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RESEARCH ARTICLE

Effect of Mineral Fertilizer and Plant Growth-Promoting Bacterial Formulations on Yield and Yield Components in Triticale (*X Triticosecale* Wittmack)

Mineral Gübre ve Bitki Büyümesini Teşvik Eden Bakteriyel Formülasyonların Tritikale (*X Triticosecale* Wittmack) Verimi ve Verim Bileşenleri Üzerindeki Etkisi

Osman Davutlar[1]✉, **Ramazan Çakmakçı**[2]

[1] *Çanakkale Onsekiz Mart University, School of Graduate Studies, Field Crops Department, Çanakkale, Türkiye*
[2] *Çanakkale Onsekiz Mart University, Faculty of Agriculture, Field Crops Department, Çanakkale, Türkiye*

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ÖZ

Bu araştırma, mineral NP gübresi, ticari bir mikrobiyal gübre (TMG) ve bitki gelişimini teşvik edici özelliklere sahip bakterilerden oluşturulan sekiz farklı biyolojik gübre formülasyonunun (F1–F8) Çanakkale koşullarında yetiştirilen Karma 2000 tritikale (×*Triticosecale* Wittmack) çeşidinin gelişme, verim ve kalite özellikleri üzerine etkilerini belirlemek amacıyla yürütülmüştür. Araştırma tesadüf blokları deneme desenine göre üç tekerrürlü olarak kurulmuştur. Uygulamaların bitki boyu, başak uzunluğu, başakta başakçık sayısı, başakta tane sayısı, başakta tane ağırlığı, klorofil içeriği, tane verimi, sap verimi, bin tane ağırlığı ve hektolitre ağırlığı üzerine etkileri önemli bulunmuştur ($P \leq 0.05$). Mineral NP gübresi ve biyolojik gübre uygulamaları incelenen özelliklerin tamamında kontrol uygulamasına göre üstün performans göstermiştir. En yüksek tane verimi F3 (4.32 t ha^{-1}), NP (4.28 t ha^{-1}), F1 (4.27 t ha^{-1}) ve F6 (4.18 t ha^{-1}) uygulamalarından elde edilmiştir. Benzer şekilde F3, F1 ve F6 uygulamaları bitki boyu, başak özellikleri, bin tane ağırlığı ve hektolitre ağırlığı bakımından mineral gübre uygulamasına yakın sonuçlar vermiştir. Tane veriminde kontrol uygulamasına göre sırasıyla F3, NP, F1 ve F6 uygulamalarında %31.20, %29.90, %29.60 ve %27.10 oranında artış belirlenmiştir. Sonuç olarak, bitki gelişimini teşvik edici bakterilerden oluşturulan biyolojik gübre formülasyonlarının tritikale yetiştiriciliğinde büyüme, verim ve kalite özelliklerini olumlu yönde etkilediği, özellikle F3, F1 ve F6 formülasyonlarının kimyasal gübre kullanımının azaltılmasına katkı sağlayabilecek sürdürülebilir alternatifler olduğu ortaya konulmuştur.

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ABSTRACT

This study was conducted to determine the effects of mineral NP fertilizer, a commercial microbial fertilizer (CMF), and eight bacterial biofertilizer formulations (F1–F8) possessing plant growth-promoting traits on the growth, yield, and quality characteristics of triticale (×*Triticosecale* Wittmack cv. Karma 2000) under Çanakkale field conditions. The experiment was established in a randomized complete block design with three replications. The effects of the treatments on plant height, spike length, number of spikelets per spike, number of grains per spike, grain weight per spike, chlorophyll content, grain yield, straw yield, thousand-grain weight, and hectoliter weight were found to be significant ($P \leq 0.05$). Both mineral NP fertilizer and

