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Agronomic Responses of Cabbage (*Brassica oleracea* L.) to Cow Dung and *Bacillus amyloliquefaciens*-decomposed Wheat Straw in Arid Saudi Soils

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Abstract. **Cabbage (*Brassica oleracea* L.) production in arid regions is limited by low soil fertility, poor organic matter content, and declining sustainability associated with overreliance on inorganic fertilizers. Residue management, particularly of high carbon (C):nitrogen (N) wheat straw, is further complicated by slow decomposition under dry conditions. This study evaluated a sustainable soil amendment strategy that integrates cow dung and wheat straw decomposed using *Bacillus amyloliquefaciens* to improve cabbage growth and productivity in arid Saudi soils. A split–split–plot experiment was conducted over two seasons; three levels each of cow dung (0, 10, 20 t·ha^{-1}), wheat straw [0, 20, 30 t·ha^{-1} plus nitrogen–phosphorus–potassium (NPK) control], and *Bacillus amyloliquefaciens* (0, 2, 4 L/plot) were tested. Agronomic parameters including head weight, total yield, harvest index, morphological traits, and dry biomass were assessed. Results showed that the combination of 20 t·ha^{-1} cow dung, 30 t·ha^{-1} wheat straw, and 4 L/plot inoculum produced the highest head weights (up to 2940 g), yields (up to 89.11 t·ha^{-1}), and harvest indices (up to 49.49%). Morphological traits such as head diameter, height, and circumference were significantly improved. These treatments outperformed the control in yield and biomass parameters, demonstrating synergistic effects among organic inputs and microbial decomposition, especially under high ambient temperatures. This study concludes that integrating cow dung with *B. amyloliquefaciens*-decomposed wheat straw can significantly improve cabbage yield and growth in arid soils, providing an effective, climate-adapted alternative to synthetic fertilization.**

Cabbage (*Brassica oleracea* L.) is an important vegetable crop valued for its nutritional and economic significance. In arid and semi-arid regions, production is often constrained by low soil organic matter, poor nutrient retention, and high evapotranspiration rates (El-Sabagh et al. 2020). Conventional fertilization practices heavily rely on inorganic nitrogen–phosphorus–potassium (NPK) fertilizers, which, although effective in the short term, can cause nitrate accumulation in edible tissues, degrade soil health, and contribute to environmental pollution (Ali et al. 2021).

Organic amendments such as cow dung and crop residues are increasingly recognized for their potential to improve soil physical, chemical, and biological properties (Suresh et al. 2020). Wheat straw, however, has a high carbon-to-nitrogen (C:N) ratio that can slow decomposition and immobilize N when applied directly (Zhao et al. 2019). Microbial decomposition, particularly using cellulolytic bacteria like *Bacillus amyloliquefaciens*, accelerates the breakdown of lignocellulosic material and synchronizes nutrient release with crop uptake (Kumar et al. 2018).

High ambient temperatures in arid environments can further accelerate microbial activity, making in situ decomposition of crop residues a practical strategy for sustainable vegetable production (Bhattacharjya et al., 2021). This study evaluated the agronomic performance of cabbage under varying combinations of cow dung, microbially decomposed wheat straw, and *B. amyloliquefaciens*, hypothesizing that the combined application would outperform single amendments or synthetic fertilizers. Figure 1 summarizes the concept of the study.

Materials and Methods

The study was conducted over two cabbage-growing seasons (2023–24 and 2024–25) at King Abdulaziz University's Agricultural Research Station in Jeddah, Saudi Arabia, an arid location with warm temperatures and scarce rainfall. A split–split plot design with three replicates tested combinations of cow dung (0, 10, 20 t·ha^{-1}) in the main plots, *B. amyloliquefaciens* inoculum (0, 2, 4 L/plot) in the sub-subplots, and wheat straw (0, 20, 30 t·ha^{-1} in subplots plus NPK control). The NPK was part of the sub-subplot as a positive control.

Newly isolated from the rhizospheric soil of Hada Al-Sham, Saudi Arabia, the *B. amyloliquefaciens* strain used in this study was selected because of its observed decomposition potential in the field. The 16S rRNA gene sequence of the isolate was submitted to GenBank under the accession number MW785874.

Wheat straw, chopped into 3- to 5-cm pieces, was inoculated with *B. amyloliquefaciens* and predecomposed outdoors for 10 d to initiate decomposition and ensure proper contact between the bacteria and the straw. Field preparation included ploughing, harrowing, leveling, and dividing the land into 108 plots (2 × 2 m). The bacterial culture was grown in nutrient media, diluted, and applied to the plots. Straw-amended plots were turned regularly and irrigated for 1 month before transplanting cabbage seedlings. Then, NPK fertilizer was applied in three split doses after transplantation. Transplanting to harvesting for seasons one and two was performed from 2 Nov 2023 to 15 Feb 2024 and from 17 Nov 2024 to 22 Feb 2025, respectively.

Crop care included drip irrigation to maintain soil moisture and standard pest and weed management. Pigment contents (determined using the Acetone Extraction and Spectrophotometry method) were measured at the end of the vegetative stage. Growth parameters (head weight, yield, harvest index, dimensions, biomass) and leaf area (using the leaf disc method) were recorded from five plants per plot at harvest, and the plot mean values were used for the statistical analysis. The data analysis used a split–split plot analysis with least significant difference (LSD) post hoc tests at $P \leq 0.05$ to evaluate treatment effects and interactions using Statistix 10 software. Figures were generated using R software. This method integrated organic amendments and beneficial microbes in an arid

