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Growth regulation in bread wheat via novel bioinoculant formulation

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Abstract

Wheat (*Triticum aestivum* L.) is one of the most significant crops and the backbone of food security worldwide. However, low wheat production remains a substantial concern in global agricultural systems. It can be attributed to several factors, including adverse climatic conditions, plant disease and poor soil quality. Recent efforts have explored bioinoculant applications as a promising approach to enhance wheat yield, trying to mitigate constraints essential for future wheat production and global food security. This study tested talc powder, wheat biochar, sugarcane bagasse biochar, and farmyard manure as carriers with two endophytic bacterial strains, *Burkholderia phytofirmans* PsJN and *Bacillus* spp. MN54 was applied to three wheat varieties (Ujala-16, Zincol-16, and Fathejang-16). The data was recorded at the seedling and maturity growth stages of plants. A pot experiment revealed significant improvements in plant growth following bioinoculant application compared to controls. Notably, the combination of sugarcane bagasse biochar with *Bacillus* sp. MN54 exhibited the most pronounced effects, promoting internodal length, spike length, tiller number per plant, grain yield per plant, and spikelets per spike. Additionally, talc powder with *Bacillus* sp. MN54 increased peduncle length, tiller number per plant, and spike length in Fathejang-16. These findings offer valuable insights into optimizing bioinoculant formulations for improved agricultural practices, adapting to climate change, and contributing to ensuring global food security.

Keywords Biofertilizer, Carrier material, Endophytic bacteria, Eco-friendly, Yield enhancement

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Introduction

In 2050, the world population is estimated to reach around 10 billion, demanding a massive increase in food supply through improved agricultural yield per unit area with lower production costs and climate problems [1]. The development of high-yielding cultivars has been a constant objective of scientists around the globe. However, in addition to developing high-yielding varieties, alternative and sustainable methods must be investigated to achieve the required agricultural yield. Wheat is the most essential domestic food crop [2]. Using low nutrient efficiency cultivars and applying unbalanced nutrients are the leading causes of low wheat output [3].

Wheat crop yield is negatively affected by biotic and abiotic diseases and changing environmental conditions worldwide. For a very long time, several strategies have been used to boost food productivity, including plant breeding, transgenic methods [4], and the use of agrochemicals. The only issues with these techniques are their high production costs, low social acceptance, and environmental concerns [5]. Accordingly, it is necessary to investigate more sustainable methods to achieve the required agricultural productivity. In addition, increased societal interest in environmentally friendly and sustainable food production methods has resulted in an enormous increase in plant cell and tissue culture technology usage in the past ten years [6].

One such promising alternative is the use of plant growth-promoting endophytes (PGPEs). These naturally occurring microorganisms form symbiotic relationships with plants and have demonstrated the ability to improve plant growth, enhance nutrient uptake, and bolster resistance to stress, all while minimizing the reliance on harmful agrochemicals [7]. By adopting PGPEs as a biotechnological solution, agriculture can move towards a more sustainable and ecologically sound future [8]. PGPEs is a technique that acts as a biofertilizer that improves the host capacity for nutrient uptake, enhances production, reduces the cost of fertilizer, and is eco-safe due to the reduction in nitrogen leaching [9]. In both types of ecosystems, either natural or managed, plant growth is increased by beneficial bacteria associated with plants [10]. Many genera of bacteria are essential soil components. Because of the involvement of bacteria in different biological activities of soil, they make soil sustainable to produce crops and nutrients [11]. Furthermore, carrier materials can be inorganic or organic. In previous formulation studies, talc, turf, peat, vermiculite, press mud, montmorillonite, kaolinite, zeolite, alginate, sawdust, and pyrophyllite were used as carrier materials [12]. Carrier materials increase the bacterial survival rate by protecting bacteria from cell death and desiccation [13]. Similarly, plant attributes such as crop yield, plant morphological and growth characteristics, and

soil microbial activities significantly increase because of carrier materials. Carrier-based inoculation helps plant growth-promoting rhizobacteria to enhance rhizosphere activity and population [14]. Furthermore, bioinoculants have been applied successfully to other crops, including tomatoes and Capsicum. The study explored the impact of nitrogen-fixing bacteria on tomato production, revealing that these microbial inoculants could enhance both crop yield and the native rhizosphere microbiota [15]. In a related study, soil bacteria could significantly promote the growth of cowpeas, reinforcing the idea that bioinoculants can be effectively utilized across different plant species [16]. These findings underscore the versatility of microbial inoculants in enhancing crop productivity and health. Moreover, the studies show microbial inoculants can restore microbial populations in agricultural soils, which have been diminished due to intensive farming practices [17]. This restoration is crucial for maintaining soil fertility and combating abiotic and biotic threats, particularly in the face of climate change challenges [18].

To enhance the efficacy of biofertilizers, it is necessary to use suitable carrier material for long-term storage, protection from harmful environmental factors, enhancement of the activity of the organisms, and transmission to the target [12, 19]. In recent years, PGPEs have gained attention as a promising strategy to enhance crop productivity, particularly in bread wheat. Among these, *B. phytofirmans* strain PsJN and *Bacillus* sp. MN54 is notable for its unique contributions to plant growth. *B. phytofirmans* PsJN improves nutrient uptake and stress tolerance by colonizing both the rhizosphere and internal tissues, significantly boosting growth under drought conditions [20]. Conversely, *Bacillus* sp. MN54 enhances nitrogen and phosphorus uptake and produces enzymes that break down organic materials, improving nutrient availability [21].

In this regard, seed coating information about carrier material and endophytic bacteria and their impact on wheat plant development efficiency is rare. Therefore, the present study was planned to enhance growth and yield attributes in different wheat varieties using *Bacillus* sp. MN54 and *Burkholderia phytofirmans* PsJN and carrier materials include wheat biochar, sugarcane bagasse biochar, farmyard manure, and talcum powder.

Materials and methods

Experiments were designed to study the response of two endophytes (*B. phytofirmans*, PsJN, and *Bacillus* sp. MN54) along with four carrier materials (talc. powder, wheat biochar, sugarcane bagasse biochar, and farmyard manure). The microbes were acquired from the Soil Microbiology Lab, Institute of Environmental Sciences, University of Agriculture Faisalabad, and have been used in our previous studies [20]. Different treatments include

talc. powder+PsJN bacteria, wheat biochar+PsJN, sugarcane bagasse biochar+PsJN, farmyard manure+PsJN, and talc. Powder+MN54, wheat biochar+MN54, sugarcane bagasse biochar+MN54, farmyard manure+MN54, PsJN, positive control (Endophytes), and negative control (No treatments) were used. The trials were performed on three wheat varieties (Ujala-16, Zincol-16, and Fathejang-16) in vitro under a complete randomized design (CRD) Table 1.

Collection of endophytic bacteria, seeds, and soil

Two endophytic bacteria, *B. phytofirmans* PsJN, and *Bacillus* sp. MN54 and carrier material (talc. powder, wheat biochar, sugarcane bagasse biochar, and farmyard manure) were obtained from the Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad. Seeds of three wheat varieties, Ujala-16, Zincol-16, and Fathejang-16, were obtained from the Wheat Research Institute, Ayub Agricultural Research Institute (AARI), Faisalabad. The potting soil was taken from the research area of the Department of Plant Pathology, University of Agriculture Faisalabad. The soil was passed through a sieve and filled into the pots.

Preparation of the formulation

The bacterial suspensions were thoroughly mixed with the carrier materials. The formulation can be made using different combinations of suitable carrier materials [22]. The carrier materials were sterilized before combining them with the bacterial suspensions to ensure the purity and viability of the bioinoculant formulation. The sterilization process was carried out using autoclaving at 121 °C for 20 min to eliminate any contaminants. After sterilization, the materials were cooled to room temperature under aseptic conditions and then thoroughly mixed with the bacterial suspensions. For this purpose, the bacterial suspensions from both strains were constantly stirred with carrier materials to make a homogeneous mixture and allowed to dry for around 48 h [23]. Each plant solution was treated with approximately 20 g of seed from each type. All three types of wheat seeds

were soaked individually for 12 h in each treatment and control (hydropriming) at room temperature [24]. Seeds were coated with each bacterial formulation of two endophytes and prepared using wheat biochar, sugarcane biochar, farmyard manure, and talcum powder. Each carrier material was placed in Petri plates separately.

Sowing of wheat varieties

The wheat seeds were surface sterilized before sowing. The seeds were sterilized by immersing them in a 70% ethanol solution for 1 min, followed by treatment with 1% sodium hypochlorite solution for 5 min. The seeds were then rinsed thoroughly three times with sterile distilled water to remove any chemical residues. After seed coating and drying, Ujala-16 wheat seeds were sown in plastic pots to assess seedling parameters. All three varieties (Ujala-16, Zincol-16, and Fathejang-16) were sown in earthen pots to study treatments at the maturity stage. Ten seeds were planted in three replicates in a sand tray for the seedling traits study. For maturity analysis, seeds were sown in earthen pots (9-inch diameter) under (CRD) in three replicates. The soil used in the experiment was intended to mimic natural field conditions. The soil was collected from an agricultural field with similar characteristics to those typically used for wheat cultivation. It was untreated and maintained at the natural pH and nutrient levels found in the field to replicate natural growing conditions closely. However, any potential contamination was minimized by using clean pots and maintaining a controlled environment in the greenhouse. The temperature was maintained at approximately 22 °C during the day and 16 °C at night. Additionally, we ensured adequate humidity levels and light exposure to support healthy plant growth. These conditions were closely monitored throughout the experiment to provide a stable environment for the wheat varieties under study. All treatments were kept in a greenhouse along with the control.