✉ **Correspondence:** osmandavutlarr@gmail.com (Osman Davutlar)
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bacterial biofertilizer applications significantly improved all investigated traits compared with the untreated control. The highest grain yields were obtained from F3 (4.32 t ha^{-1}), NP (4.28 t ha^{-1}), F1 (4.27 t ha^{-1}), and F6 (4.18 t ha^{-1}) treatments. Similarly, F3, F1, and F6 applications produced plant height, spike characteristics, thousand-grain weight, and hectoliter weight values comparable to those achieved with mineral NP fertilization. Compared with the control treatment, grain yield increased by 31.20%, 29.90%, 29.60%, and 27.10% in F3, NP, F1, and F6 treatments, respectively. The results demonstrated that bacterial biofertilizer formulations positively affected the growth, yield, and quality traits of triticale. In particular, F3, F1, and F6 formulations showed considerable potential as sustainable alternatives for reducing chemical fertilizer inputs in triticale production.

Introduction

Triticale (*X Triticosecale* Wittmack), an intergeneric hybrid derived from wheat (*Triticum* spp.) and rye (*Secale cereale* L.), is a valuable cereal crop that combines the high yield potential and grain quality of wheat with the superior stress tolerance and adaptability of rye (Han et al., 2025; Cui et al., 2025). Owing to its balanced nutritional composition, high biomass production, and adaptability to diverse environmental conditions. Triticale is widely utilized for forage, grain, malt, bioethanol production, and sustainable cropping systems (Hanoğlu Oral, 2024). The incorporation of rye genetic material has enhanced the tolerance ability of triticale against the adverse environmental conditions, including soil salinity, nutrient deficiencies, pH extremes, drought, and temporary waterlogging (Blum, 2014). Furthermore, triticale exhibits rapid growth, high forage quality, lodging resistance, and a favorable amino acid composition. Compared with wheat, triticale grain contains higher lysine concentrations, resulting in improved protein quality and biological value (Spina & Zingale, 2023).

Plant growth-promoting bacteria (PGPB) have emerged as an important component of sustainable agricultural systems due to their ability to enhance plant growth and productivity through multiple direct and indirect mechanisms. These beneficial microorganisms contribute to biological nitrogen fixation, phosphorus solubilization, phytohormone production, nutrient mobilization, organic matter decomposition, suppression of plant pathogens, induction of systemic resistance, siderophore production, ACC deaminase activity, and enhancement of plant–microbe symbioses (Şahin et al., 2004; Canbolat et al., 2006; Çakmakçi et al., 2006; Cakmakci et al., 2007; 2014; Wong et al., 2015; Çakmakçı, 2016; Çakmakçı et al., 2017; Kumar et al., 2022; Güler, 2024; Moharrami et al., 2026; Salata et al., 2026). Through these mechanisms, PGPB improve nutrient acquisition, stimulate root development, mitigate environmental stresses, and ultimately increase crop productivity.

The intensive use of chemical fertilizers in modern agricultural systems has contributed substantially to environmental degradation, including nitrate contamination of groundwater, eutrophication of aquatic ecosystems, soil acidification, biodiversity loss, and depletion of non-renewable phosphorus and energy resources. Long-term and unbalanced fertilizer applications may also adversely affect soil microbial communities, nutrient cycling processes, and overall soil fertility (Çakmakçı, 2019; Che et al., 2021; Nosheen et al., 2021). Consequently, biofertilizers have gained increasing attention as environmentally friendly, cost-effective, and sustainable alternatives or supplements to chemical fertilizers within integrated nutrient management strategies (Çakmakçı, 2019). The use of PGPB to maintain soil fertility and improve crop productivity has therefore become a key approach in sustainable agriculture, leading to the development of numerous microbial inoculants for crop nutrition, growth promotion, and disease suppression (Şahin et al., 2004; Çakmakçi et al., 2006; Singh et al., 2011; Bhattacharyya & Jha, 2012; Çakmakçı et al., 2017).

