1}), which was at par with CT (2.49 µmol NO_2^- produced g^{-1} FW hr^{-1}) and lowest in ZT (2.25 µmol NO_2^- produced g^{-1} FW hr^{-1}). Higher NR activity was reported under weed management practices compared to the weedy check. The maximum NR activity was recorded in H_2 (2.74 µmol NO_2^- produced g^{-1} FW hr^{-1}), followed by H_1 (2.59 µmol NO_2^- produced g FW/hr) and H_3(2.10 µmol NO_2^- produced g^{-1} FW hr^{-1}). At 40 DAS, NR activity followed the same trend, but the activity of the enzyme had reduced compared to 30 DAS.

Nitrogen is a critical plant macronutrient, essential for synthesizing amino acids, proteins, nucleic acids and chlorophyll. It is often a limiting factor in plant growth. Plants primarily absorb nitrogen in the form of nitrates (NO_3-) from the soil. This uptake occurs through specialized nitrate transporters in the root membranes. Inside the plant, nitrate is reduced to nitrite (NO_2-) by the enzyme NR. This reaction requires electrons and is typically driven by NADH or NADPH, which are produced during photosynthesis. Following this, nitrite is further reduced to ammonia (NH_3) by nitrite reductase, which is then incorporated into organic compounds via the glutamine synthetase/glutamate synthase (GS/GOGAT) pathway. The activity of NR is a key regulatory step in the overall nitrogen assimilation process, influencing how efficiently plants can utilize available nitrogen for their growth and development.

Higher NR activity in CT+R compared to ZT may be due to better organic matter decomposition. Residue application added organic matter to the soil, improving soil nutrient availability. In contrast, ZT without residue maintained a compact soil structure, leading to less uptake of nutrients, especially nitrate, which may have decreased the NR activity. The activity of the enzyme does not indicate any inhibitory effect of herbicides. Increase in NR activity in response to different systemic herbicides has also been reported in different crops (44). The enhancement in enzymatic activity might be attributed to the crop's absorption of a good amount of soil nitrate in the absence of weeds, which the application of herbicides has swept away. As the vegetative stage progressed, total nitrogen content in the plant decreased with age, especially from 30 to 40 DAS and this may be due to nitrogen translocation from leaves to reproductive parts.

Effect of tillage and weed management on soil microbial population

Results on microbial population at rhizosphere soil after harvest of crop (Table 12) revealed that the different microbial groups were abundantly available in way of bacteria > actinomycetes > fungi at root rhizosphere soil.

Tillage practices significantly impacted the soil bacterial population at 40 DAS and after crop harvest. The population of bacteria was found to be the highest in CT+R (32.8 × 10^5 CFU g^{-1}), followed by ZT+R (31.4 × 10^5 CFU g^{-1}), CT (30.4 × 10^5 CFU g^{-1}) and ZT (29.3 × 10^5 CFU g^{-1}), respectively, at 40 DAS. A similar trend was

Table 12. Effect of tillage and weed management on microbial population of the experimental soil

TREATMENTS	Bacterial Population (×10^5 CFU/g)			Fungal Population (×10^3 CFU/g)			Actinomycetes Population (×10^4 CFU/g)		
	Initial	40 DAS	After harvest	Initial	40 DAS	After harvest	Initial	40 DAS	After harvest
Tillage Practices (T)									
CT		30.8	26.3		9.6	8.5		12.0	10.7
ZT		29.3	23.4		11.3	9.1		12.2	11.3
CT+R		32.8	31.3		11.5	10.1		15.9	13.4
ZT+R		31.4	28.9		14.4	10.5		14.7	13.1
SEm (±)		0.38	1.04		0.28	0.61		0.75	0.37
CD (p=0.05)	26.3	1.31	3.59		0.97	NS		2.60	1.28
Weed Management (H)				9.7			10.4		
H_1		30.6	27.3		11.5	9.7		13.5	12.2
H_2		30.5	28.4		11.5	9.4		13.5	12.1
H_3		32.0	26.7		12.1	9.6		14.1	12.4
SEm (±)		0.40	0.65		0.24	0.27		0.27	0.34
CD (p=0.05)		NS	NS		NS	NS		NS	NS
Interaction		30.6	27.3		NS	NS		NS	S