Table 1 The combinations of bacterial strains, carrier materials, and wheat varieties were used in the study

Treatment no.	Bacterial strain	Carrier material	Wheat variety
1	<i>B. phytofirmans</i> PsJN	Talc powder	Ujala-16, Zincol-16, Fathejang-16
2	<i>B. phytofirmans</i> PsJN	Wheat biochar	Ujala-16, Zincol-16, Fathejang-16
3	<i>B. phytofirmans</i> PsJN	Sugarcane bagasse biochar	Ujala-16, Zincol-16, Fathejang-16
4	<i>B. phytofirmans</i> PsJN	Farmyard manure	Ujala-16, Zincol-16, Fathejang-16
5	<i>Bacillus</i> sp. MN54	Talc powder	Ujala-16, Zincol-16, Fathejang-16
6	<i>Bacillus</i> sp. MN54	Wheat biochar	Ujala-16, Zincol-16, Fathejang-16
7	<i>Bacillus</i> sp. MN54	Sugarcane bagasse biochar	Ujala-16, Zincol-16, Fathejang-16
8	<i>Bacillus</i> sp. MN54	Farmyard manure	Ujala-16, Zincol-16, Fathejang-16
9	Positive control (<i>B. phytofirmans</i> PsJN and <i>Bacillus</i> sp. MN54)	No carrier material	Ujala-16, Zincol-16, Fathejang-16
10	Negative control	No treatments	Ujala-16, Zincol-16, Fathejang-16

Determination of wheat growth and yield parameters

Data recording at the seedling stage

After two weeks, the seedlings of plastic pots were uprooted, washed in running tap water, and pressed gently with a paper towel to remove debris, i.e., water drops, sand particles, and other particles. Seedling parameters, i.e., seedling leaf area (cm²), root length (cm), shoot length (cm), fresh shoot weight (g), fresh root weight (g), dry root weight (g), and dry shoot weight (g), were measured. After recording seedling fresh weight parameters and seedling leaf area, the samples were oven-dried at 55°C for 48 h. After 48 h, the samples were dried, and dry root and shoot weights were determined using an electric balance (Elektronische wage, JJ623BC).

Data recording of growth and yield parameters at the maturity and harvesting stages

The mature plants were collected from the pots to measure the parameters related to growth and yield (from each variety and treatment). For this purpose, data were collected for the number of tillers/plants, plant height (cm), peduncle length (cm), internodal length (cm), spike length (cm), spike weight (g), number of grains per spike, number of spikelets per spike, chlorophyll content, flag leaf area (cm²), grain yield per plant (g), and 1000 grain weight (g).

The number of tillers was counted from three treatments and varieties from each replicate. Similarly, three plant tillers from each treatment were randomly selected to measure the inter-nodal length (cm). The average was then determined according to Bijay-Singh et al. [25], chlorophyll was determined from flag leaves at the post-anthesis stages using a device (Minolta SPAD-502 DL Meter), followed by Wellburn [26]. When the leaf area was measured in the morning, flag leaves at the post-anthesis stage were turgid. Each treatment collected leaf length and width data from three plant leaves.

The flag leaf area was calculated using the formula:

$$A = (L \times W) \times b$$

Where 'L' is length, 'W' is width, and 'b' is constant (b=0.75), as reported by Muhae-Ud-Din et al. [27]

At harvest time, the awns' length was measured in cm. After the plants were removed from the pots, the roots were cut using scissors and oven-dried. Their weight was measured with the help of an electrical balance (Elektronische wage, JJ623BC). At harvest time, the electrical balance was used to determine the shoot weight and a meter rod was used to measure the length of the shoot in cm. The length of a spike was calculated from its base to the tip of the last spikelet, excluding awns. Five spikes were chosen randomly from each pot, the number of spikelets was counted, and the spike weight (g) was

calculated. All spikes from the plants were threshed using a single plant thresher machine, and the grains were weighed using an electrical balance. Each treatment's average grain production per plant was determined.

Statistical analysis

The efficacy of different treatments and varieties was evaluated using an analysis of variance. Mean comparisons were conducted using the least significant difference (LSD) test at a 95% confidence level. Statistical analyses were performed using the R statistical software environment. The following packages were used: ggplot2, psych, and Factominer. Scatter plots were generated to visualize the relationship between the variables [28, 29]. The correlation coefficient was calculated to quantify the strength of the relationship between the two variables. Principal component analysis (PCA) was performed to identify the underlying factors contributing to the variation in the studied parameters [30]. Data were imported into R using the read.csv function, scatter plots were generated using the ggplot function, the correlation coefficient was calculated with the cor function, and PCA was performed using the FactoMineR package [31]. The results of the statistical analyses were saved as PNG files for further interpretation.

Results and discussion

Carrier-based delivery of endophytic bacteria leads to enhanced plant growth

The present experiment was conducted in pots to study the response of wheat varieties to various seedling parameters. Seeds were treated with different carrier material-based endophytic bacteria. After inoculation, seedlings from the inoculated and non-inoculated seeds were grown in a tray. In the current experiment, statistical analysis of the collected data revealed that the three varieties were significantly different ($P \leq 0.05$) from each other for all growth and yield-related attributes in wheat (Table 2).

Regarding carrier materials, among all the treatments at the seedling stage, the combination of sugarcane bagasse biochar+MN54 showed maximum seedling fresh shoot weight (0.26 g). In comparison, MN54 (positive control) exhibited minimum seedling fresh shoot weight (0.14 g). Applying wheat biochar+MN54 resulted in a maximum seedling fresh root weight (0.28 g). While talc. Powder+PsJN treatment demonstrated minimum seedling fresh root weight (0.10 g). Similarly, sugarcane bagasse biochar+MN54 indicated maximum seedling shoot length (11.40 cm). However, the negative control exhibited minimum seedling fresh shoot length (8.20 cm). Among the treatments, wheat biochar+MN54 showed maximum seedling dry root weight (0.06 g) and talc. Powder+PsJN treatment showed minimum seedling

Table 2 Effect of different carrier materials and endophytic bacteria on growth parameters of wheat seedlings in Ujala-16

Carrier material	Endophytes	SFSW	SFRW	SFSL	SLA	SDSW	SDRW
WB	MN54	0.21abc	0.28a	11.17a	1.65a	0.03ab	0.06a
WB	PsJN	0.20abc	0.14 cd	10.10a	1.80a	0.03abc	0.04ab
SBB	MN54	0.26a	0.23ab	11.40a	1.93a	0.03abc	0.05a
SBB	PsJN	0.18bc	0.19bc	10.70a	1.68a	0.03bcd	0.04ab
FYM	MN54	0.19abc	0.22ab	9.83a	1.55a	0.02bcd	0.03ab
FYM	PsJN	0.20abc	0.13 cd	10.40a	1.65a	0.03bc	0.04ab
TP	MN54	0.21abc	0.18bcd	9.17a	1.34a	0.01d	0.03ab
TP	PsJN	0.22ab	0.10d	10.16a	1.66a	0.01d	0.02b
(+ve) Cont.	MN54	0.14c	0.16bcd	9.18a	1.23a	0.02 cd	0.05a
(+ve) Cont.	PsJN	0.16bc	0.20abc	10.53a	1.80a	0.04a	0.049a
(-ve) Cont.	(-ve) Cont.	0.22ab	0.23ab	8.20a	1.33a	0.02bcd	0.05ab

SFSW Seedling fresh shoot weight, **SFRW** Seedling fresh root weight, **SFSL** Seedling fresh shoot length, **SLA** Seedling leaf area, **SDSW** Seedling dry shoot weight, **SDRW** Seedling dry root weight, **WB** Wheat biochar, **SBB** Sugarcane bagasse biochar, **FYM** Farmyard manure **TP** Talc. powder. The alphabets shown next to the values indicate significant differences between treatments as determined by statistical analysis (ANOVA followed by post-hoc tests). Treatments that do not share the same letter are significantly different at the specified level of confidence ($p < 0.05$)

dry root weight (0.02 g) (Table 2). These results indicate an increase in crop output and growth rate in various crops, as several endophytic bacteria and carrier materials were examined as growth enhancers [32]. In the literature, researchers have reported using endophytes and carrier materials. For example, wheat grain production significantly improved when seeds were inoculated with *Pseudomonas striata* using a soil and fly ash (1:1) mixture as the carrier. This combination created an optimal environment for bacterial growth and viability, leading to enhanced plant growth and nutrient uptake [33]. Likewise, endophytes have been determined to be present in all plant species and are extremely important for plant growth and development [34]. Furthermore, several endophytes have been discovered to be associated with roots, stems, leaves, flowers, fruits, and seeds of the plant [35]. Similarly, by the combination of talc. Powder+MN54, farmyard manure+MN54, farmyard manure+PsJN, and wheat biochar+PsJN, statistically significant results were recorded (Table 3). This improved growth and yield attributes of the Fathejang-16 and Zincol-16 wheat varieties. For example, the application of multiple endophytes yields more substantial effects compared to a single inoculation [20, 36, 37].