Several studies have demonstrated the beneficial effects of microbial inoculants on triticale growth and productivity. Batykova et al., (2024) reported that several bacterial strains isolated from the rhizosphere and endophytic tissues of triticale exhibited growth-promoting and antifungal properties, highlighting their potential for biofertilizer development. Fitouri et al., (2022) suggested that the integration of bacterial biofertilizers and mycorrhizal fungi in vetch–oat–triticale intercropping systems can significantly enhance growth and yield while improving land-use efficiency. Similarly, Mazurenko et al., (2020) demonstrated that seed inoculation with *Azospirillum brasilense* and *Bacillus polymyxa* increased spike productivity, thousand-kernel weight, and grain yield of spring triticale, with the greatest improvements observed under co-inoculation. Lestingi et al., (2007) further reported that combined bacterial and fungal inoculations promoted seedling development and improved forage quality.

Recent studies have also emphasized the role of novel microbial species in improving triticale performance. Zenelt et al., (2024) demonstrated that phosphate-solubilizing strains of *Lactococcus lactis*, *L. garvieae*, *Acinetobacter* sp., and *Rothia kristinae* enhanced shoot growth in several crops, including triticale, by increasing phosphorus availability. Under abiotic stress conditions, inoculation with PGPR, alone or in combination with nanomaterials, has been shown to improve chlorophyll content, water status, antioxidant enzyme activities, and grain yield (Aghaei et al., 2024). Likewise, Naseri-Minabi et al., (2025) reported that combining PGPR with reduced rates of mineral fertilizers improved grain yield, biomass production, and water-use efficiency under water-limited conditions. Barati et al., (2020) found that microbial inoculants combined with nitrogen fertilization enhanced grain yield, nitrogen remobilization, and water-use efficiency in triticale grown under Mediterranean climatic conditions. Furthermore, Salama and Badry (2021) demonstrated that inoculation with *Azotobacter chroococcum* reduced nitrogen fertilizer requirements by up to 50% without compromising forage yield, grain yield, or grain protein content.

The composition and activity of soil microbial communities also play a crucial role in triticale productivity. Zhang et al. (2025) reported that diazotrophic bacterial communities differed significantly among crop rotation systems and that genera such as *Anaeromyxobacter*, *Bradyrhizobium*, *Geoalkalibacter*, *Sinorhizobium*, and *Azoarcus* were strongly associated with triticale growth and yield. Although, the beneficial effects of PGPB have been widely documented, their effectiveness is strongly influenced by crop genotype, environmental conditions, soil characteristics, and microbial adaptation to local ecosystems (Rowinska et al., 2025). Therefore, the development and evaluation of locally adapted bacterial consortia remain essential for maximizing the agronomic benefits of microbial inoculants.

Considering the growing need to reduce chemical fertilizer inputs while maintaining crop productivity, the use of beneficial microorganisms represents a promising strategy for sustainable agriculture. Therefore, the present study was conducted to evaluate the effects of optimum mineral NP fertilization, a commercial microbial fertilizer, and eight bacterial biofertilizer formulations developed from locally isolated plant growth-promoting bacteria on the growth, yield, and quality characteristics of triticale under field conditions.

Materials and Methods

The study was conducted to evaluate the effects of mineral NP fertilizer (120 kg N ha^{-1} and 80 kg P_2O_5 ha^{-1}), a commercial microbial fertilizer (CMF), and eight bacterial biofertilizer formulations consisting of plant growth-promoting rhizobacteria (PGPR) possessing biological nitrogen fixation, phosphate solubilization, indole-3-acetic acid (IAA) production, and 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity on the growth, yield, and quality characteristics of triticale (*X Triticosecale* Wittmack cv. Karma 2000) under field conditions.

The bacterial formulations consisted of the following combinations: F1 (*Pseudomonas putida* G08 + *Bacillus subtilis* RA7 + *Bacillus megaterium* G81), F2 (*Pseudomonas koreensis* A96 + *Bacillus licheniformis* A38 + *Comamonas* sp. A3), F3 (*Pseudomonas putida* A110 + *Bacillus megaterium* G81), F4 (*Pseudomonas putida* A128 + *Pseudomonas stutzeri* B171 + *Bacillus pumilus* A54), F5 (*Pseudomonas putida* A128 + *Pseudomonas* sp. A71 + *Bacillus pumilus* A54), F6 (*Pseudomonas putida* G08 + *Bacillus subtilis* RA7 + *Bacillus megaterium* RA12), F7 (*Pseudomonas putida* RA1 + *Bacillus megaterium* G180 + *Bacillus atrophaeus* RA16), and F8 (*Pseudomonas stutzeri* B171 + *Peribacillus simplex* B12 + *Bacillus megaterium* G180).