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 $g.ha^{-1}$ followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

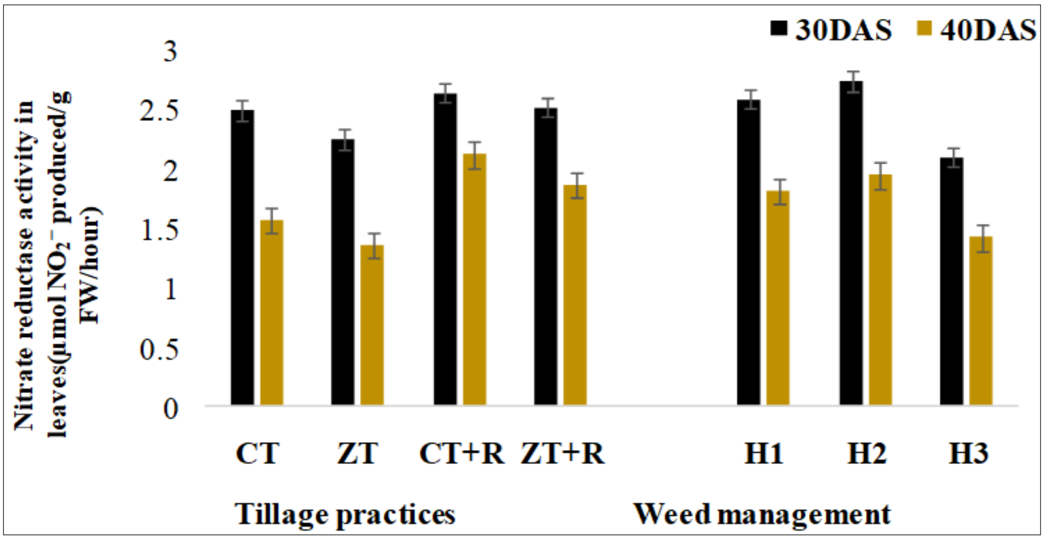

Fig. 7. Effect of tillage and weed management on nitrate reductase activity of leaves at 40 DAS. (CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (*P*=0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

followed after the harvest of the crop. The bacterial population in soil was found to be statistically nonsignificant among the weed management practices. However, highest population of bacteria was found in H_3(32 × 10^5 CFU g^{-1}) followed by H_2(30.6 × 10^5 CFU g^{-1}) and H_1(30.5×10^5 CFU/g). The same trend was observed after the harvest of the crop.

The fungal population was significantly affected by tillage practices but not weed management practices. The maximum population was recorded under ZT+R (14.4 × 10^3 CFU g^{-1}), followed by CT+R (11.5 × 10^3 CFU g^{-1}), ZT (11.3 × 10^3 CFU g^{-1}) and CT (9.6 × 10^3 CFU g^{-1}). Among weed management strategies, H3 recorded the highest number of fungi (12.1 × 10^3 CFU g^{-1}), followed by H2 (11.5 × 10^3 CFU g^{-1}), which was at par with H1 (11.5 × 10^3 CFU g^{-1}). After crop harvesting, both tillage and weed management practices did not significantly impact the soil fungal population.

Among tillage practices, CT+R (15.9 × 10^4 CFU g^{-1}) recorded the maximum actinomycetes population followed by ZT+R (14.7 × 10^4 CFU g^{-1}), CT (12.2 × 10^4 CFU g^{-1}), which was at par with ZT (12.0 × 10^4 CFU g^{-1}). Weed management practices exerted a nonsignificant impact on the soil actinomycetes population. Weedy check (14.2 × 10^4 CFU g^{-1}) recorded the highest actinomycetes population, followed by H2 (11.9 × 10^4 CFU g^{-1}), which was at par with H1 (11.7 × 10^4 CFU g^{-1}) at 40 DAS.