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We declare that we have no relevant financial or nonfinancial competing interests related to this work.
All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were performed by Mohammed Saba. Kamal A. M. Abo-Elyousr and Samir Gamil Al-Solaimani are supervisors. The first draft of the manuscript was written by Mohammed Saba from the already approved thesis.
The datasets analyzed during the current study are available from the corresponding author upon reasonable request.
Perplexity was used to correct grammar.
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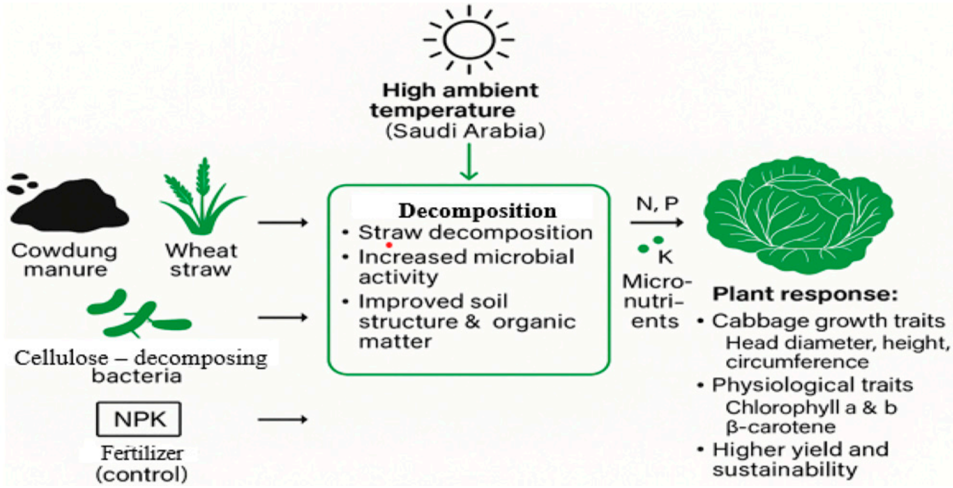

Fig. 1. Summary of the study.

climate to assess impacts on cabbage productivity and soil health.

Results

The results of the pre-experimental soil analysis are presented in Table 1. The soil was sandy loam composed of 76% sand, 14% silt, and 10% clay that offered good drainage with moderate moisture and nutrient retention. The soil was slightly alkaline (pH 7.90), which may impact micronutrient availability. Electrical conductivity (EC) was moderate (340 $\mu S \cdot cm^{-1}$) and unlikely to affect cabbage growth. Organic matter (0.28%) and total N (0.02%) were low, indicating limited fertility. Macronutrients such as P, magnesium (Mg), K, and sulfur (S) were abundant, while zinc (Zn) and copper (Cu) levels were sufficient for crop needs. These baseline qualities set the stage for studying how organic amendments influence cabbage growth and nutrient uptake.

This study analyzed the chemical composition of cow dung and wheat straw as organic amendments (Table 2). Cow dung contained high N (2.97%), P (1.34%), and K (2.31%), making it a rich source of essential macronutrients with moderate calcium (Ca) and Mg and low sodium, minimizing the salinity risk. It was also rich in micronutrients such as iron (Fe), manganese (Mn), Cu, and Zn. Its C:N ratio of 26.3 indicates a relatively fast decomposition rate, allowing quick nutrient release.

In contrast, wheat straw had much lower N (0.41%) but higher Ca and Mg. Its P and K were lower, and micronutrient levels were relatively poor. The high C:N ratio of 83 suggests slow decomposition, contributing to long-term soil organic matter and improved structure. Mixing cow dung with straw lowers the overall C:N ratio, improving conditions for microbial breakdown.

The bacterium *B. amyloliquefaciens* was used to accelerate decomposition by secreting enzymes that degrade lignocellulosic materials. Combined, cow dung, straw, and bacterial inoculants synergize to enhance nutrient cycling, organic matter content, and crop productivity.

Regarding crop outcomes, cow dung at 20 $t \cdot ha^{-1}$ significantly increased cabbage head weight, yield, and harvest index, with improved morphology and biomass (Table 3). Bacterial inoculation at 4 L/plot also enhanced yield and growth parameters dose-dependently. Wheat straw at 30 $t \cdot ha^{-1}$ improved head weight, yield, harvest index, and biomass compared with controls. Overall, integrating organic manure, bacterial inoculation, and straw management substantially boosted cabbage productivity.

Interaction effects

The two-way and three-way interaction results (Fig. 2A-2C) revealed that the combined application of cow dung with bacterial inoculation, cow dung with wheat straw, and bacterial inoculation with wheat straw significantly improved cabbage head weight, total yield, and harvest index across both seasons. The most pronounced enhancements were consistently obtained under the highest application rates of each input in combination—particularly 20 $t \cdot ha^{-1}$ cow dung with 4 $L \cdot plot^{-1}$ bacterial inoculum, and treatments involving cow dung–straw or bacteria–straw combinations supplemented with NPK—where yield and harvest index values markedly exceeded those of individual applications.

For example, the 20 $t \cdot ha^{-1}$ cow dung+ NPK+ wheat straw treatment produced the greatest recorded performance in season 2, achieving a head weight of 1938 g and total yield of 2940 $g \cdot plant^{-1}$. In contrast, control plots with no amendments consistently recorded the lowest values for all measured traits.

More specifically, the cow dung× wheat straw interaction demonstrated that the combination of 20 $t \cdot ha^{-1}$ cow dung with 30 $t \cdot ha^{-1}$ wheat straw achieved the highest head weight (1938 g in season 1 and 2940 g in season 2), total yield (58.74 $t \cdot ha^{-1}$ and 89.11 $t \cdot ha^{-1}$, respectively), and harvest index (42.79% and 48.38%, respectively) (Fig.2A). The cow dung × bacterial inoculation interaction indicated that pairing 20 $t \cdot ha^{-1}$ cow dung with 4 $L \cdot plot^{-1}$ inoculum resulted in the development of the largest heads and the

Table 1. Physical and chemical properties of the soil used in the experiment.

Parameters	Values	Evaluation	Method
pH (1:1 soil:water)	7.90	Slightly alkaline	Brady and Weil (2016)
EC (1:1 soil:water) ($\mu S \cdot cm^{-1}$)	340	Moderate	Richards (1954)
	%		
Organic matter	0.28	Very low	US Department of Agriculture, Natural Resources Conservation Service (1998
Total N	0.02	Very low	Havlin et al. (2014)
Clay	10		FAO (2006)
Silt	14		FAO (2006)
Sand	76		FAO (2006)
Textural class	Sandy loam		
	$mg \cdot kg^{-1}$		
Available P	93.5	Very high	Havlin et al. (2014)
Available Mg	529	High	Soil Science Society of America (2000)
Extractable K	371	High	Cornell Cooperative Extension (2007)
Available S	173.3	Very high	Soil Science Society of America (2000)
Available Zn	2.24	Sufficient	Soil Science Society of America (2000)
Available Cu	2.24	High	Havlin et al. (2014)

Cu = copper; EC = electrical conductivity; K = potassium; Mg = magnesium; N = nitrogen; P = phosphorus; S = sulfur; Zn = zinc.

