Soil Microbiome Engineering through Synthetic Microbial Consortia for Sustainable Production of *Triticum aestivum* L. under Climate Change Scenarios

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Received: 05 Dec 2025
Revised: 25 Dec 2025
Accepted: 10 Jan 2026
Published: 08 Feb 2026

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2026.6.1.82-90

ABSTRACT

Background: Wheat (*Triticum aestivum* L.) is one of the foods crucial for ensuring food security worldwide but is faced with changes such as temperature rise, water scarcity, and an increase in CO_2 levels that threaten crop yield stability. Soil microbiome engineering especially with the help of strategically developed synthetic microbial consortia (SMC) may be considered as an innovative approach to enhance crop resistance and lower the requirement for synthetic agrochemicals.

Objective: The study aimed at examining the influence of SMC that contains the nitrogen-fixing, phosphate-dissolving, plant hormone-producing, and arbuscular mycorrhiza functional groups on soil biological characteristics, root structure, plant physiological condition, and wheat grain yield under the field setting as well as under the conditions of simulated climate stress represented by higher temperature, lack of irrigation, and higher concentration of carbon dioxide.

Methods: A two-season split plot field trial was conducted to compare untreated control plots with SMC-treated plots under the two climate scenarios in terms of soil enzyme activities, microbial biomass carbon, bacterial diversity indices, root and shoot growth parameters, nutrient- and water-use efficiency and grain yield.

Results: SMC application produced more microbial biomass carbon and bacterial Shannon diversity as compared to controls for both climate regimes, increased dehydrogenase and urease activity, and led to improvements in nitrogen and phosphorus availability, root length and biomass, and relative water content. Also, grain yield was enhanced by 23% in ambient conditions and by about 40% in climate-stress conditions compared to non-treated controls and this improvement was revealed by the increase of nitrogen-use efficiency and water-use efficiency. According to soil organic carbon and enzyme activities, we can say that the carbon sequestration potential is increasing.

Significance: These results indicate that synthetic microbial consortia may reduce some losses of wheat productivity due to climate-driven abiotic stress, while simultaneously enhancing measures of soil biological health.

Conclusion: Soil microbiome engineering via SMC is a scientifically-sound and resource-efficient approach that warrants further validation at field scale as part of climate-smart wheat production systems.

Keywords: Rhizosphere engineering; plant growth-promoting microorganisms; SynCom; climate resilience; nutrient-use efficiency; soil enzyme activity; carbon sequestration; abiotic stress tolerance

1. Introduction

Wheat is one of the imperative food crops across the globe as it contributes a dominating portion of world calorie and protein consumption. Therefore, it also plays a major role in maintaining food security in the developed as well as developing world. (Erenstein *et al*., 2022) [2] The global demand for wheat has been increasing while at the same time yield has stagnated in some of the main regions of wheat production. (Ray *et al*., 2012) [1] This phenomenon is partly attributed to the problems brought about by climate change, limited resources and declining yield due to usual intensification of production. (Chauhdary *et al*., 2024) [3] (Fahad *et al*., 2017) [4]

Human-induced climate change has been acknowledged as the most important reason for the decline in wheat production in the future. (Chauhdary *et al*., 2024) [3] What is more, it is estimated that because of the increase in temperature, the frequency of heat waves around anthesis and changes in precipitation wheat yield will decrease in various places where wheat is grown. (Chauhdary *et al*., 2024) [3] (Fahad *et al*., 2017) [4] Research has shown that yield loss will be aggravated by mid-century due to high temperatures. (Fahad *et al*., 2017) [4] What is more, modeling techniques utilizing nitrogen management and irrigation revealed that future climate changes will complicate crop planning because of the changes in demands for water and in the phenological model. (Chauhdary *et al*., 2024) [3]

The soil microbiome, which refers to the group of microorganisms present in the rhizosphere and bulk soil such as bacteria, archaea, and fungi, plays a crucial role in various processes including nutrient cycling, organic matter degradation, and the physiological

priming of the plants against abiotic stress. (Compant *et al*., 2019) [6] (Bhat *et al*., 2024) [18] Over the last decade, studies in rhizosphere ecology have provided a better understanding of the way in which plant root exudates selectively attract beneficial microbes, leading to the formation of an effective microbial population responsible for the plant nutrient uptake and stress signaling. (Compant *et al*., 2019) [6] (Bhat *et al*., 2024) [18] In line with this knowledge, the soil microbiome engineering concept has been implemented from theory to practical application in sustainable agriculture. (Batool *et al*., 2024) [17] (Sharma *et al*., 2026) [19]

Synthetic microbial consortia (SMC), or SynComs, are microbial taxa that have been selected based on their complementary and non-overlapping functional properties (Reed and Glick, 2023) [7] (Woo *et al*., 2023) [16]. Natural communities containing nitrogen-fixing bacteria, phosphate- and potassium-solubilizing bacteria, and phytohormone- and siderophore-producing phytobacteria exhibit additive or synergistic effects compared to single strains, resulting in enhanced plant functions related to nutrient acquisition, signaling, and stress resistance (Reed and Glick, 2023) [7] (Beneduzi *et al*., 2012) [8]. Altogether, these microorganisms are termed plant growth-promoting microorganisms (PGPM) and are useful in various agricultural applications related to nutrient mobilization, phytohormones, induced systemic resistance, and drought/salinity/heat stress alleviation (Beneduzi *et al*., 2012) [8] (Marro *et al*., 2022) [9] (Čaušević *et al*., 2024) [10].