Effects of carrier materials and endophytic bacteria on Ujala-16 wheat

The results of wheat varieties demonstrated significant differences for growth-related parameters in bread wheat in a pot experiment over the negative control (Table 3). However, different treatments of endophytes were not significantly different for growth parameters. Furthermore, the results evaluated the performance of varying carrier materials and endophytic bacteria in Ujala-16. Among the carrier materials evaluated, wheat biochar with the endophytic bacteria MN54 showed the highest values for most of the growth parameters, including

internode length (16.93), peduncle length (5.57), and plant height (72.73). Compared with our results, the carrier materials sustain the inoculated microorganisms for extended intervals. The properties and nature of the carrier material play a vital role in improving the performance of inoculated bacteria [38, 39]. This supports the findings of this study. Similarly, WB with the endophytic bacteria PsJN exhibited favorable growth characteristics, with high values for internode length (17.28 cm) and plant height (73.73 cm).

In terms of the carrier material, SBB (sugarcane bagasse biochar) with the endophytic bacteria MN54 showed promising results, with several tillers (5.27) and spikelets per spike (14.97). Further, FYM (farmyard manure) combined with the endophytic bacteria MN54 displayed favorable growth characteristics, such as high values in flag leaf area (28.79 cm²) and 1000-grain weight (37.42 g). TP (talc powder) with the endophytic bacteria MN54 exhibited positive results, particularly in terms of plant height (76.30 cm) and 1000-grain weight (38.55 g). The positive control groups (MN54 and PsJN) performed well across the different carrier materials, showing favorable growth parameters. The negative control group, which had no carrier material or endophytic bacteria, exhibited lower values for most growth parameters (Table 3).

Growth parameter responses in bread wheat varieties

The wheat varieties (Zincol-16, Ujala-16, and Fatehjang-16) demonstrated significant differences in growth- and yield-related parameters in bread wheat in a pot experiment (Table 4). Among the three varieties, Zincol-16 demonstrated the highest internode length (17.82 cm) and number of leaves (18.64), indicating vigorous vegetative growth. However, it had the lowest number of tillers (5.14) and grains per spike (52.79), suggesting a lower reproductive potential. Ujala-16 also had a relatively longer spike length (7.27 cm) and spike weight

Table 3 Effect of different carrier materials and endophytic bacteria on maturity stage and growth parameters in bread wheat Ujala-16

Carrier	Endophyte	IL	PL	PH	NOT	FLA	SL	SPS	SW	GPS	1000GW	YPP	CC
WB	MN54	16.93a	5.57ab	72.73ab	3.25a	23.217e	7.47abc	13.61ab	2.48a	58.13b	37.86b	3.13b	63.00a
WB	PsJN	17.28a	5.45bc	73.73ab	3.20a	21.98f	7.68abc	12.68abc	1.95bc	57.63b	40.21a	3.57ab	63.9a
SBB	MN54	17.48a	5.27 cd	74.08ab	4.48a	19.60 h	8.93a	14.97a	2.22ab	60.46ab	38.67ab	5.06a	65.1a
SBB	PsJN	17.30a	5.40bc	72.0ab	4.00a	16.15k	7.73abc	12.92abc	1.75c	60.01ab	36.83b	3.36b	60.38a
FYM	MN54	17.35a	5.40bc	72.79ab	3.85a	28.79a	5.93c	13.97ab	2.20ab	61.15ab	37.42b	4.14ab	59.80a
FYM	PsJN	16.67a	5.48bc	66.40c	3.32a	18.31i	7.45abc	13.06abc	1.93bc	62.9a	37.95b	3.15b	59.0a
TP	MN54	17.32a	5.80a	76.30a	3.59a	21.37 g	8.63ab	13.03abc	2.19ab	58.01b	38.55ab	4.35ab	66.83a
TP	PsJN	17.08a	5.15d	74.70ab	3.97a	16.78j	8.03ab	14.02ab	2.02bc	58.11b	38.35ab	3.80ab	66.67a
(+ve) Cont.	MN54	17.27a	3.48f	72.20ab	3.82a	24.69d	7.02bc	11.00c	1.71c	45.30c	33.83c	3.40b	64.53a
(+ve) Cont.	PsJN	16.50a	5.48bc	75.87ab	3.52a	28.01b	8.92b	14.87a	2.42a	59.57ab	38.17b	4.67ab	56.87a
(-ve) Cont.	(-ve) Cont.	17.37a	3.78e	70.35bc	4.31a	25.28c	7.65abc	11.78bc	1.68c	45.18c	31.92c	3.58ab	65.13a

Whereas: IL Internodal length (cm), PL Peduncle length (cm), PH Plant height (cm), NOT Number of tillers, FLA Flag leaf area (cm²), SL Spike length (cm), SPS Spikelets per spike, SW Spike weight (g), GPS Grains per spike, 1000 Grains per spike (g), YPP Yield per plant, and CC Chlorophyll content. WB Wheat biochar, SBB Sugarcane bagasse biochar, and FYM Farmyard manure TP Talc. powder. Means followed by various letters within the column indicate statistical significance by LSD at P≤0.05. Treatments with the same letter do not differ significantly, while those with different letters show statistically significant differences; Significance level: * = Significant (P<0.05), ** = Highly significant (P<0.01). (+ve) Cont. Positive control, (-ve) Cont. Negative control

(2.06 g) than Zincol-16. Furthermore, Fatehjang-16 displayed a slightly shorter internode length (16.54 cm) but had the highest number of tillers (5.37) among the three varieties. It also had the largest flag leaf area (27.11 cm²), indicating good photosynthetic capacity.

The possible increase in flag leaf area is assumed to be due to endophytic bacteria on photosynthesis. Fatehjang-16 exhibited a moderate plant height (73.26 cm), spike length (8.15 cm), and spike weight (2.01 g). In addition, it had the highest number of grains per spike (61.4) and 1000-grain weight (38.02 g). Similarly, a maximum 1000-grain weight was recorded due to the talc powder+PsJN interaction in Zincol-16. This could be due to the availability of indole acetic acid (IAA) and nitrogen maximum 1000 grain weight increased and improved the solubilization ability of phosphate [40]. The choice of the variety depends on the specific requirements and objectives of wheat cultivation, such as prioritizing vegetative growth or maximizing grain yield (Table 4). It has been shown that there is a positive association between flag leaf area and grain yield. Therefore, the productivity of wheat would be positively affected by an increase in flag leaf [41]. Additionally, the interaction of sugarcane bagasse biochar+MN54 × Fatehjang-16 results in maximum grain yield. A similar increase in wheat yield was also found in previous studies. Application of the bioformulation of *Trichoderma* species and farmyard manure enhanced grain yield in bean plants. Likewise, the production was enhanced because of endophytic along with carrier material farmyard manure [42].

Effects of carrier materials and endophytic bacteria on wheat growth parameters

Under greenhouse conditions, the results of variety × treatment interactions demonstrated significant differences (P≤0.05) for growth-related parameters such as spike length, number of tillers, shoot weight, leaf area, spikelet/spike, internodal distance, tillers/plant, and yield/plant in bread wheat (Table 5). Regarding carrier material, the highest PL, PH, and NOT were noted in the interaction of talc. powder+MN54 × Fatehjang-16 (6.00), (81.30), and (81.12), respectively, while the minimum PH was seen in FYM+PsJN × Zincol-16 (64.95). Similarly, SL was highest in talc. powder+MN54× Fatehjang-16 (10.3) and lowest in FYM+MN54× Ujala-16 (5.51), whereas SPS was maximum in talc. powder+PsJN × Ujala-16 (16.15) and minimum in MN54 × Fatehjang-16 (9.95). Previous studies mainly focused on indicating that root and shoot lengths can be enhanced using endophytic bacteria [43]. Although SW was maximum in wheat biochar+MN54× Fatehjang-16 (2.95) and minimum in negative control × Fatehjang-16 (1.28), GPS was higher in FYM+PsJN × Fatehjang-16 (70.95) and lower in talc. powder+PsJN × Zincol-16 (37.95). However, in the

Table 4 Response of different varieties to growth parameters

Variety	IL	PL	PH	NOT	FLA	SL	SPS	SW	GPS	1000GW	YPP	CC
Zincol-16	17.82a	5.14b	72.38a	3.27b	18.64c	7.88a	13.50a	2.07a	52.79c	38.81a	3.69a	58.52b
Ujala-16	17.06ab	4.82c	72.86a	4.20a	20.84b	7.27a	13.56a	2.06a	56.67b	34.91b	3.71a	70.33a
Fatehjang-16	16.54b	5.37a	73.26a	3.79ab	27.11a	8.15a	12.72a	2.01a	61.4a	38.02a	4.12a	59.67b

Whereas: IL Intermodal length (cm), PL Peduncle length (cm), PH Plant height (cm), NOT Number of tillers, FLA Flag leaf area (cm²), SL Spike length (cm), SPS Spikelet's per spike, SW Spike weight (g), GPS Grains per spike, 1000 Grains per spike (g), YPP Yield per plant, and CC Chlorophyll content

current study, 1000GW was shown to be maximum in talc. powder+PsJN × Zincol-16 (41.65) and minimum in two interaction sugarcane bagasse biochar+PsJN × Ujala-16 (31.20) and PsJN × Zincol-16 (31.20). In contrast, sugarcane bagasse contains monosaccharides, amino acids, and hemicellulose, which are active sources of nutrients for the healthy growth of bacteria [44]. Likewise, YPP was noted highest in sugarcane bagasse biochar+MN54× Fatehjang-16 (6.73) and lowest in FYM+MN54× Zincol-16 (2.37). Biochar provides habitat and protection to bacteria, supporting bacterial growth and viability. It has also been reported that the biochar surface can easily absorb phosphate. Because of this, inorganic phosphorus might be easily accessible to bacteria [45].