Table 2. Experimental materials.

Materials	Macronutrients						Micronutrients				C:N
	N	P	K	Ca	Mg	Na	Fe	Mn	Cu	Zn	
	(%)						(mg/kg)				%
Cow dung	2.97	1.34	2.31	0.59	0.34	0.55	473.55	278.7	29.08	113.9	26.3
Wheat straw	0.41	0.48	0.34	0.87	0.57	0.14	196	38	5.5	34.1	83

C = carbon; Ca = calcium; Cu = copper; EC = electrical conductivity; Fe = iron; K = potassium; Mg = magnesium; N = nitrogen; Na = sodium; P = phosphorus; S = sulfur; Zn = zinc.

Table 3. Single effects of cow dung, bacteria and straw on cabbage head weight (g), total yield (g), and harvest index.

	Head weight (g)		Total yield (t·ha^{-1})		Harvest index	
Cow dung (t·ha^{-1})	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
0	1047 b[1]	1535 c	31.74 b	46.50 c	35.09 b	42.32 c
10	1107 b	2140 b	33.56 b	64.85 b	33.21 b	46.82 b
20	1681 a	2636 a	50.94 a	79.89 a	41.26 a	49.49 a
Bacteria (L/plot)						
0	1077 c	1889 c	32.63 c	57.24 c	33.31 b	44.64 c
2	1276 b	2148 b	38.68 b	65.08 b	37.26 a	46.37 b
4	1482 a	2275 a	44.92 a	68.94 a	39.00 a	47.62 a
Straw (t·ha^{-1})						
0	1014 c	1780 d	30.73 c	53.94 d	ns	46.66 a
20	1237 b	2028 c	37.49 b	61.47 c		46.29 a
30	1338 b	2244 b	40.54 b	68.00 b		46.58 a
600 kg/ha NPK	1525 a	2363 a	46.22 a	71.59 a		45.31 b

[1] Means within a column followed by different letters differ significantly at $P < 0.05$ according to the least significant difference test.

NPK = nitrogen–phosphorus–potassium; ns = nonsignificant; season 1 = 2023–24 season; season 2 = 2024–25 season.

highest biomass accumulation. Similarly, under the bacteria× wheat straw interaction, the application of 4 L·plot^{-1} inoculum with 30 t·ha^{-1} wheat straw yielded head weights of 1884 g and 2587 g in season 1 and season 2, respectively.

Single Effects on Head Growth Traits

Cow dung, bacterial inoculation, and wheat straw each had significant ($P < 0.05$) effects on cabbage head growth traits (Table 4). Head diameter, height, and circumference increased consistently with higher levels of each factor. The greatest values were obtained with 20 t·ha^{-1} cow dung, 4 L/plot bacteria, and NPK straw application, while the control treatments recorded the lowest values. These results indicate that organic manure improves soil fertility, bacterial inoculants stimulate nutrient uptake, and straw residues conserve soil moisture and add organic

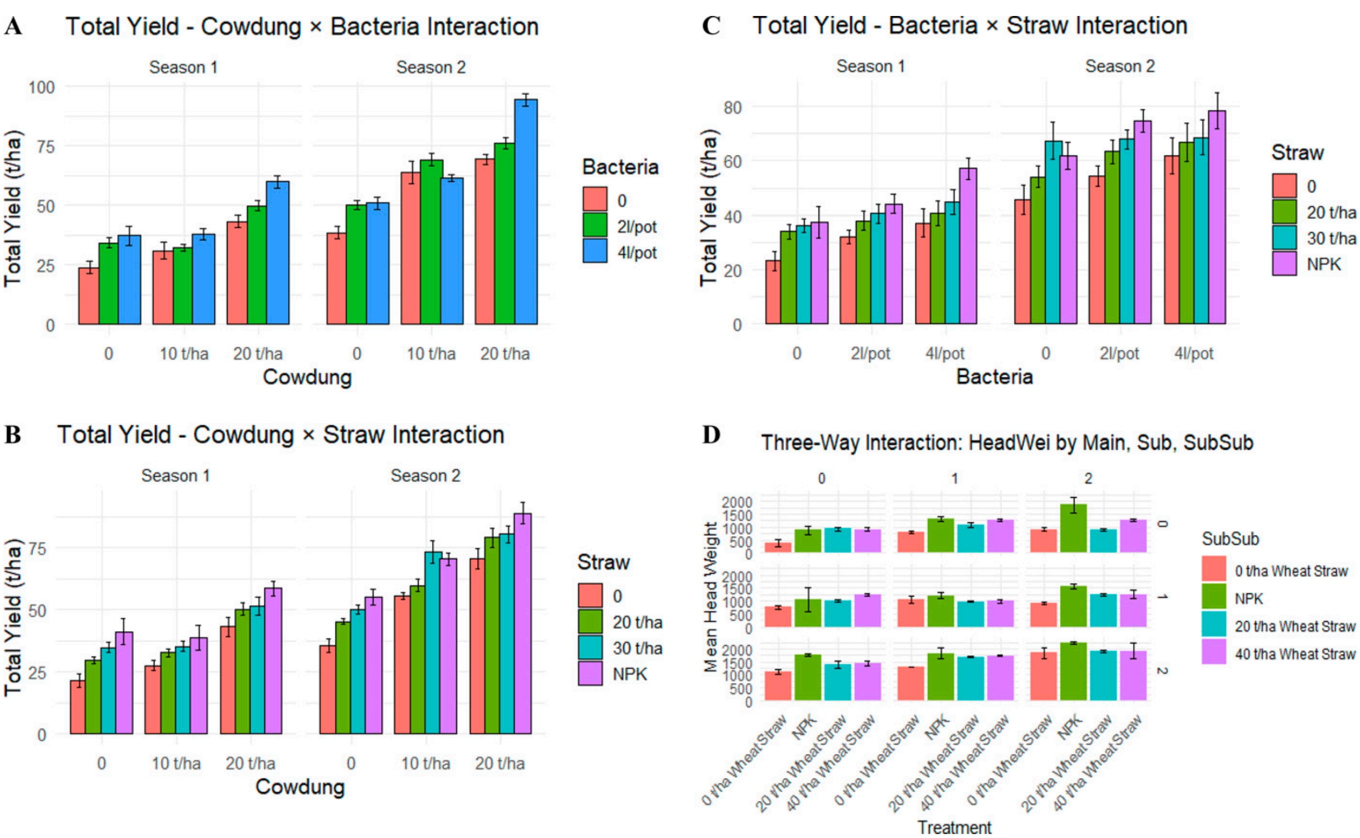

Fig. 2. (**A**) Interaction effects of cow dung and bacterial inoculation on cabbage total yield during two growing seasons. (**B**) Interaction effects of cow dung and straw applications on cabbage total yield (t·ha^{-1}) during two growing seasons. (**C**) Interaction effects of bacterial inoculation and straw applications on cabbage total yield during two growing seasons. (**D**) Interaction effects of cow dung, bacterial inoculation, and straw applications on cabbage head weight, total yield, and harvest index during two growing seasons. HeadWei = head weight.