Pure bacterial colonies were transferred into Nutrient Broth (NB) medium and incubated for 24 hours under continuous shaking. Bacterial cultures were subsequently multiplied in sterilized liquid NB medium prepared according to the procedure described by Çakmakçı et al. (2013). Equal volumes of each bacterial culture were combined to obtain the respective formulations, with a final concentration of approximately 10^8 CFU mL^{-1} for each strain.

Prior to inoculation, triticale seeds were surface sterilized with 70% ethanol for 2 min. followed by 1.2% sodium hypochlorite for 10 min. and then rinsed thoroughly with sterile distilled water. Seeds were inoculated immediately before sowing by immersing them in the appropriate bacterial suspension and gently shaking for uniform coating. After inoculation, seeds were air-dried in the shade for approximately 60 min. and sown directly in the field. To ensure adequate contact between bacterial cells and germinating roots, the remaining inoculum suspension was sprayed onto the seeds immediately before covering the rows with soil. The final inoculum density was adjusted to approximately 10^8 CFU seed^{-1}.

The field experiment was conducted at the Dardanos Research and Application Farm of the Faculty of Agriculture, Çanakkale Onsekiz Mart University, Türkiye, during the growing season of 2024-2025. The experiment was established in a randomized complete block design using three replications.

Prior to sowing, the experimental field was prepared through conventional tillage, including deep plowing followed by secondary surface cultivation. The triticale cultivar 'Karma 2000' was used as plant material. Experimental plots measured 1 m × 5 m (5 m^2), with 0.5 m spacing between plots and 1.0 m spacing between blocks.

Sowing was performed on 28 November 2024 at a seeding rate of 500–550 seeds m^{-2}. Seeds for each plot were weighed individually and manually sown to ensure uniform plant density. Field emergence was satisfactory, and no significant plant losses were observed during winter or spring growth. No chemical pesticides or herbicides were applied throughout the experimental period.

Plant height, spike length, number of spikelets per spike, number of grains per spike, grain weight per spike, chlorophyll content (SPAD), grain yield, straw yield, thousand-grain weight, and hectoliter weight were recorded at the appropriate growth stages following standard agronomic procedures.

Results and Discussion

The effects of mineral NP fertilizer, commercial liquid biofertilizer (CLBF), and bacterial biofertilizer formulations on agronomic growth, yield components, grain yield, and grain quality characteristics of triticale are presented in Tables 1–3. Significant treatment effects were observed for most of the investigated parameters.

The effects of fertilizer and bacterial formulations on heading time, plant height, spike length, and chlorophyll content at the early dough stage are presented in Table 1. Heading time varied between 146.2 and 158.4 days, with the earliest heading recorded in the F7 treatment and the latest in F6. Plant height ranged from 110.0 cm in the control treatment to 139.5 cm in the NP treatment. All treatments increased plant height compared with the control, although the increases observed with F4 and F7 were less pronounced. Among the bacterial formulations, F3, F1, and F6 produced plant heights statistically comparable to those obtained with mineral NP fertilization. Similar responses were observed for spike length and chlorophyll content. The highest chlorophyll values were recorded in NP (53.94 SPAD) and F3 (53.16 SPAD) treatments, indicating improved nutrient acquisition and enhanced photosynthetic activity. Increased chlorophyll content in inoculated plants may be attributed to improved nitrogen availability and uptake resulting from the biological nitrogen fixation and nutrient mobilization activities of the bacterial strains.