Similarly, Mayak et al. [46] reported that *Bacillus* species can be helpful for plants in the production of siderophores and atmospheric nitrogen fixation, which solubilize iron in different plants. Many growth-promoting agents such as abscisic acid (ABA), cytokinin, gibberellic acid (GA), and auxins are produced by these bacteria, which play vital roles in plant growth and defense mechanisms [47].

The growth parameters varied in the positive control groups, where the endophytic bacteria MN54 and PsJN were used without any carrier material. MN54 exhibited a lower growth parameter than PsJN with higher values (Table 5). The negative control group, which had no endophytic bacteria or carrier material, showed relatively lower growth parameters than the treatment groups. These findings suggest the effectiveness of using carrier material and endophytic bacteria in enhancing specific morphophysiological parameters in wheat samples, underscoring the potential benefits of these interventions in agricultural practices. Compared with the results, the abundance of specific operational taxonomic units (otus) was influenced by microbial inoculation, with the effect varying depending on the wheat cultivar. These findings mark the initial phase of using advantageous endophytes from wheat roots. In addition, *Pantoea agglomerans* identified as a wheat root endophyte in this study were previously shown to enhance Zn bioavailability in wheat [48]. A specific strain of *Pantoea alhagi* was found to colonize wheat roots and improve wheat resilience to drought [49]. Further investigations into the mechanisms underlying these interactions could offer valuable insights for optimizing crop growth and yield in wheat cultivation.

Boxplot analysis

In this study, an analysis was conducted of various wheat seedling parameters under different treatment groups, using boxplots to visualize the distribution of the data. The x-axis of each boxplot represents the treatment groups, whereas the y-axis displays the respective parameter values (Figs. 1 and 2). The boxplots provide a clear

Table 5 Effect of different carrier materials and endophytic bacteria on maturity stage growth parameters in bread wheat

Treatment Interaction			Mean Response											
Car.	Endo.	Variety	IL	PL	PH	NOT	FLA	SL	SPS	SW	GPS	1000GW	YPP	CC
WB	MN54	Z-16	16.05 ^{ab}	5.40cdefg	71.45bcdef	3.25bcd	17.85rs	7.10abcde	14.30abcd	2.26bcdef	57.95defghij	40.00abc	3.38bc	80.150a
WB	MN54	U-16	18.400a	5.50bcdef	73.950abcdef	3.66abcd	17.350st	6.650bcde	13.600abcde	2.23bcdefg	58.80cdefghij	35.600defgh	3.43bc	56.40ab
WB	MN54	F-16	16.35ab	5.80abc	72.80abcdef	3.40bcd	34.45c	8.65abcde	12.95abcde	2.95a	57.65defghij	38.00abcde	2.58bc	52.450ab
WB	PsJN	Z-16	17.55ab	5.50bcdef	74.30abcdef	74.30abcdef	23.35kl	7.50abcde	12.30abcde	2.38abcd	45.80kl	41.00ab	3.66bc	68.25ab
WB	PsJN	U-16	16.15ab	5.10fghi	74.60abcde	74.60abcde	16.85tu	7.41abcde	12.60abcde	1.72efghi	64.95abc	41.30ab	4.32abc	67.47ab
WB	PsJN	F-16	18.15ab	5.75abcd	72.30abcdef	72.30abcdef	25.75 h	8.15abcde	13.15abcde	1.76defghi	67.30ab	38.35abcde	2.745bc	56.0ab
SBB	MN54	Z-16	16.65ab	5.70abcd	69.30def	69.30def	16.43u	8.70abcde	15.00abc	2.10bcdefgh	62.95bcdef	41.10ab	4.44abc	62.50ab
SBB	MN54	U-16	17.15ab	4.40jk	74.00abcdef	74.00abcdef	19.05p	8.65abcde	14.30abcd	2.32abcdef	56.30fghi	36.15cdefg	4.01abc	80.925a
SBB	MN54	F-16	18.30a	5.70abcd	78.95abc	78.95abc	23.33kl	9.45abc	15.30ab	2.22bcdefgh	62.15bcdefg	38.75abcde	6.73a	51.90ab
SBB	PsJN	Z-16	18.60a	5.60abcde	71.60bcdef	71.60bcdef	15.10w	8.80abcd	13.95abcde	2.05bcdefgh	52.65jk	39.35BCD	4.320abc	56.30ab
SBB	PsJN	U-16	17.00ab	5.20efghi	75.60abcde	75.60abcde	21.60n	7.25abcde	13.15abcde	1.92cdefghi	60.10cdefghi	31.20 K	3.37bc	64.55ab
SBB	PsJN	F-16	16.30ab	5.40cdefg	68.80def	68.80def	11.75y	7.15abcde	11.65bcde	1.52hi	62.15bcdefg	40.05abc	2.40c	60.30ab
FYM	MN54	Z-16	16.75ab	5.05ghi	71.95abcdef	71.95abcdef	20.80o	5.97de	14.30abcd	2.43abc	65.15abc	33.80fghij	2.37c	65.70ab
FYM	MN54	U-16	17.05ab	5.40cdefg	72.10abcdef	72.10abcdef	27.06 g	5.51e	14.30abcde	2.11bcdefgh	57.15efghij	38.65abcde	5.24ab	61.45ab
FYM	MN54	F-16	18.25a	5.75abcd	74.30abcdef	74.30abcdef	38.50a	6.31cde	13.30abcde	2.06bcdefgh	61.15bcdefgh	39.80abc	4.84abc	52.25ab
FYM	PsJN	Z-16	15.85ab	5.80abc	64.95f	64.95f	16.90tu	8.30abcde	13.95abcde	1.59ghi	62.65bcdef	40.75ab	3.04bc	73.20ab
FYM	PsJN	U-16	18.05ab	4.80ij	68.15def	68.15def	23.25kl	6.25cde	12.60abcde	2.25bcdef	55.30ghij	32.50ijk	3.49bc	44.80b
FYM	PsJN	F-16	16.10ab	5.85ab	66.10ef	66.10ef	14.80w	7.80abcde	12.65abcde	1.95cdefgh	70.95a	40.60ab	2.92bc	59.00ab
TP	MN54	Z-16	16.80ab	5.85ab	73.30abcdef	73.30abcdef	15.75v	8.20abcde	15.00abc	1.98bcdefgh	56.45fghij	39.75abc	3.18bc	73.90ab
TP	MN54	U-16	16.50ab	5.55bcde	74.30abcdef	74.30abcdef	14.65w	7.40abcde	12.30abcde	2.26bcdef	53.80ij	36.75cdefg	3.33bc	50.65ab
TP	MN54	F-16	18.65a	6.00a	81.12a	81.12a	33.73d	10.30a	11.80bcde	2.35abcde	63.80bcde	39.15abcd	6.55a	75.95ab
TP	PsJN	Z-16	17.90ab	4.90i	80.30ab	80.30ab	13.10x	8.05abcde	12.60abcde	2.03bcdefgh	37.95 m	41.65a	3.67bc	58.70ab
TP	PsJN	U-16	17.25ab	4.95hi	75.50abcde	75.50 acbde	22.30 m	7.90abcde	16.15a	2.05bcdefgh	70.80a	34.65efghi	4.28abc	57.75ab
TP	PsJN	F-16	16.05ab	5.60abcde	68.30def	68.30def	14.95w	8.15abcde	13.30abcde	1.970cdefgh	65.45abc	38.75abcd	3.46bc	83.55a
Treatments with a positive control														
(-ve)	MN54	Z-16	17.80ab	3.40 l	73.00abcdef	73.00abcdef	18.08p	6.65bcde	10.60de	1.67fghi	42.80 m	37.10bcdef	4.43abc	84.45a
(-ve)	MN54	U-16	16.30ab	3.50 l	68.80 def	68.80def	22.85	7.15abcde	12.45abcde	1.75defghi	40.30 lm	32.35ijk	2.29c	51.50ab
(-ve)	MN54	F-16	17.55ab	3.55 l	74.80abcde	74.80abcde	33.15e	7.25abcde	9.95e	1.72efghi	52.80j	32.05jk	3.48bc	57.65ab
(-ve)	PsJN	Z-16	18.90a	5.45bcdef	75.45abcde	75.45abcde	23.60jk	9.65ab	15.65ab	2.65ab	54.80hij	31.20k	5.05ac	65.95ab
(-ve)	PsJN	U-16	18.25a	5.35defgh	77.65abcd	77.65abcd	24.20i	8.20abcde	14.95abc	2.27bcdef	64.45abcd	31.10k	4.22abc	52.02ab
(-ve)	PsJN	F-16	15.30ab	5.65abcd	74.50abcdef	74.50abcdef	36.25b	8.90abcd	14.30abcd	2.36abcde	59.45cdefghij	33.35hijk	4.73abc	52.65ab
Treatments with a negative control														
(-ve)	(-ve)	Z-16	18.60a	3.75 l	70.60cdef	70.60cdef	24.10ij	7.75abcde	10.95cde	1.71efghi	41.30 m	41.30ab	3.02bc	84.50a
(-ve)	(-ve)	U-16	16.50ab	3.4000 l	66.80ef	66.80ef	20.10p	7.60abcde	12.80abcde	1.82cdefghi	41.30 m	33.80ghijk	2.84bc	56.20ab
(-ve)	(-ve)	F-16	14.40b	4.20k	73.65abcdef	73.65abcdef	31.63f	7.60abcde	11.60bcde	1.28i	52.95j	39.40abc	4.91abc	54.70ab