Table 4. Single effects of cow dung, bacteria, and straw on cabbage head diameter (cm), height (cm), and circumference (cm).

	Head diam (cm)		Head height (cm)		Head circumference (cm)	
Cow dung (t·ha^{-1})	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
0	12.75 c[i]	13.01 c	14.54 c	14.90 c	45.70 c	46.80 c
10	15.05 b	15.79 b	15.55 b	15.96 b	48.87 b	50.15 b
20	16.51 a	17.31 a	17.58 a	18.12 a	55.25 a	56.92 a
Bacteria (L/plot)						
0	14.41 b	14.95 c	15.23 c	15.76 c	47.84 c	49.80 c
2	14.70 ab	15.31 b	15.82 b	16.33 b	49.70 b	50.15 b
4	15.19 a	15.85 a	16.64 a	16.89 a	52.27 a	56.92 a
Straw (t·ha^{-1})						
0	13.10 c	13.43 d	14.95 c	15.03 d	46.97 c	47.21 d
20	14.75 b	14.99 c	15.82 b	15.98 c	49.72 b	50.19 c
30	15.39 a	15.95 b	16.27 a	16.75 b	51.13 a	52.64 b
600 kg/ha NPK	15.84 a	17.12 a	16.53 a	17.54 a	51.94 a	55.12 a

[i] Means within a column followed by different letters differ significantly at $P < 0.05$ according to the least significant difference test.
NPK = nitrogen–phosphorus–potassium; ns = nonsignificant; season 1 = 2023–24 season; season 2 = 2024–25 season.

matter, all of which contribute to enhanced cabbage head development.

Interaction Effects on Cabbage Head Morphology

The interaction between cow dung × bacterial inoculation had a significant effect on cabbage head morphological characteristics, including head diameter, height, and circumference (Fig. 3A). The combination of 20 t·ha^{-1} cow dung with 4 L·plot^{-1} bacterial inoculum consistently produced the largest head dimensions across both seasons, whereas the untreated control had the smallest values.

The cow dung × wheat straw interaction exhibited a marked influence on cabbage head traits (Fig. 3B). The highest head diameter, height, and circumference were achieved with the combined application of 20 t·ha^{-1} cow dung and NPK-supplemented wheat straw, while the absence of both amendments resulted in the lowest measurements. This highlights the complementary benefits of cow dung and wheat straw in enhancing head size and overall crop performance.

The interaction between bacterial inoculation × wheat straw application also resulted in significant improvements in head morphology (Fig. 3C). The application of 4 L·plot^{-1} bacterial inoculum with NPK-supplemented wheat straw produced the largest cabbage heads in terms of diameter, height, and circumference, whereas the control treatment without either input consistently recorded the lowest values.

Single Effects on Physiological Traits

The single-factor effects of cow dung, bacterial inoculation, and wheat straw on chlorophyll a, chlorophyll b, β-carotene, and leaf area (Table 5) were also significant. The highest pigment contents and leaf areas were recorded at 20 t·ha^{-1} cow dung, 4 L/plot bacteria, and NPK straw, reflecting improved photosynthetic efficiency and biomass accumulation. Conversely, the lowest values were observed under untreated controls, confirming that organic and biological inputs not only improve growth but also strengthen physiological capacity and crop vigor.

The results of the two-way and three-way interaction analyses (Fig. 4A-4D) clearly

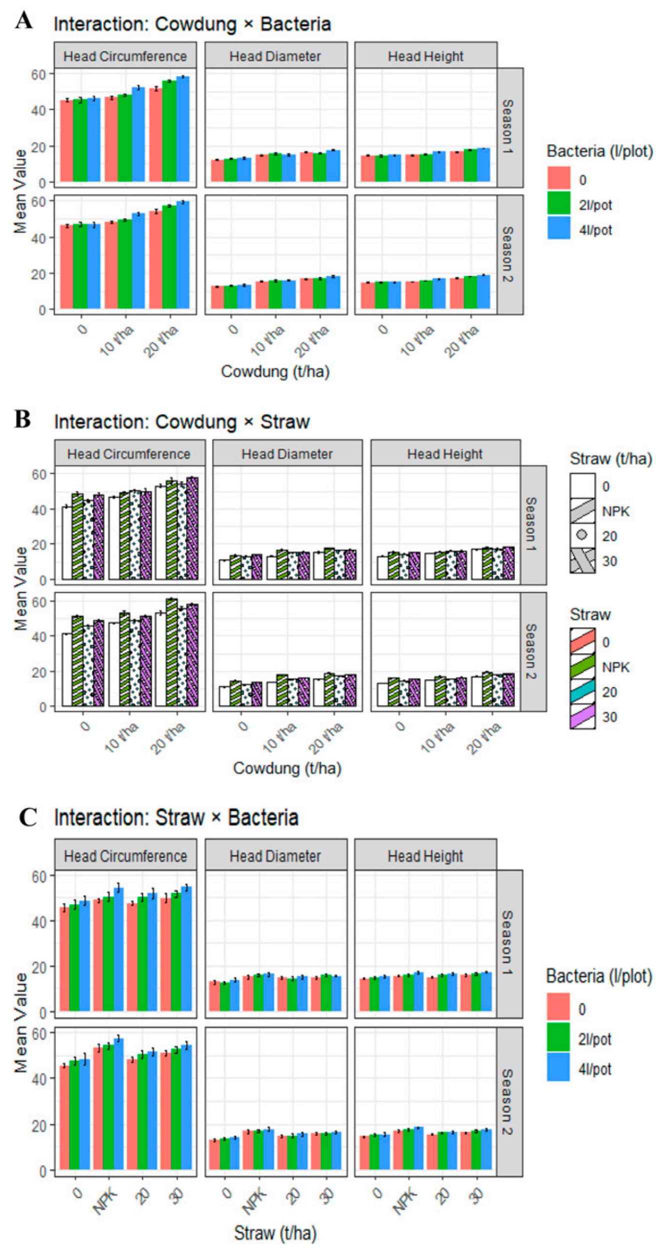

Fig. 3. (**A**) Interaction effects of cow dung and bacterial inoculation on cabbage head diameter, height, and circumference during two growing seasons. (**B**) Interaction effects of cow dung and straw applications on cabbage head diameter, height, and circumference during two growing seasons. (**C**) Interaction effects of straw and bacterial inoculation on cabbage head diameter, height, and circumference during two growing seasons.