Different tillage practices have a significant impact on soil environments and shape the habitats of soil microorganisms. Our findings indicated that both CT and ZT, when combined with residue retention, showed increased populations of total bacteria and actinomycetes. However, ZT without residue retention significantly reduced microflora populations. This result is aligned with the findings of a previous research (45). Improved air and water movement in tilled soil with adequate oxygen and moisture led to an increased soil microbial population dominated by aerobic microorganisms. Residue cover in ZT increased the availability of nutrients and carbon sources.

Additionally, the residue cover maintained consistent moisture levels and regulated temperature, which helped promote the bacterial population in the soil. This result was found to conform to a previously conducted work (46). Fungi are the dominant soil microbes in undisturbed soil and crop residues are mainly decomposed by the fungal community. In ZT practices, soil disturbance prevention promotes fungal hyphal growth (45). This might be due to the fact that tillage affects the fungal network structure and mycorrhizal network complexity.

Weed management practices did not significantly affect the soil microbial population. Herbicides applied as pre-emergence and post-emergence did not significantly influence total bacterial, fungal and actinomycetes populations. However, H_3 recorded the maximum bacterial, fungal and actinomycetes population, closely followed by H_2 and H_1. The lower residual effect of pre-emergence herbicides in the soil and reduced contact of herbicides with soil by directly applying post-emergence herbicides to weed foliage might not have influenced the soil microbial population. Similar results were obtained in another study (47).

Effect of tillage and weed management on yield attributes and yield of black gram

Table 13 summarizes and depicts the data on the number of pods per plant, number of seeds per pod, pod length, pod yield, stover yield, test weight and seed yield of black gram.

Number of pods per plant

A thorough data analysis showed that tillage practices significantly increased the number of pods per plant. CT+R recorded the highest number of pods per plant (30.20), followed by ZT+R (23.87), CT (20.73), which significantly outperformed ZT (18.13). The analysis also revealed that weed control treatments notably affected the number of pods per plant. H_2 resulted in a significantly higher number of pods per plant (29.55) compared to H_1 (26.40) and both significantly outperformed the weedy check (13.75).

Number of seeds per pod

A scrutiny of the data indicated that tillage practices had no significant influence on the number of seeds per pod. Among the tillage practices, CT+R recorded the maximum number of seeds per pod (5.77), followed by ZT+R (5.5), ZT (5.27) and CT (5.20). However, weed management practices substantially impacted the number of seeds per pod. H_2 recorded the highest number of seeds, i.e. 5.65, followed by H_1 (5.58); whereas the lowest number of seeds per plant was observed in H_3 (5.08).

Table 13. Effect of tillage and weed management on yield and yield attributes of black gram

TREATMENTS	No. of pods per plant	No. of seeds per pod	Pod length (cm)	Pod yield (kg ha^{-1})	Stover yield (kg ha^{-1})	Test weight (g)	Seed yield (kg ha^{-1})
				Tillage Practices(T)			
CT	20.73	5.20	4.3	1103.85	2597.43	35.37	786.05
ZT	18.13	5.27	4.2	993.96	2263.02	31.97	746.42
CT+R	30.20	5.77	4.5	1826.39	3601.13	35.71	1055.57
ZT+R	23.87	5.50	4.3	1412.61	3137.57	35.34	818.31
SEm (±)	0.47	0.12	0.12	56.00	96.640	0.77	10.31
CD (p=0.05)	1.62	NS	NS	29.82	334.390	2.68	35.680
				Weed Management (H)			
H_1	26.40	5.58	4.3	1450.11	3220.18	35.48	930.19
H_2	29.55	5.65	4.5	1657.47	3568.65	35.98	959.72
H_3	13.75	5.08	4.1	895.03	1910.52	32.33	664.84
SEm (±)	0.72	0.09	0.09	40.88	68.600	0.90	8.98
CD (p=0.05)	2.11	0.26	0.27	119.29	200.215	2.63	26.18
Interaction	S	NS	NS	S	S	NS	S

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

Pod length

Tillage practices had no significant impact on pod length. Nevertheless, the longest pods were observed under CT+R (4.5 cm), followed by ZT+R (4.3 cm), CT (4.3 cm) and ZT (4.2 cm). Weed management practices exhibited significant differences in pod length. The maximum pod length was observed in H_2 (4.5 cm), which was at par with H_1(4.3 cm) and the minimum pod length was observed under the untreated weedy check (4.1 cm).