The effects of treatments on spikelet number, grain number per spike, total spike weight, and grain weight per spike are shown in Table 2. All fertilizer and bacterial applications significantly improved these yield components compared with the control treatment. The highest number of grains per spike was obtained from NP (63.59), followed by F3 (61.66), F6 (59.94), F2 (59.95), and F1 (59.37). Similar trends were observed for total spike weight and grain weight per spike. The superior performance of F3, F1, and F6 formulations suggests that these bacterial consortia effectively enhanced nutrient uptake and assimilate accumulation during reproductive development, leading to improved grain formation and spike productivity.

Straw yield, grain yield, thousand-grain weight, and hectoliter weight as affected by fertilizer and bacterial formulations are presented in Table 3. Grain yield varied from 3.29 t ha^{-1} in the control treatment to 4.32 t ha^{-1} in the F3 treatment. The highest grain yields were obtained from F3 (4.32 t ha^{-1}), NP (4.28 t ha^{-1}), F1 (4.27 t ha^{-1}), F6 (4.18 t ha^{-1}), and F2 (4.15 t ha^{-1}). Compared with the control treatment, these applications increased grain yield by 31.2%, 29.9%, 29.6%, 27.1%, and 26.0%, respectively. Likewise, straw yield increased substantially, with F3 and F1 producing biomass yields statistically similar to those obtained under mineral NP fertilization. These findings indicate that selected bacterial formulations can maintain productivity levels comparable to conventional fertilization while reducing dependence on chemical fertilizers.

Grain quality characteristics were also positively influenced by bacterial inoculation (Table 3). Thousand-grain weight increased from 39.17 g in the control treatment to 47.38 g in F3 and 46.73 g in NP-treated plots. Similarly, hectoliter weight increased from 69.34 kg hL^{-1} in the control to values exceeding 80 kg hL^{-1} in NP, F1, F2, F3, and F6 treatments. The improvements in grain weight and hectoliter weight indicate enhanced grain filling and more efficient translocation of assimilates to developing kernels.

The positive effects observed in this study can be attributed to the multiple plant growth-promoting mechanisms of the bacterial strains used in the formulations. These microorganisms possess the ability to fix atmospheric nitrogen, solubilize phosphorus, produce indole-3-acetic acid (IAA), and synthesize ACC deaminase, thereby improving root development, nutrient uptake efficiency, photosynthetic activity, and stress tolerance. Such mechanisms likely contributed to the observed increases in chlorophyll content, yield components, grain yield, and grain quality.

The present findings are consistent with previous studies reporting beneficial effects of plant growth-promoting bacteria on triticale performance. Mazurenko et al. (2020) demonstrated that inoculation with *Azospirillum brasilense* and *Bacillus polymyxa* increased spike productivity and grain yield in spring triticale. Similarly, Barati et al. (2020) reported that microbial inoculants combined with mineral fertilizers improved grain yield and water-use efficiency under Mediterranean conditions. Naseri-Minabi et al. (2025) found that PGPR inoculation reduced yield losses under water-limited environments, whereas Aghaei et al. (2024) reported improvements in physiological characteristics and grain yield following inoculation with beneficial bacterial strains. Batykova et al. (2024) further emphasized the potential of IAA-producing bacterial isolates associated with triticale as effective biofertilizers.

Among the tested formulations, F3 (*Pseudomonas putida* A110 + *Bacillus megaterium* G81), F1 (*Pseudomonas putida* G08 + *Bacillus subtilis* RA7 + *Bacillus megaterium* G81), and F6 (*Pseudomonas putida* G08 + *Bacillus subtilis* RA7 + *Bacillus megaterium* RA12) consistently produced superior agronomic performance. In most measured parameters, these formulations performed similarly to the recommended mineral NP fertilizer treatment. Therefore, these locally developed bacterial consortia represent promising biofertilizer candidates for sustainable triticale production and may contribute to reducing chemical fertilizer inputs while maintaining high yield and grain quality.

Table 1. Effects of fertilizer and bacterial formulations on, heading time, plant height, Spike length, and chlorophyll content at early dough stage in Karma-2000 triticale cultivar.