Table 5. Single effects of cow dung, bacteria, and straw on cabbage leaf chlorophyll a, chlorophyll b, and beta carotene.

	Chlorophyll a		Chlorophyll b		Beta carotene		Leaf area (m^2)	
Cow dung ($t{\cdot}ha^{-1}$)	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
0	10.56 c[i]	11.17 c	10.13 b	11.66 c	2.22 b	1.98 c	1.70 c	1.64 c
10	12.50 b	14.49 b	11.46 ab	13.74 b	3.08 a	2.79 b	2.10 b	2.07 b
20	14.58 a	16.36 a	13.00 a	15.91 a	3.08 a	4.00 a	2.55 a	2.56 a
Bacteria (L/plot)								
0	11.10 b	12.61 c	10.83 b	12.93 c	2.16 b	2.50 c	1.94 c	1.91 c
2	11.84 b	14.06 b	11.74 ab	13.61 b	2.40 b	2.91 b	2.13 b	2.14 b
4	14.70 a	15.36 a	12.02 a	14.77 a	3.82 a	3.34 a	2.28 a	2.22 a
Straw ($t{\cdot}ha^{-1}$)								
0	10.39 d	11.71 d	9.18 b	10.72 d	1.83 c	1.72 d	1.49 d	1.45 d
20	12.14 c	13.35 c	12.24 a	13.32 c	2.71 b	2.48 c	2.05 c	1.89 c
30	13.10 b	14.62 b	11.90 a	14.54 b	2.81 b	3.07 b	2.28 b	2.32 b
600 kg/ha NPK	14.58 a	16.36 a	12.80 a	16.49 a	3.83 a	4.39 a	2.65 a	2.71 a

[i]Means within a column followed by different letters differ significantly at $P < 0.05$ according to the least significant difference test.
NPK = nitrogen–phosphorus–potassium; ns = nonsignificant; season 1 = 2023–24 season; season 2 = 2024–25 season.

demonstrated that the combined application of cow dung with bacterial inoculation, cow dung with wheat straw, and bacteria with wheat straw produced significant enhancements in physiological and biochemical attributes of cabbage leaves, particularly in chlorophyll a, chlorophyll b, and β-carotene concentrations, across both growing seasons. The magnitude of improvement was most pronounced when the highest levels of each input were applied concurrently—most notably the combined use of 20 $t{\cdot}ha^{-1}$ of cow dung with 4 $L{\cdot}plot^{-1}$ of bacterial inoculum—which consistently outperformed lower-dose or single-factor treatments. In addition, the integration of cow dung–wheat straw or bacteria–wheat straw treatments, when further supplemented with recommended NPK fertilization, resulted in pronounced increases in both marketable yield and harvest index, indicating an enhanced efficiency of resource use and biomass partitioning toward economically valuable plant parts.

These outcomes provide compelling evidence of the existence of a robust synergistic interaction among organic manure, beneficial microbial inoculants, and crop residue amendments. Such synergy appears to operate through complementary improvements in soil physical properties, nutrient mineralization rates, and rhizosphere microbial activity, collectively fostering superior plant growth and metabolic activity. Therefore, the integrated approach markedly surpasses the performance of any single-factor application, underscoring the agronomic value and sustainability potential of combining organic and microbial amendments with crop residues under balanced nutrient management regimes for optimizing cabbage productivity.

Single effects of cow dung, bacteria, and wheat straw on cabbage growth dry biomass components, which responded positively to the