Whereas IL Intermodal length (cm), PL Peduncle length (cm), PH Plant height (cm), NOT Number of tillers, FLA Flag leaf area (cm²), SL Spike length (cm), SPS Spikelets per spike, SW Spike weight (g), GPS Grains per spike, 1000 Grains per spike (g), YPP Yield per plant, and CC Chlorophyll content. WB Wheat biochar, SBB Sugarcane bagasse biochar, and FYM Farmyard manure TP Talc. powder, Z-16 Zincol-16, F-16 Fathejang-16, U-16 Ujala-16. Means followed by different letters within the same column are significantly different from each other, as determined by the least significant difference (LSD) test at $P \leq 0.05$. Treatments with the same letter do not differ significantly, while those with different letters show statistically significant differences; Significance level: * = Significant ($P < 0.05$), ** = Highly significant ($P < 0.01$), (+-ve) Cont. Positive control, (-ve) Cont. Negative control

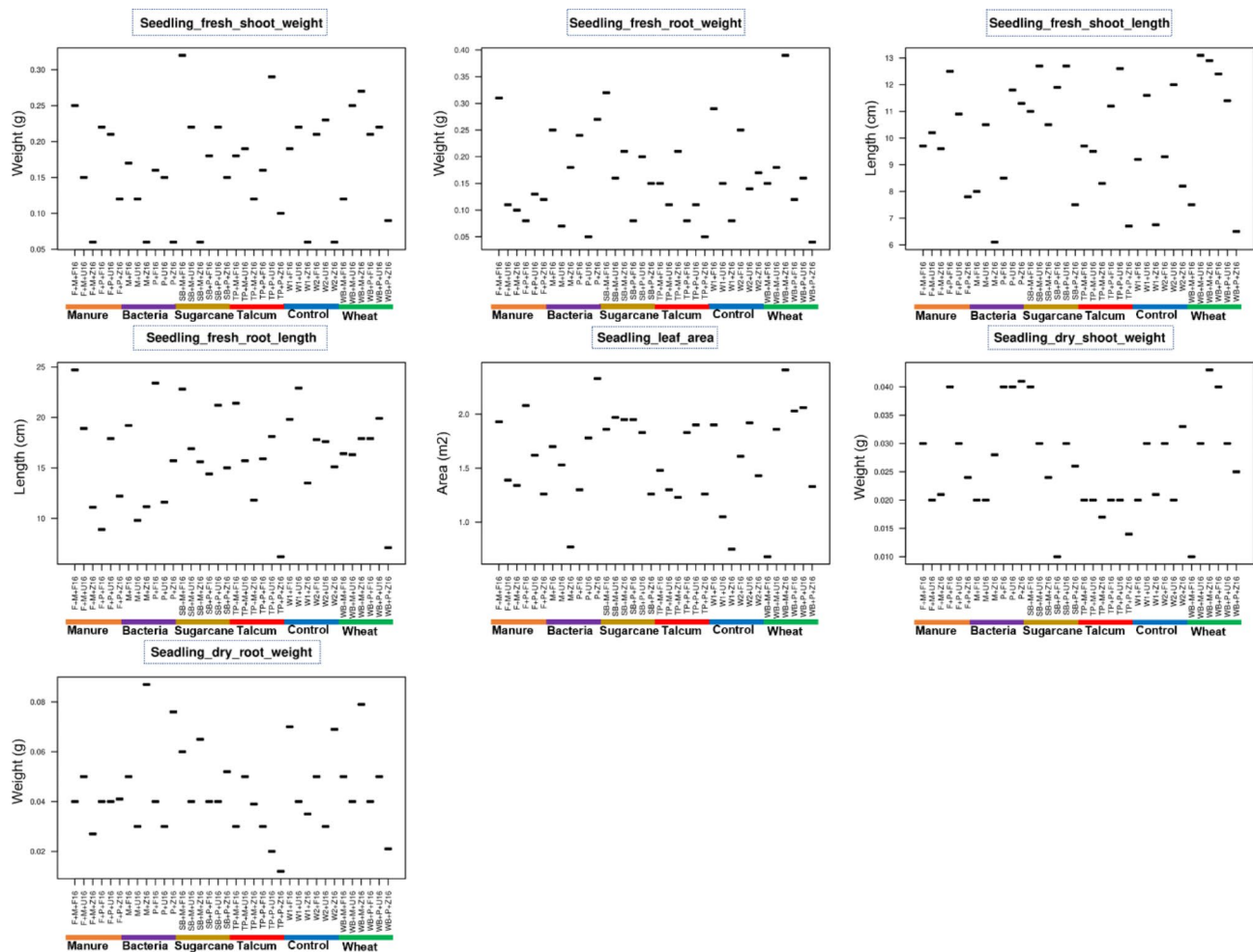


Fig. 1 Boxplots illustrating the distribution of different wheat seedling parameters across treatments. The x-axis represents the treatment groups, and the y-axis represents the respective parameter values

depiction of the central tendencies and variability of each parameter across the different treatments. Each box plot consists of a box representing the interquartile range (IQR), which contains 50% of the data [50]. Furthermore, the upper dot in each boxplot indicates the best performance observed for each wheat seedling growth parameter within its respective treatment group. This highest performance value signifies the optimal growth achieved under specific conditions.

At the seedling stage, the maximum performance was shown by seedling fresh shoot length followed by dry shoot weight and seedling dry root weight, respectively (Fig. 1). At the maturity stage, the maximum performance was demonstrated by peduncle length followed by internodal length and 1000-g weight (Fig. 2). According to existing literature, certain traits such as 1000 grain weight, spike weight, and the number of grains per spike have been identified as important factors in the selection of high-yielding wheat cultivars. The findings from this study contribute to a better understanding of the factors

influencing wheat growth and can be used to optimize agricultural practices and improve crop yields.

Simplified correlation coefficients of the characteristic traits among wheat varieties and various treatments

The studies focused on analyzing the simple coefficient correlations between various characteristics in different wheat varieties subjected to different treatments. Exploring correlation coefficients provides an opportunity to simultaneously select favorable traits and cultivate ideal plant varieties [51]. A total of nine correlations were examined (Table 6). The association between plant length and spikelets per spike, plant length and grains per spike, and plant height and yield per plant showed a relatively strong positive coefficient of 0.5113. The correlation was highly significant ($p=0.0000$), indicating a strong positive relationship between these two variables, suggesting that plant height is positively associated with yield per plant. Similarly, the relationship between the weight of 1000 grains and chlorophyll content resulted