Pod yield

Data on pod yield revealed that different tillage practices substantially impacted the pod yield of BG. The pod yield under CT+R increased by 29.29 % compared to ZT+R, 65.45 % compared to CT and 83.74 % compared to ZT. Weed management approaches had a significant impact on pod yield. There was an 85.18 % increase in pod yield in H_2 compared to the weedy check (H_3).

Stover yield

The stover yield data indicate that CT+R resulted in significantly higher stover production (3601.13 kg ha^{-1}), followed by ZT+R (3137.57 kg ha^{-1}), CT (2597.43 kg ha^{-1}) and all three tillage practices outperformed ZT (2263.02 kg ha^{-1}). Weed management practices also markedly affected stover yield, with all treatments producing significantly more stover than the weedy check (1910.52 kg ha^{-1}). H_2 led to the highest stover yield (3568.65 kg ha^{-1}), significantly greater than H_1 (3220.18 kg ha^{-1}).

Test weight

A detailed review of the data in Table 8 revealed that tillage practices significantly influenced the test weight. CT+R recorded the maximum test weight (35.71 g), which was statistically similar to CT (35.37 g) and ZT+R (35.34 g); whereas, the minimum was observed in ZT (31.97 g). Weed management strategies had a notable effect on test weight. All weed control treatments significantly increased the test weight compared to the untreated control (H_3) (32.33 g). H_2 resulted in the highest test weight (35.98 g), which was at par with H_1 (35.48 g).

Seed yield

An analysis of grain yield data showed that tillage practices impacted black gram production. CT+R resulted in the highest grain yield (1055.0 kg ha^{-1}), followed by ZT+R (818.3 kg.ha^{-1}), which was statistically similar to CT (786.0 kg.ha^{-1}). All these practices significantly outperformed ZT, which had a lower yield (746.4 kg ha^{-1}). There was notable variation in grain yield across weed management strategies. All weed control practices produced substantially more grain than the untreated weedy control (664.8 kg.ha^{-1}). The highest grain yield was achieved with H_2 (959.0 kg ha^{-1}), which was significantly higher than H_1 (930.0 kg.ha^{-1}). A significant interaction was observed for seed yield (Table 14), with the maximum under CT+R–H_2 (1195.67), followed by CT+R–H_1 (1160.09) and ZT+R–H_2 (923.22), while the minimum was recorded under ZT–H_3 (577.70).

The superior performance of CT+R in almost all yield attributes and yield over other tillage methods might be due to the increased surface area of roots in tilled plots. Increased root surface area resulted in better plant nourishment due to uptake of more nutrients from the soil, which in turn contributed to the plant's robust growth and better yield indices. On the contrary, greater weed control efficiency of CT encouraged the uptake of nutrients and moisture, which positively impacted the rate of photosynthesis as well as storage and translocation of photosynthates. Efficient partitioning of accumulated photosynthates helped in the establishment of favorable yield characteristics. Similar results had been reported by a separate study (48). Better results under CT+R might also be attributed to higher growth and improved yield attributes, increased chlorophyll content, better soil moisture

Table 14. Interaction effects of tillage practices and weed management on seed yield (kg ha^{-1})

Treatments	H_1	H_2	H_3
CT	858.79	878.32	621.05
ZT	819.89	841.68	577.70
CT+R	1160.09	1195.67	810.95
ZT+R	882.01	923.22	649.69
	SEm (±)	CD (p=0.05)	
T within H	17.91	55.50	
H within T	17.94	52.37	