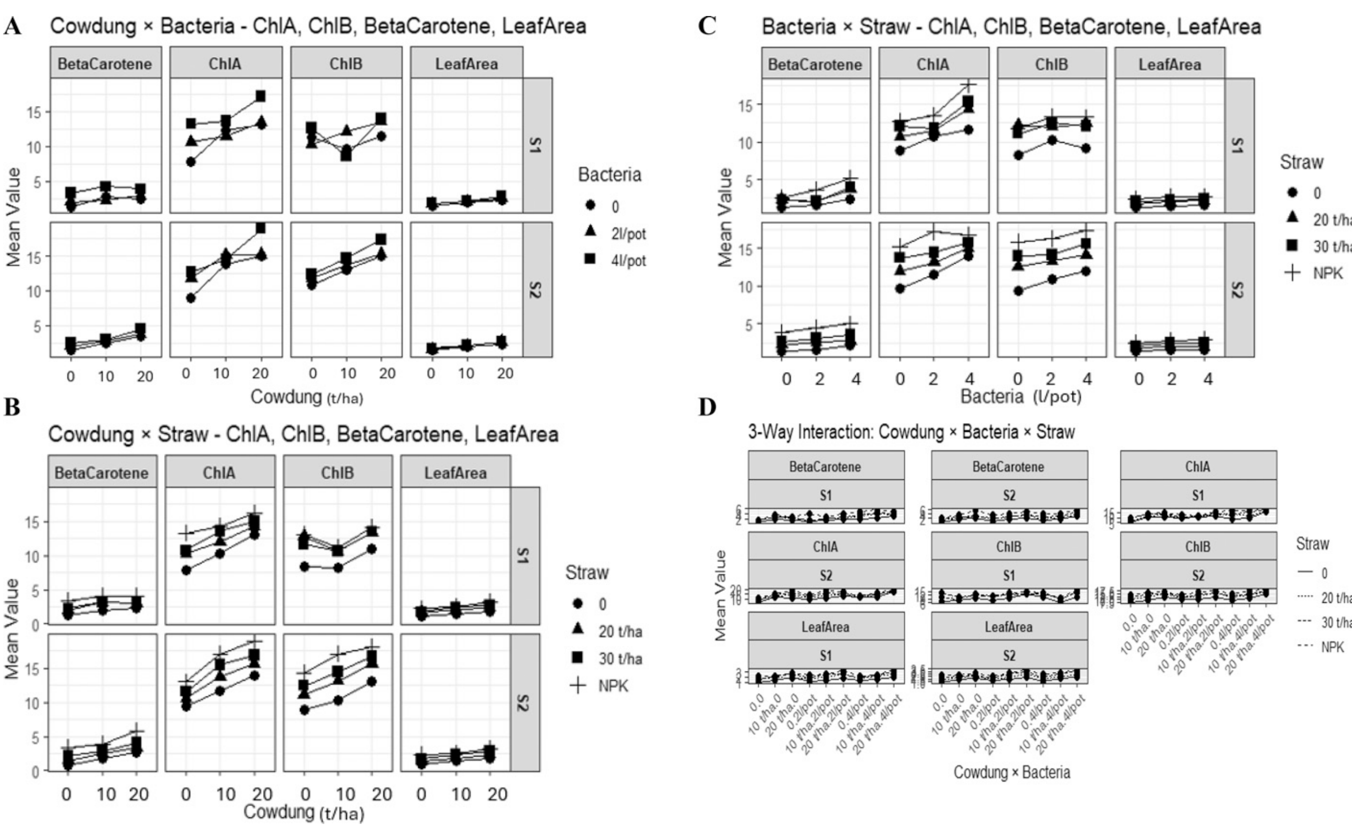

Fig. 4. (**A**) Interaction effects of cow dung and bacterial inoculation on cabbage leaf chlorophyll a, chlorophyll b, and beta carotene during two growing seasons. ChlA = chlorophyl a; ChlB = chlorophyl b. (**B**) Interaction effects of cow dung and straw applications on cabbage leaf chlorophyll a, chlorophyll b, and beta carotene during two growing seasons. (**C**) Interaction effects of bacterial inoculation and straw applications on cabbage leaf chlorophyll a, chlorophyll b, and beta carotene during two growing seasons. (**D**) Interaction effects of cow dung, bacterial inoculation, and straw applications on cabbage leaf chlorophyll a, chlorophyll b, and beta carotene during two growing seasons.

Table 6. Single effects of cow dung, bacteria, and straw on cabbage dry leaf, stem, root, and biomass weights (g).

	Dry leaves weight (g)		Dry stem weight (g)		Dry root weight (g)		Dry biomass (g)	
Cow dung ($t{\cdot}ha^{-1}$)	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2	Season 1	Season 2
0	162 c[i]	170 c	53.30 b	56.29 c	23.61 a	25.10 a	342.94 c	347.08 c
10	210 b	202 b	63.82 a	71.58 b	23.94 a	26.54 a	412.75 a	403.78 b
20	224 a	253 a	67.38 a	79.17 a	18.34 b	22.41 b	387.81 b	476.75 a
Bacteria (L/plot)								
0	181 c	196 c	57.00 c	64.88 c	20.55 b	23.34 b	348.45 c	383.58 c
2	195 b	207 b	61.91 b	73.14 a	21.20 b	23.98 b	385.61 b	407.93 b
4	220 a	221 a	65.60 a	69.02 b	24.13 a	26.72 a	409.44 a	436.10 a
Straw ($t{\cdot}ha^{-1}$)								
0	145 d	155 d	50.30 c	57.99 c	17.22 d	19.81 d	272.56 d	301.57 d
20	180 c	191 c	67.31 a	74.43 a	21.21 c	23.79 c	354.54 c	384.29 c
30	215 b	223 b	62.04 b	70.17 b	26.02 a	29.14 a	416.85 b	444.29 b
600 kg/ha NPK	256 a	264 a	66.35 a	73.46 a	23.40 b	25.98 b	480.72 a	506.63 a

[i] Means within a column followed by different letters differ significantly at $P < 0.05$ according to the least significant difference test.
NPK = nitrogen–phosphorus–potassium; ns = nonsignificant; season 1 = 2023–24 season; season 2 = 2024–25 season.

treatments, are listed in Table 6. In season 1, dry leaf weight ranged from 106 to 291 g/plant, dry stem ranged from 40.6 to 81.1 g, and dry root ranged from 15.3 to 37.9 g, with total dry biomass ranging from 217 to 519 g/plant. In season 2, the ranges increased slightly as follows: dry leaves, 119 to 323 g; stems, 44.9 to 92.1 g; roots, 17.5 to 40.5 g; and total biomass, 227 to 579 g. The highest values were again observed in treatments combining cow dung, CDB, and wheat straw.

The results of the two-way and three-way interaction analyses (Fig.5A-5D) unequivocally demonstrated that the combined application of cow dung with bacterial inoculation, cow dung with wheat straw, and bacterial inoculation with wheat straw elicited significant improvements in the physiological and biochemical parameters of cabbage dry leaves, stems, and roots across both growing seasons. The most substantial enhancements were consistently achieved under treatments where the highest input levels were applied in combination—particularly the integration of 20 $t{\cdot}ha^{-1}$ cow dung with 4 $L{\cdot}plot^{-1}$ bacterial inoculum—which consistently surpassed the performance of reduced-rate combinations or single-factor applications.

Figure 5E shows the strength and direction of relationships among fresh leaf, stem, and root weights of cabbage measured in two different seasons. The scatter plot matrix shows pairwise scatter plots and distributions, providing insights into the patterns and associations between these growth parameters under varying treatment conditions.

Discussion

The pre-experimental assessment of the soil revealed several limiting factors to sustainable cabbage production in the arid agroecological zone of Haddat ash Sham, Saudi Arabia. The soil was classified as a sandy loam with a slightly alkaline pH of 7.9, which, although well-drained, is typically low in fertility because of poor nutrient and water retention. This was confirmed by the very low organic matter (0.28%) and total N (0.02%) values that fell significantly below agronomic thresholds for optimal vegetable production (Brady and Weil 2016; US Department of Agriculture, Natural Resources Conservation Service 1998). Such low levels of soil organic C and N severely restrict microbial biomass, soil respiration, and nutrient turnover, ultimately compromising crop growth and productivity.