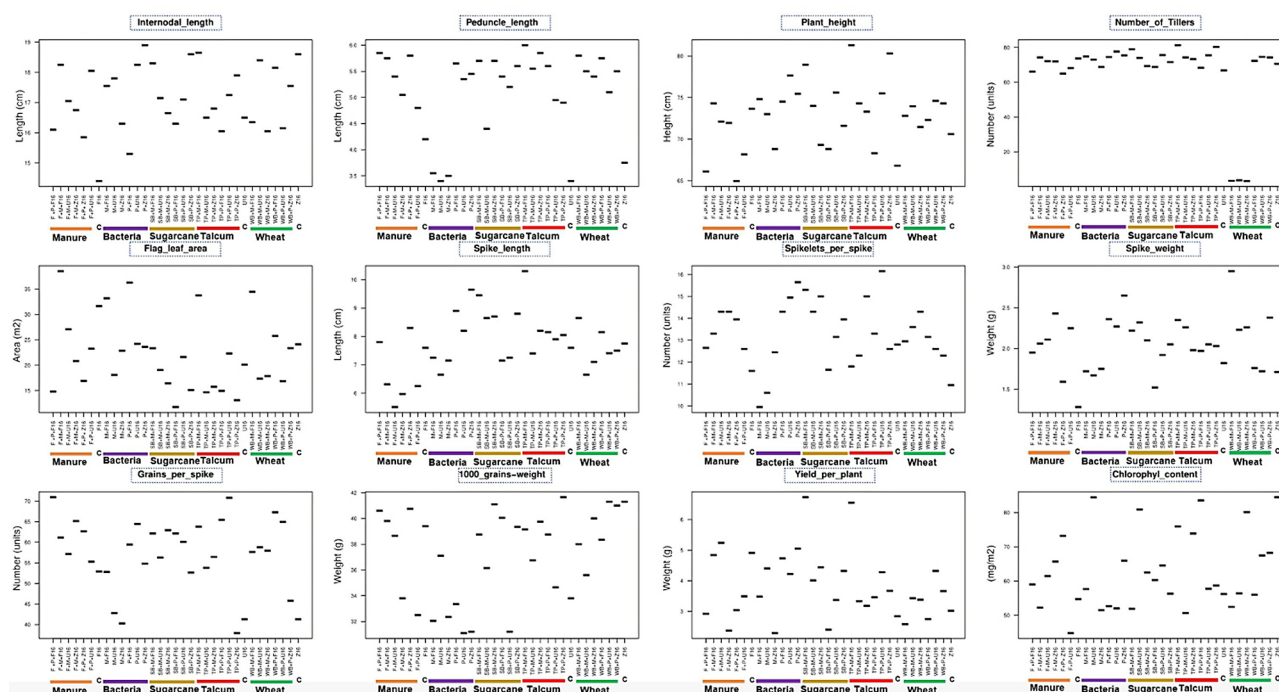


Fig. 2 Boxplots illustrate the distribution of different wheat maturity stage parameters across treatments. The x-axis represents the treatment groups, and the y-axis represents the respective parameter values

Table 6 Noticeable correlation coefficients among important characteristics for different wheat varieties under various treatments

Sr. No	Characteristics under correlation	r^2	p-value
1	Internodal length vs. plant height	0.4351	0.0114
2	Plant length vs. spikelets per spike	0.5113	0.0024
3	Plant length vs. Spike weight	0.4491	0.0087
4	Plant length vs. grains per spike	0.6654	0.0000
5	Plant height vs. yield per plant	0.6087	0.0002
6	Flag leaf area versus yield per plant	0.3672	0.0355
7	Spikelets per spike vs. spike weight	0.4646	0.0064
8	Spikelets per spike vs. grains per spike	0.4587	0.0073
9	1000-Grain Weight vs. Chlorophyll Content	0.3452	0.0492

Whereas r^2 = Correlation coefficient, P value = Probability value

in a relatively weaker positive correlation coefficient of 0.3452. Although the correlation coefficient was lower, it was still statistically significant ($p=0.0492$), indicating a potential relationship between these two traits. Finally, these findings demonstrate significant correlations between various characteristics in different wheat varieties under different treatments (Table 6). These results have been reported in previous studies because the enhancement of grain yield is often correlated with plant growth parameters [30]. Increased plant growth and drought stress resistance may result from treating endophytes found in maize seeds [52]. Therefore, the current outcomes contribute to a better understanding of the relationships between different traits, which can aid

in selecting and improving wheat varieties with desirable characteristics. A similar correlation among the clusters has been described under normal and drought conditions for many crop plants such as mustard (*Brassica juncea*) [53], sorghum (*Sorghum bicolor* L. Moench) [54], and wheat (*Triticum* spp.) [55] and maize (*Zea mays*) [56]. Moreover, the correlation matrices for wheat seedlings and maturity stage physiological parameters provide valuable insights into the relationships between different variables. In these matrices, the diagonal represents a histogram illustrating the distribution of the values for each variable. This allows us to observe each parameter's frequency and range of values. Above the diagonal, each square displays the Pearson correlation coefficient (R) between the two variables.

The Pearson correlation coefficient ranges from -1 to $+1$, with negative values indicating a negative correlation (when one variable increases, the other tends to decrease) and positive values indicating a positive correlation (when one variable increases, the other tends to grow as well [57]). A star rating system is employed to assess the strength of the correlation. The number of stars assigned to each correlation indicates its strength, with a higher number representing a stronger correlation. This rating system allows quick assessment of the relationship between variables. Below the diagonal, each square presents a scatter plot that visually represents the distribution of data points between the two physiological traits. The scatter plot helps understand the relationship between

the variables (Fig. 3). By examining the dispersion of data points, patterns or trends can be identified, providing further insights into the correlation between traits. These correlation matrices offer a comprehensive overview of the relationships between various physiological parameters at the seedling and maturity stages of wheat growth, combining statistical values, visual representations, and a star rating system to facilitate the interpretation of the results (Figs. 3 and 4).

Cluster analysis based on principal component analysis

The cluster analysis results for different treatments' performance at the wheat seedling and maturity stages were obtained using principal component analysis (PCA). PCA is a statistical technique that reduces the dimensionality of the data while retaining the most valuable information. In this case, it allows for the visualization and interpretation of complex multivariate data [41, 58]. The plot generated from PCA displays the distribution of wheat samples in PC1 and PC2. To aid in understanding, the sample in the plot is color-coded based on their respective treatments. This color-coding allows for a

visual assessment of the grouping or clustering patterns within the dataset. In addition, the plot includes ellipses representing the 95% confidence interval for each cluster. These ellipses provide a graphical representation of the uncertainty associated with the estimated cluster boundaries. By considering the overlap or separation of the ellipses, we can assess the distinctiveness of different treatment groups (Figs. 5 and 6). Individual samples are represented by dots in the plot, allowing for the identification of specific data points within the overall distribution. This enables the detection of any outliers or unusual observations that may deviate from the general clustering patterns.

The principal component analysis (PCA) results are shown in Figs. 7 and 8, indicating a clear separation between the diverse groups. This suggests that the samples from each group clustered separately, indicating that they possessed distinct wheat growth attributes that were enhanced by applying carrier material and endophytic bacteria. The separation between groups is evident in PC1, which accounts for 30.2% of the total variance, and PC2, which accounts for 18.9% of the total variance

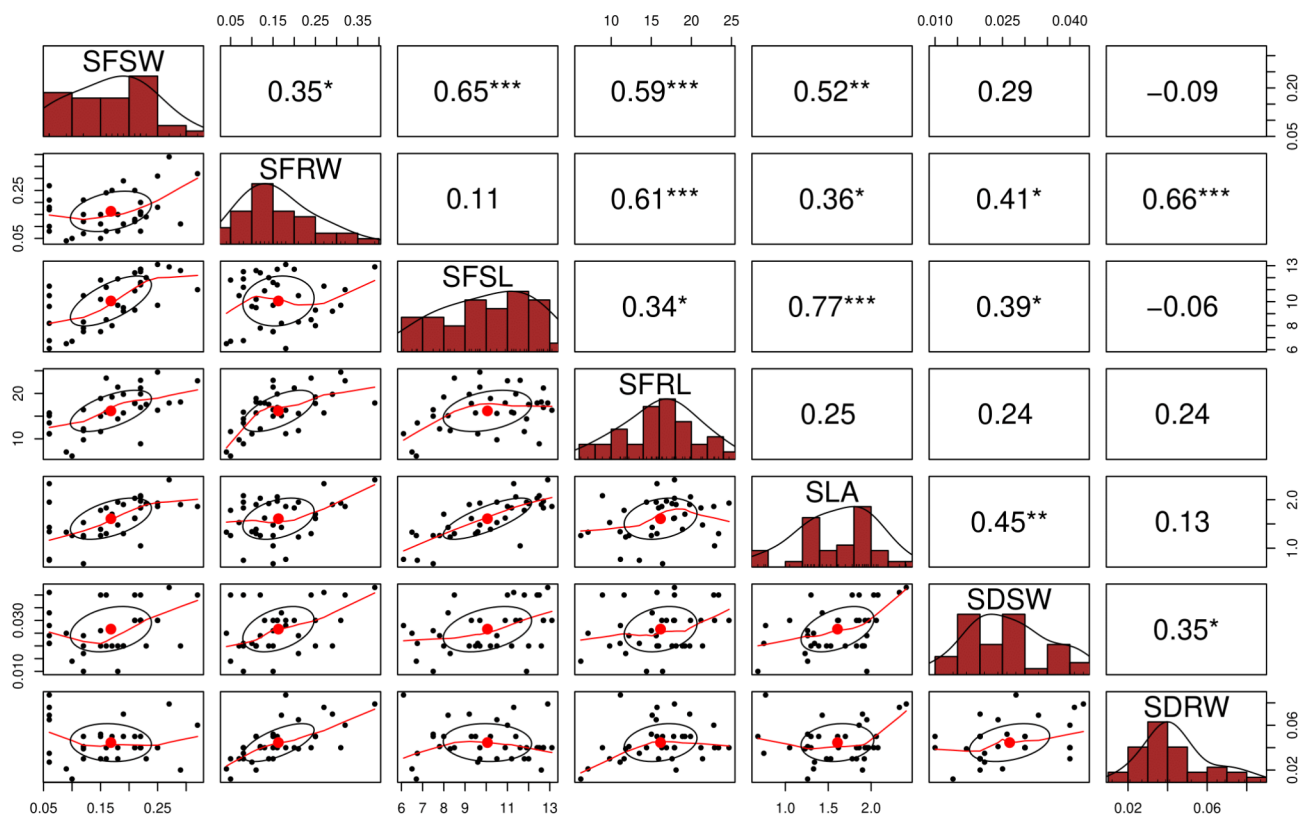


Fig. 3 Correlation matrices for wheat physiological parameters at seedlings stages. The diagonal elements display histograms representing the distribution of each variable's values. Each square above the diagonal shows the Pearson correlation coefficient (R), ranging from -1 to +1, indicating the correlation strength between two variables: negative values denote negative correlations, while positive values denote positive correlations. The star rating system above the diagonal indicates the significance level of the correlation, with more stars denoting stronger correlations. Each square below the diagonal contains scatter plots illustrating the data distribution between pairs of physiological traits. Significance level: Significant ($P < 0.05$), ** = Highly significant ($P < 0.01$), *** = Very highly significant ($P < 0.001$)