Treatments*	Heading time (day)**	Plant height (cm)	Spike length (cm)	Chlorophyll content (SPAD) at early dough stage
Control	149.4±5.3 a-c	110.0±2.3 f	10.53±0.49 c	43.21±0.34 c
NP	150.4±2.8 a-c	139.5±5.1 a	12.47±0.47 a	53.94±3.44 a
CLBF	156.2±6.5 ab	120.0± 3.2 e	11.53±0.35 a-c	47.27±0.52 b
F1	151.7±6.7 a-c	133.1±4.1 a-c	12.17±0.61 ab	48.54±2.74 b
F2	153.9±5.5 a-c	127.42±2.9 cd	11.43±0.49 bc	47.54±1.33 b
F3	147.8±1.7 bc	135.3±3.6 ab	11.97±0.61 ab	53.16±1.61 a
F4	155.9±3.7 a-c	116.5±3.1 ef	11.23±0.81 bc	46.77±0.56 b
F5	153±4.6 a-c	127.6±4.6 cd	11.77±0.45 ab	47.42±1.63 b
F6	158.4±4.9 a	131.6±4 a-c	11.6±0.56 ab	47.57±0.95 b
F7	146.2±0.6 c	114±4.1 ef	11.2±0.46 bc	46.74±3.45 b
F8	153±5 a-c	120.9±3.8 de	11.43±0.35 bc	47.18±0.87 b
Average	152.4±5.30	125.1±9.50	11.58±0.67	48.12±3.31

*Control: Without bacteria and fertilizer, NP fertilizer (120 kg N ha^{-1}+ 80 kg P ha^{-1}); CLBF (BMusaGreen, commercial liquid bio-fertilizer) and N2-fixing and P-solubilizing bacteria based four bacterial formulations in three strains combinations (F1: *Pseudomonas putida* G08 + *Bacillus subtilis* RA7 + *Bacillus megaterium* G81; F2: *Pseudomonas koreensis* A96 + *Bacillus licheniformis* A38 + *Comamonas* sp. A3; F3: *P. putida* A110 + *B. megaterium* G81; F4: *P. putida* A128 + *Pseudomonas stutzeri* B171 + *Bacillus pumilus* A54; F5: *P. putida* A128+ *Pseudomonas* sp. A71 + *B. pumilus* A54; F6: *P. putida* G08+ *B. subtilis* RA7 + *B. megaterium* RA12; F7*:* *P. putida* RA1+ *B. megaterium* G180 + *Bacillus atrophaeus* RA16, ve F8: *P. stutzeri* B171+ *Peribacillus simplex* B12 + *B. megaterium* G180); ** Values are means ± SE; Different letters within the same column indicate significant differences according to Duncan's Multiple Range Test ($P \leq 0.05$).

Table. 2. Effects of fertilizer and bacterial formulations on number of spikelets per spike, number of grains per spike, total weight per spike, and grain weight per spike in Karma-2000 triticale cultivar.

Treatments*	Number of spikelets per spike (number) **	Number of grains per spike (number)	Total weight per spike (g)	Grain weight per spike (g)
Control	29.33±0.99 c	52.40±1.26 f	4.14±0.12 d	2.94±0.07 e
NP	32.8±0.53 a	63.59±2.11 a	5.15±0.30 a	3.61±0.15 a
CLBF	33±1.39 a	58.79±1.71 cd	4.84±0.09 a-c	3.43±0.07 a-c
F1	31.47±1.17 ab	59.37±1.4 bc	5.09±0.04 ab	3.55±0.12 ab
F2	31.6±1.25 ab	59.95±1.75 bc	5.04±0.1 ab	3.48±0.08 a-c
F3	32.37±0.57 ab	61.66±1.63 a	5.08±0.14 ab	3.61±0.12 a
F4	31.6±0.72 ab	56.47±0.82 de	4.69±0.2 c	3.29±0.06 cd
F5	31.53±0.76 ab	58.46±1.35 c-e	4.84±0.17 a-c	3.45±0.11 a-c
F6	32.87±0.31 a	59.94±1 bc	5.13±0.21 a	3.53±0.12 ab
F7	30.73±1.29 bc	56.09±0.6 e	4.56±0.25 c	3.23±0.12 d
F8	31.69±0.76 ab	59.25±1.69 bc	4.79±0.15 bc	3.38±0.08 b-d
Average	31.73±1.30	58.73±3.12	4.85±0.33	3.41±0.21

*Values are means±SE; Different letters within the same column indicate significant differences according to Duncan's Multiple Range Test ($P \leq 0.05$).