Despite this, available macronutrients including P (93.5 $mg{\cdot}kg^{-1}$), K (371 $mg{\cdot}kg^{-1}$), Mg (529 $mg{\cdot}kg^{-1}$), and S (173.3 $mg{\cdot}kg^{-1}$) were found to be high to very high, potentially because of residual effects of past mineral fertilizer use or inherent parent material contributions. However, high soil pH (7.9) and EC (0.34 dS/m) can antagonize nutrient uptake, especially for micronutrients, by inducing precipitation or ionic competition at the root–soil interface (Food and Agriculture Organization 2006; Richards 1954). While Zn and Cu levels were within sufficient ranges (2.24 $mg{\cdot}kg^{-1}$ each), their bioavailability may still be compromised under these alkaline and saline conditions.

These findings justify the use of the integrated organic and microbial strategy adopted in this study. Cow dung was used as a source of labile organic N and to improve organic matter content, thereby enhancing microbial activity and soil structure. The application of wheat straw as a C-rich amendment aligns with the goal of long-term soil rehabilitation, but it is commonly associated with N immobilization during decomposition. To overcome this constraint, cellulose-decomposing bacteria (*B. amyloliquefaciens*) were applied to accelerate the breakdown of wheat straw, ensuring synchronized nutrient release and C cycling under the high ambient temperatures characteristic of the region.

The success of this approach was clearly demonstrated in the experimental results. Treatments involving cow dung and bacteria-enhanced straw significantly improved cabbage head weight, yield per hectare, and harvest index compared with the NPK control and untreated soils. Improvements in postharvest soil parameters—including organic matter, total N, and microbial counts—further affirm that the selected treatments effectively addressed the baseline fertility constraints. These outcomes not only validate the amendment strategy but also reinforce the potential of microbially enhanced organic inputs in restoring productivity to degraded arid soils.

Straw decomposition in soil is strongly regulated by the C:N ratio, with high-C residues often causing temporary N immobilization and slower breakdown rates unless additional N sources are supplied (Recous et al. 1995). Composting studies have shown that initial C:N ratios play a critical role in determining decomposition efficiency and nutrient release, with more balanced ratios promoting faster mineralization (Bernal et al. 1998). Microbial community succession during organic matter breakdown is a key driver of decomposition, and inoculating compost with selected microorganisms can enhance the degradation of lignocellulosic materials such as straw (de Gannes et al. 2013). For example, in tea plantation systems, combining plant litter and cow dung at optimized ratios with microbial inoculants has been shown to accelerate compost maturation and improve its fertilization effects (Ling et al. 2020).

The observed increases in cabbage head weight, total yield, and harvest index with higher cow dung application align with previous findings that organic manure enhances soil fertility and boosts crop performance (Gogoi et al. 2021; Ilahi et al. 2021). In our study, the dose-dependent response—where higher application rates consistently outperformed the control—echoed reports that cow dung or farmyard manure significantly improves yields compared with unfertilized plots. Such benefits likely result from improved soil aggregation, water retention, and slow-release nutrient supply, which are especially critical in sandy, arid soils (Gogoi et al. 2021; Ilahi et al. 2021).

Increasing bacterial inoculant levels, particularly *B. amyloliquefaciens* (CDB), produced similar positive trends. This mirrors the well-documented effects of plant growth-promoting bacteria, such as *Pseudomonas*, *Azotobacter*, and *Bacillus* spp., which mobilize nutrients, synthesize phytohormones, and stimulate root growth, thereby enhancing yield (Bonanomi et al. 2018; Gupta et al. 2022). The role of CDB in accelerating wheat straw decomposition and synchronizing nutrient release agrees with previous reports of increased enzymatic activity and rhizosphere dynamics that improve nutrient uptake and