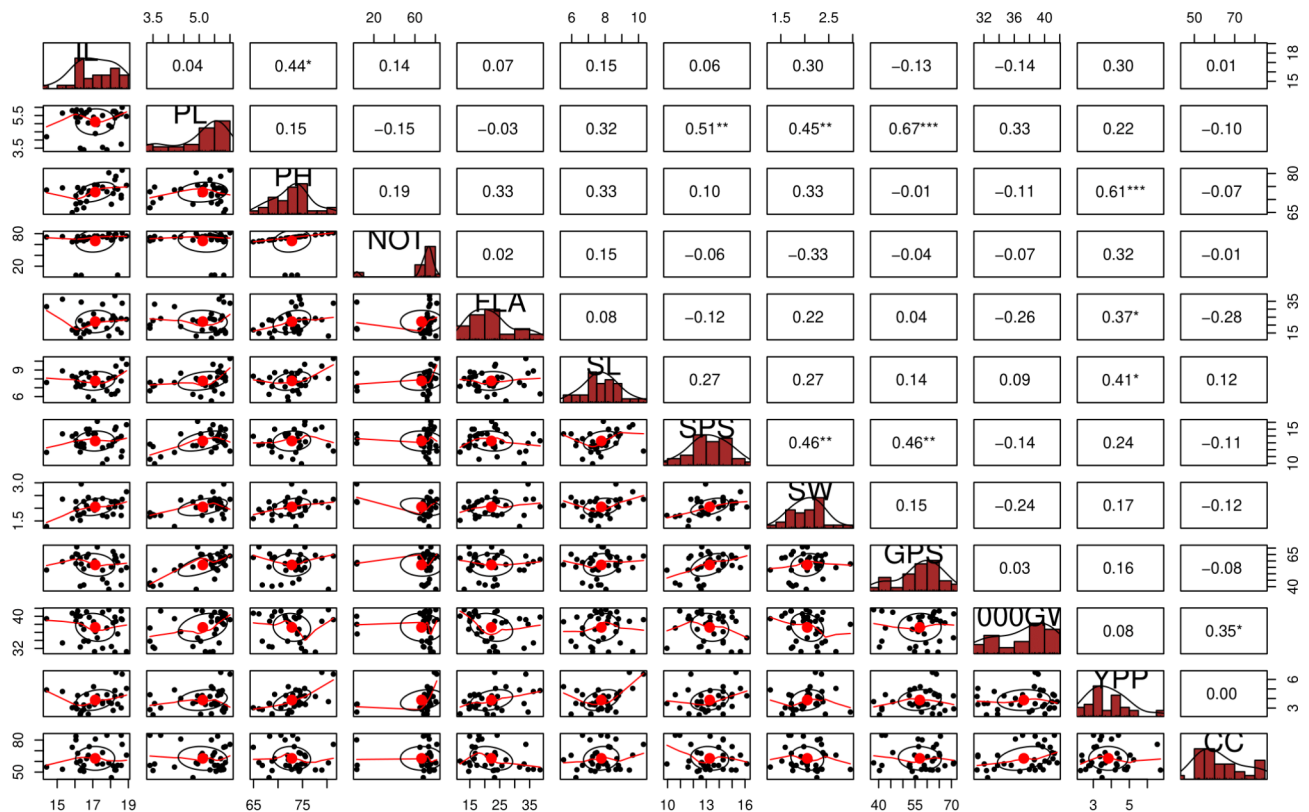


Fig. 4 Correlation matrices for wheat physiological parameters at maturity stages. The diagonal elements display histograms representing the distribution of each variable's values. Each square above the diagonal shows the Pearson correlation coefficient (R), ranging from -1 to $+1$, indicating the correlation strength between two variables: negative values denote negative correlations, while positive values denote positive correlations. The star rating system above the diagonal indicates the significance level of the correlation, with more stars denoting stronger correlations. Each square below the diagonal contains scatter plots illustrating the data distribution between pairs of physiological traits. Significance level: Significant ($P < 0.05$), ** = Highly significant ($P < 0.01$), *** = Very highly significant ($P < 0.001$)

for wheat seedling parameters (Fig. 7). The separation between groups is evident in PC1, which accounts for 16.8% of the total variance, and PC2, which accounts for 12.8% of the total variance for wheat maturity parameters (Fig. 8). Similarly, Jabran et al. [59] revealed that the first four principal components, with eigenvalues greater than 1, accounted for 73.578% and 82.80% of the total variation under diseased and control conditions, respectively. Cluster analysis categorized 35 wheat genotypes into four distinct clusters. Within cluster 1, the highest disease severity was observed under control conditions, whereas cluster 4 exhibited the highest disease severity under diseased conditions. The scatter plot indicated that none of the clusters exhibited a distinct separation. In the current study, separation in the PCA plot showed that the different treatments significantly impacted the morphophysiological parameters during the seedling and maturity stages. Each treatment group exhibited specific characteristics that were distinguished from the others. This finding suggests that using carrier material and endophytic bacteria contributed to developing unique growth attributes in the wheat samples. To further investigate

and identify the different morphophysiological parameters with greater accuracy, a cluster analysis was performed on the seedling and maturity stage parameters based on the PCA results [30, 60]. This analysis allowed for a more detailed examination of the similarities and dissimilarities between the samples within each treatment group (Fig. 5). Cluster analysis helps identify potential subgroups or patterns within the treatment groups, providing a deeper understanding of the variations in morphophysiological parameters [61].

Furthermore, the cluster analysis results indicate that the groups of samples were significantly different from each other. The parallel samples within each group, which share similar substrates, demonstrated proximity to each other regarding their morphophysiological attributes. This consistency within each group enhances the reliability of the samples. It suggests that the observed differences between the groups are not random but are associated with the specific treatments applied. Furthermore, the cluster analysis based on PCA, and the accompanying plot provides a visual representation of the relationships and groupings among the performance of

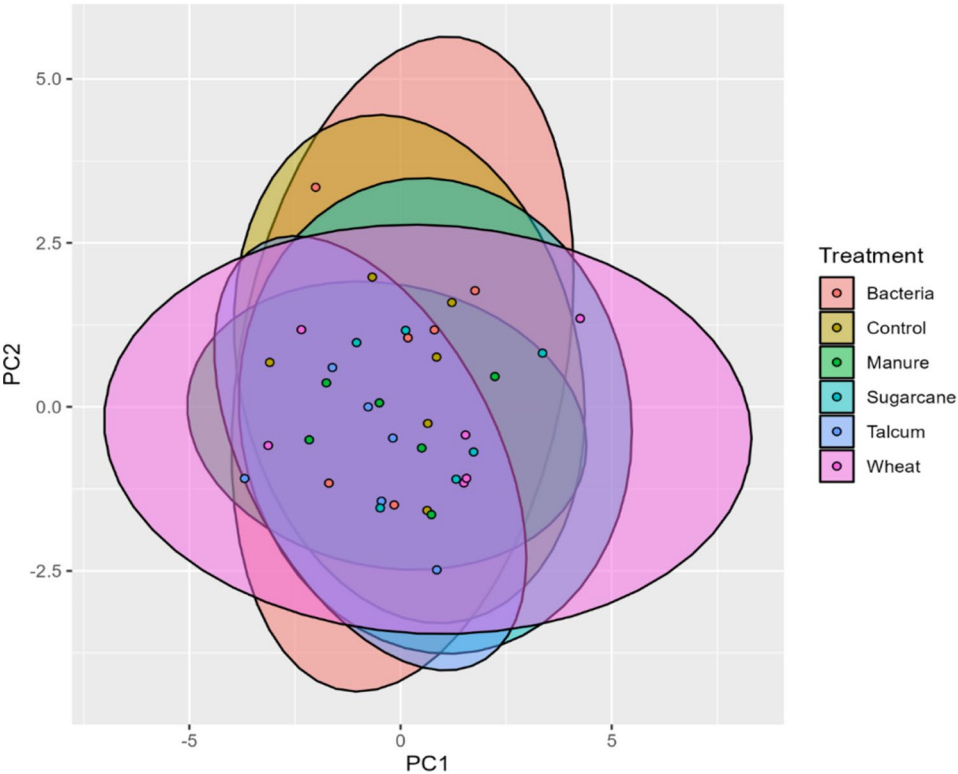


Fig. 5 Cluster analysis of wheat performance at maturity based on PCA. The plot displays the distribution of wheat samples in PC1 and PC2 space, color-coded by treatment. Ellipses represent 95% confidence intervals for each treatment group, while black dots indicate individual samples