Table 3. Effects of fertilizer and microbial formulations on straw and grain yield, thousand grain weight hectoliter weight in Karma-2000 triticale cultivar.

Treatments	Straw yield (t ha^{-1}) *	Grain yield (t ha^{-1})	Thousand grain weight (g)	Hectoliter weight (kg hl^{-1})
Control	8.04±0.29 f	3.29±0.12 e	39.17±0.98 e	69.34±3.02 c
NP	10.82±0.39 a	4.28±0.15 a	46.73±1.01 ab	83.87±0.70 a
CLBF	9.11±0.29 c-e	3.92±0.14 bc	46.35±1.18 a-c	76.14±2.48 b
F1	10.41±0.38 ab	4.27±0.17 a	45.63±1.11 a-c	80.25±2.72 a
F2	9.67±0.39 cd	4.15±0.15 ab	45.24±0.89 cd	80.34±1.25 a
F3	10.51±0.28 ab	4.32±0.20 a	47.38±0.85 a	81.23±2.24 a
F4	8.95±0.32 e	3.74±0.11 cd	44.33±0.64 d	73.33±1.77 b
F5	9.91±0.51 bc	4.09±0.15 ab	44.72±1.42 cd	75.67±1.18 b
F6	9.88±0.36 bc	4.18±0.18 ab	46.13±1.3 a-c	82.38±1.27 a
F7	8.72±0.38 e	3.61±0.16 d	44.64±1.48 d	72.80±2.82 bc
F8	9.27±0.38 c-e	3.90±0.14 bc	44.99±0,57 cd	75,63±2,06 b
Average	9.57±0.87	3.98±0.34	45.03±2.28	77.36±4.75

*Values are means±SE; Different letters within the same column indicate significant differences according to Duncan's Multiple Range Test ($P \leq 0.05$).

Conclusion

The present study demonstrated that both mineral NP fertilizer and bacterial biofertilizer formulations significantly improved the growth, yield, and grain quality characteristics of triticale under the ecological conditions of Çanakkale. All microbial treatments positively affected most of the investigated parameters compared with the unfertilized control, indicating the effectiveness of plant growth-promoting bacterial consortia in enhancing triticale performance. Among the tested formulations, F3 (*Pseudomonas putida* A110 + *Bacillus megaterium* G81), F1 (*Pseudomonas putida* G08 + *Bacillus subtilis* RA7 + *Bacillus megaterium* G81), and F6 (*Pseudomonas putida* G08 + *Bacillus subtilis* RA7 + *Bacillus megaterium* RA12) consistently produced superior results for plant growth, yield components, grain yield, and grain quality traits. These formulations achieved grain yields comparable to those obtained with the recommended mineral NP fertilizer treatment and substantially outperformed the uninoculated control. The observed improvements are likely associated with the multiple plant growth-promoting activities of the bacterial strains, including biological nitrogen fixation, phosphate solubilization, indole-3-acetic acid production, and ACC deaminase activity, which collectively enhance nutrient availability, root development, and plant physiological performance. Overall, the results indicate that locally developed bacterial biofertilizer formulations have considerable potential to partially replace mineral fertilizers in triticale cultivation while maintaining high productivity and grain quality. Their use may contribute to reducing chemical fertilizer inputs, lowering production costs, and improving the environmental sustainability of cereal production systems.

Further multi-location and multi-year studies are recommended to validate the consistency of these promising formulations under different soil, climatic, and management conditions and to determine their long-term effects on soil fertility and crop productivity.

Additional Information and Declarations

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