(CT: Conventional tillage; ZT: Zero tillage; CT+R: Conventional tillage with residue; ZT+R: Zero tillage with residue; H_1: Pendimethalin at 750 g/ha followed by imazethapyr at 70 g/ha; H_2: H_1 + one hand weeding; H_3: Weedy check; DAS: Days after sowing; SEm (±): Standard error of the mean; CD (p = 0.05): Critical difference at 5 % significance level; S: Significant; NS: Nonsignificant)

retention and better soil microbial population. Further, decomposition of the added residue as mulch might have improved the nutrient content of the soil. This result agrees with the result of another experiment (36). CT reduced soil compaction and bulk density, increasing root length, biomass, nodulation and bacterial activity. Furthermore, it lowered the crop-weed competition and improved the availability of plant nutrients, moisture, space and sunshine in the crops during their growth and reproductive stages. The lower yield under ZT might be due to greater bulk density, leading to harsh physical conditions of soil that restricted the penetration of roots to a deeper layer and ultimately affected the uptake of nutrients and water (49).

While CT+R demonstrated clear yield advantages in terms of pod number and other yield components under the present conditions, it is essential to note that ZT systems with residue retention are often more sustainable in the long term. Despite sometimes showing lower yields in the initial years, conservation agriculture practices can improve soil structure, organic matter and biological activity over time, ultimately narrowing the performance gap with CT-based systems. Hence, the superiority of CT+R observed here should be interpreted alongside the sustainability benefits of residue-based ZT in long-term cropping systems.

Hand weeding with the combined application of pre- and post-emergence herbicides controls weed density considerably for an extended period. It also reduced crop weed competition from initial growth to reproductive stages and helped increase growth, uptake of nutrients and their translocation. These had a positive impact on the photosynthesis rate and photosynthate accumulation. Effective partitioning of photosynthates, in turn, contributed to the development of yield attributes and improved the yield indices. This consequence aligns more closely with previous findings (30, 32, 50).

Collectively, these analyses converge on two key recommendations: residue retention, particularly under zero-tillage, is the primary driver of improved morphological, physiological, biochemical and yield outcomes; and herbicide-only weed management generally outperforms delayed mechanical weeding by preserving early growth and metabolic integrity (1, 2). The interaction between residue and chemical weed control fosters resilience by sustaining favourable microclimatic and soil conditions supporting coordinated trait expression from vegetative growth to yield formation (50). These findings inform the design of conservation-agriculture systems that integrate minimal soil disturbance, surface mulch and strategic herbicide use to maximize legume productivity and stability under diverse stressors.

Conclusion

The combination of CT with residue retention (CT+R) and integrated weed management (H_2) proved most effective for enhancing black gram productivity under Eastern Indian conditions. A novel outcome of this study is the differential response of soil microbes, with CT+R favouring bacterial and actinomycetes populations, while ZT+R supported higher fungal activity. These findings indicate that tillage–residue practices shape crop performance and influence the microbial balance that underpins soil health. Adopting CT+R with integrated weed management for farmers in Eastern India can deliver immediate yield benefits, while gradual integration of residue -based ZT may offer long-term sustainability advantages.

Acknowledgements

The authors gratefully acknowledge the facilities and support provided by Odisha University of Agriculture and Technology, Bhubaneswar, for the successful execution of this research work.

Authors' contributions

JT carried out the research, performed the investigation, formal analysis and visualization. PS conceptualized the study, supervised the project, developed the methodology, curated data, drafted the manuscript, reviewed & edited the manuscript, performed the investigation, visualization and managed project administration. KKP conceptualized the study, developed the methodology, curated data, drafted the manuscript, reviewed & edited the manuscript, supervised the project and managed project administration. RD conceptualized the study, developed the methodology, curated data, drafted the manuscript, performed the investigation and visualization. IK conceptualized the study, developed the methods and curated data. AM curated data, performed formal analysis, wrote, reviewed & edited the manuscript and managed project administration. RB conceptualized the study and supervised the project.

Compliance with ethical standards

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

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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