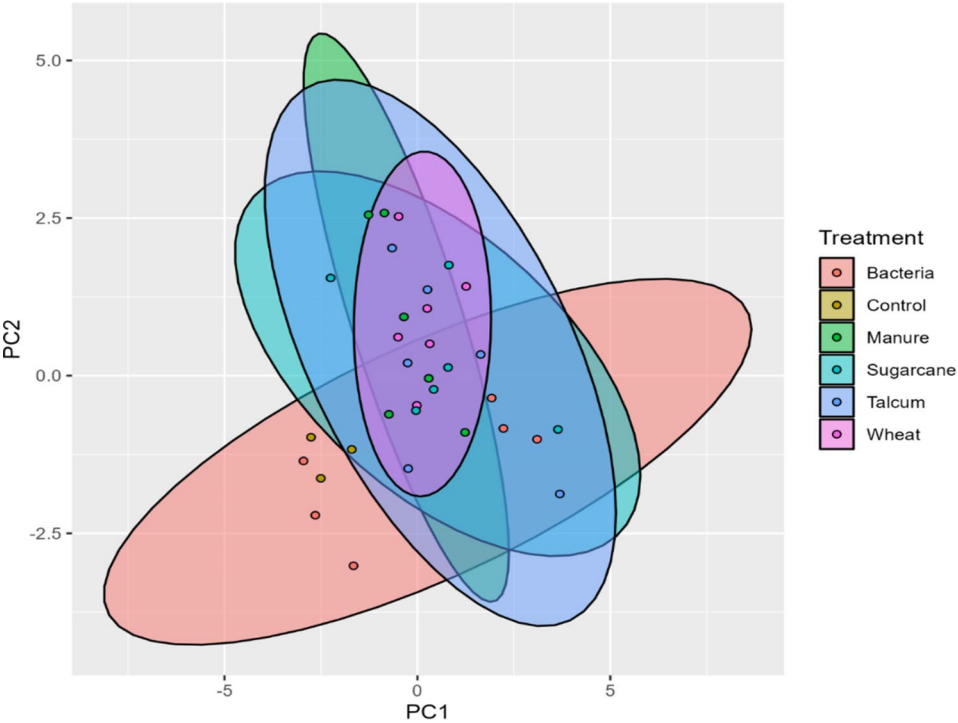


Fig. 6 Cluster analysis of wheat performance at maturity based on PCA. The plot displays the distribution of wheat samples in PC1 and PC2 space, color-coded by treatment. Ellipses represent 95% confidence intervals for each treatment group, while black dots indicate individual samples

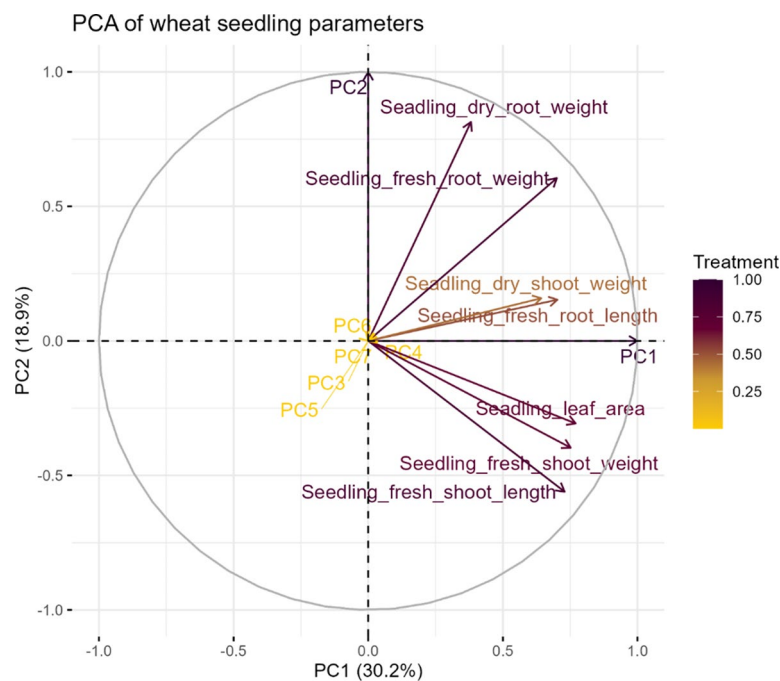


Fig. 7 Principal component analysis (PCA) plot illustrating the distribution of wheat seedling samples across the first two principal components (PC1 accounting for 30.2% and PC2 accounting for 18.9%, explains 49.1% of the total variance), with each sample color-coded by treatment group. The accompanying correlation circle on the right details how each seedling parameter contributes to both principal components

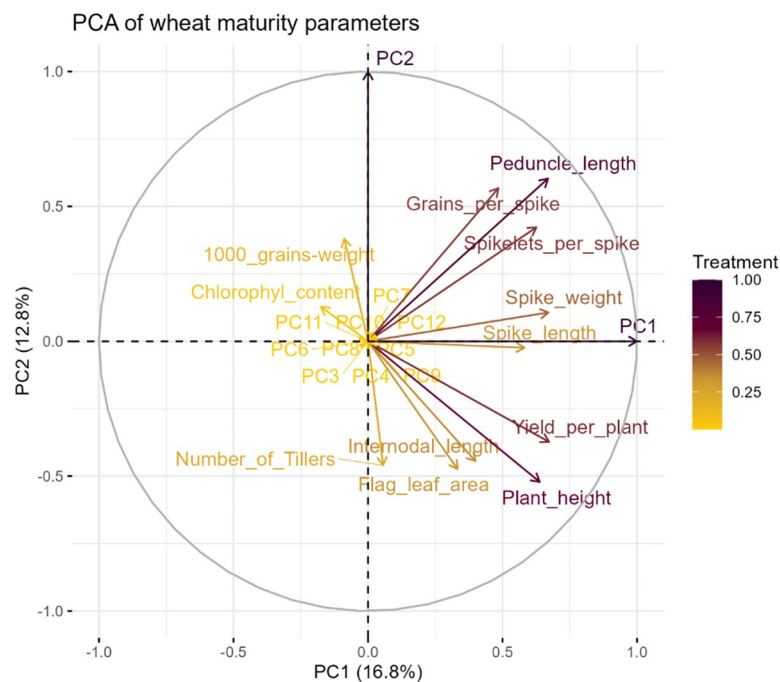


Fig. 8 Principal component analysis (PCA) plot illustrating the distribution of wheat maturity stage samples across the first two principal components (PC1 accounting for 16.8% and PC2 accounting for 12.8%, which explains 29.6% of the total variance). Each point represents a sample colored by its corresponding treatment group. The correlation plot on the right provides a clear understanding of the contribution of each variable to the principal components

different treatments at the wheat seedling and maturity stages. The plot's colour-coding, ellipses, and individual sample dots enhance the interpretation of the results, enabling a comprehensive understanding of the dataset's structure and variability. These findings highlight the effectiveness of using carrier material and endophytic bacteria in enhancing specific morphophysiological parameters in wheat samples, underscoring the potential benefits of these interventions in agricultural practices. Further investigations into the mechanisms underlying these interactions could offer valuable insights for optimizing crop growth and yield in wheat cultivation.

Conclusions

This study has revealed significant improvements in plant growth parameters, such as internodal length, spike length, tiller number per plant, grain yield per plant, and spikelets per spike, using bacterial-carrier treatments. The consortium treatment (Talc. powder and MN54 in Fathejang-16) demonstrated a leading effect, suggesting the potential of plant growth-promoting endophytes. Importantly, this bioinoculant strategy offers a sustainable alternative to chemical use, contributing to the development of sustainable farming practices. These findings underscore the promising potential of bioinoculant formulations, especially those utilizing sugarcane bagasse biochar and *Bacillus* spp., in promoting growth and potential yield in bread wheat. However, further research is necessary to optimize these formulations, explore their underlying mechanisms, and evaluate their performance under field conditions. This study provides valuable insights into the application for regulating wheat development, paving the way for advancements in sustainable agricultural practices and improved food security.

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Author contributions

M. J. Writing – original draft, Methodology, M. A. A. Conceptualization, writing—review & editing, T.A. Revision of the article, A. Z. Formal analysis, Software, A. A. Validation, U. A. Resources, M. N. Data curation, M. M. Formal analysis, A. G. Literature sources, L.G. Supervision, Funding acquisition, Project administration. All authors have read and agreed to the published version of the manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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