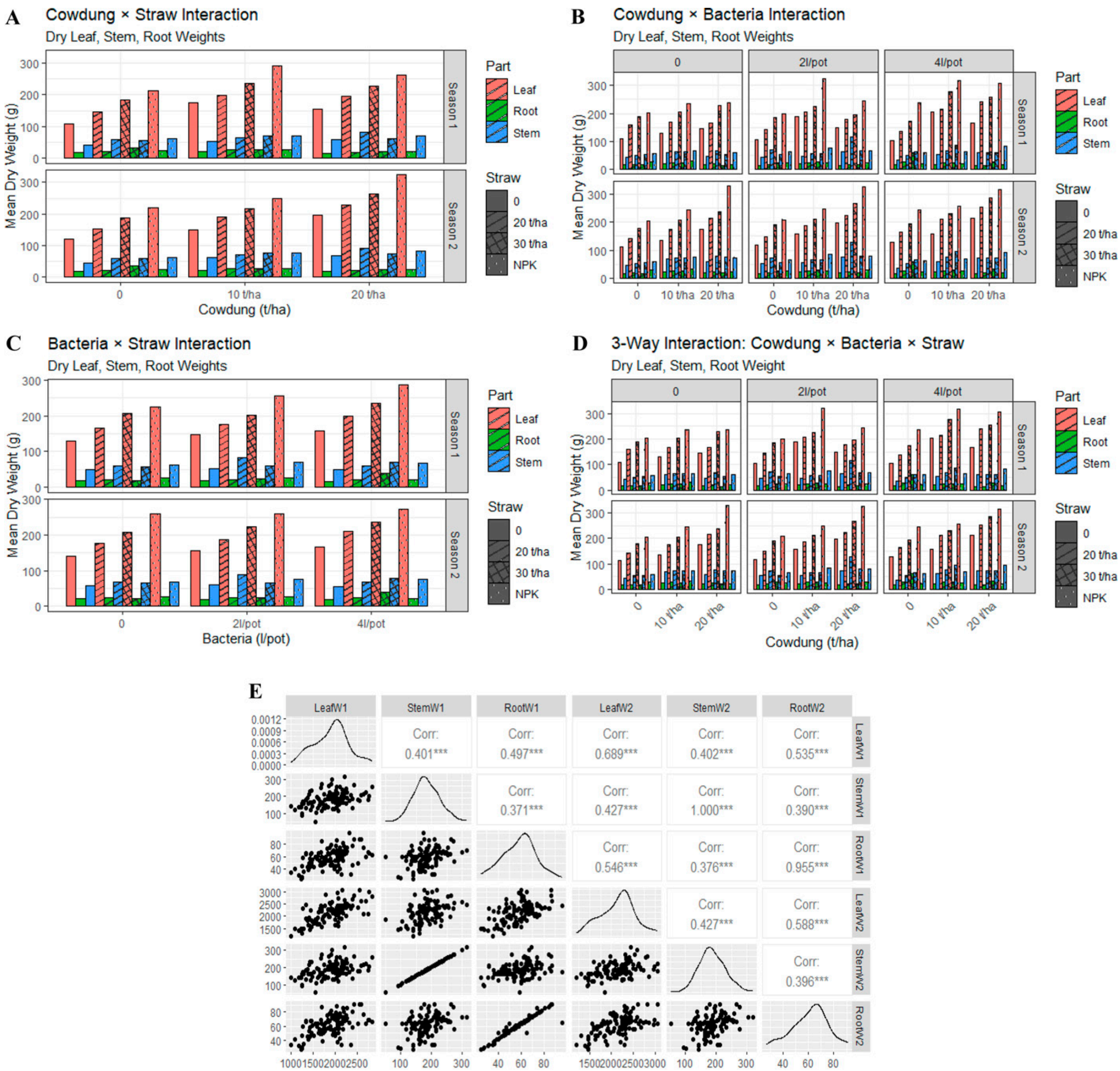

Fig. 5. (**A**) Interaction effects of cow dung and straw applications on cabbage leaf, stem, and root weight during two growing seasons. (**B**) Interaction effects of cow dung and bacterial inoculation on cabbage leaf, stem, and root weight during two growing seasons. (**C**) Interaction effects of bacterial inoculation and straw applications on cabbage leaf, stem, and root weight during two growing seasons. (**D**) Interaction effects of cow dung, bacterial inoculation, and straw applications on cabbage leaf, stem, and root weight during two growing seasons. (**E**) Correlation and scatter plot matrix of cabbage fresh weights. W = weight for seasons 1 and 2.

biomass accumulation (Gupta et al. 2022; Shahwar et al. 2023).

Wheat straw application also significantly improved yield components, in line with studies that showed that crop residue return and mulching enhance soil organic matter, moisture retention, and microbial activity—factors that collectively drive biomass production (Bhunia et al. 2023; Lasmini et al. 2022). In our trial, the microbial pretreatment of straw effectively overcame its high C:N ratio, enabling faster mineralization and nutrient release, consistent with findings of organic residue decomposition and nutrient dynamics (Lasmini et al. 2022; Shahwar et al. 2023). However, straw effects on the harvest index remained nonsignificant; this pattern was also observed where residue amendments increased total biomass without altering biomass partitioning (Bhunia et al. 2023; Gogoi et al. 2021).

The integrated treatment of 20 $t{\cdot}ha^{-1}$ cow dung + 30 $t{\cdot}ha^{-1}$ straw + 4 L/plot CDB outperformed the NPK control in both total yield and harvest index. This synergy supports the climate-smart input strategies proposed for vegetable production in arid zones (Gupta et al. 2022; Ilahi et al. 2021), showing that organic and microbial inputs, applied in combination, can surpass the productivity of conventional chemical fertilizers while improving soil health.

Morphological traits, including head diameter and circumference, and physiological parameters such as chlorophyll content were also significantly enhanced. These improvements indicate benefits beyond nutrient supply, likely linked to better water status, root development, and photosynthetic capacity. Such outcomes agree with integrated nutrient management studies of cabbage and other vegetables (Bonanomi et al. 2018; Gupta et al. 2022).

Observed synergistic interactions between cow dung × bacteria as well as between cow dung × straw further underline the capacity of organic amendments to enhance microbial efficiency, improve soil moisture retention, and promote plant physiological performance (Bonanomi et al. 2018; Gupta et al. 2022). The bacteria× straw combination also yielded strong gains, supporting evidence that microbial inoculants and organic residues jointly stimulate soil health, nutrient cycling, and yield potential in leafy vegetables (Bhunia et al. 2023; Shahwar et al. 2023).

Organic manure application improved both fresh and dry biomass, including root weight, highlighting its role in improving soil structure, water retention, and nutrient availability (Gogoi et al. 2021; Ilahi et al. 2021). The CDB inoculation amplified these gains by accelerating organic matter breakdown and nutrient uptake, consistent with findings from other vegetable systems (Gupta et al. 2022). The contribution of wheat straw as a C source is well-established; however, its initial tendency to immobilize N can be offset by microbial predecomposition (Bonanomi et al. 2018; Lasmini et al. 2022).

Synergistic effects and seasonal dynamics. The combined application of cow dung, CDB, and wheat straw produced the highest values for both nutrient content and biomass. This mirrors evidence from other cropping systems where integrated use of organic fertilizers, crop residues, and microbial inoculants yields greater benefits than individual inputs (Gupta et al. 2022; Shahwar et al. 2023). Slightly higher values recorded in season 2 suggest cumulative soil quality improvements or more favorable climatic conditions, a trend frequently observed in long-term organic amendment trials (Bonanomi et al. 2018; Gogoi et al. 2021).

Implications for sustainable production. The results clearly demonstrate that integrating cow dung, microbially decomposed wheat straw, and CDB inoculation significantly enhances yield, morphological traits, physiological performance, and nutrient content of cabbage under arid conditions. This bio-organic strategy reduces reliance on synthetic fertilizers, builds soil organic matter, and strengthens nutrient cycling, making it especially relevant for low-resource farming systems in arid and semi-arid regions (Gupta et al. 2022; Ilahi et al. 2021; Shahwar et al. 2023).

Conclusion

The results of this two-season study clearly demonstrate that the combined application of cow dung at 20 t·ha^{-1}, wheat straw at 30 t·ha^{-1}, and *B. amyloliquefaciens* at 4 L/plot significantly enhances cabbage agronomic performance in arid soils. This integrated organic amendment strategy outperformed the control in head weight, total yield, harvest index, and morphological traits, indicating superior nutrient availability, improved soil health, and more effective residue decomposition.

The synergy between cow dung and microbially decomposed wheat straw likely improved the C:N balance and facilitated faster nutrient release, especially under the high ambient temperatures of arid Saudi Arabia. These findings are consistent across seasons and support the growing body of research favoring organic inputs and microbial enhancement as tools for sustainable crop production in low-input systems.

Importantly, the approach addresses multiple challenges of farming in arid regions because it increases productivity, reduces dependency on chemical fertilizers, and uses locally available organic materials, promoting both environmental and economic sustainability.

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