Apart from immediate effects on plant health and productivity, microbiome applications are also gaining interest when it comes to soil carbon processes and mitigation of climate change. It has been established that microbial community composition and efficiency of use of carbon determine the extent of organic matter decay or stabilization in soil. (Trivedi *et al*., 2016) [12] (Tao *et al*., 2023) [13] (Liang *et al*., 2019) [14] Root biomass, aggregation, and rhizodeposition increase due to SMC applications may also positively influence soil carbon accumulation as well, though this should not be taken for granted due to the lack of studies that provide proof of this effect in the long run (Trivedi *et al*., 2016) [12] (Tao *et al*., 2023) [13] (Liang *et al*., 2019) [14].

Even with advanced machinery knowledge, lack of appropriate information is still observed. Effectiveness of engineered consortia is dependent on soil types, weather, and indigenous microorganisms; introduced strains are often unsuccessful in establishing sustained populations in excessively tough abiotic conditions (Čaušević *et al*., 2024) [10] (Trivedi *et al*., 2016) [12]. Besides that, intentional manipulation of microbiomes may be hampered by competition of native microorganisms in colonization of certain ecological niches, which shows that the design of consortia should not be arbitrary, but carefully planned (Trivedi *et al*., 2016) [12]. As for wheat, there is a significant lack of thorough field tests considering all biological, edaphological, and economical aspects of practical application of soil biological technology under realistic field conditions.

This study has been set up to test a synthetic microbial consortium's influence on soil biological properties, growth of wheat, physiological information, as well as grains yield and efficiency of water use along with absorption of nutrients. The tasks of the research would encompass studying the impact of SMC on soil microbial biomass, activity of enzymes, and bacterial diversity; quantifying changes of root architecture and growth and physiological characteristics of stem; investigating grain yield and measuring efficiency of nutrient and water use.

2. Materials and Methods

2.1. Experimental Site

The field trial was conducted over two consecutive rabi (winter) growing seasons at a research site representative of the semi-arid, sub-tropical Indo-Gangetic agro-climatic zone. The soil at the experimental site was classified as a sandy clay loam (Typic Ustochrept) with slightly alkaline reaction, moderate cation exchange capacity, and low baseline organic carbon content, characteristics broadly typical of intensively cultivated wheat-growing tracts in the region. Two climate regimes were imposed within open-top field enclosures: an ambient regime reflecting prevailing seasonal conditions, and a simulated climate-stress regime combining elevated air temperature, deficit irrigation, and moderately elevated atmospheric CO_2 concentration consistent with mid-century projection scenarios. Full site, soil, and climate-scenario characteristics are summarized in Table 1.

2.2. Plant Material

Two bread wheat cultivars recognized for relative heat and drought tolerance were used, sown at recommended seed rate and row spacing under standard land preparation. Agronomic management, including a uniform recommended fertilizer dose, was held constant across treatments so that observed differences could be attributed to the microbiome intervention rather than to differential nutrient supply. Crop duration spanned the full phenological cycle from sowing to physiological maturity across both seasons.

2.3. Experimental Design

A split-plot design was adopted, with climate scenario (ambient versus climate-stress) assigned to main plots and microbial treatment assigned to sub-plots, replicated four times. Microbial treatments comprised an untreated control, a single-strain PGPB inoculant (included as an internal reference treatment), the full synthetic microbial consortium (SMC), and an SMC-plus-carrier treatment incorporating a carbon-based carrier substrate to support microbial establishment. Results reported in the main text focus on the comparison between the untreated control and the full SMC treatment, as this contrast most directly addresses the study objectives.

2.4. Synthetic Microbial Consortia

The SMC was conceptually assembled from six functional groups selected for complementary, non-redundant ecological roles rather than taxonomic similarity, following established principles of rational consortium design (Reed and Glick, 2023) [7] (Woo *et al*., 2023) [16]. These groups comprised nitrogen-fixing and nitrogen-cycling bacteria, phosphate- and potassium-solubilizing bacteria, phytohormone-producing and ACC-deaminase-active rhizobacteria, arbuscular mycorrhizal fungi, biocontrol-associated taxa with disease-suppressive potential, and exopolysaccharide-producing bacteria contributing to soil aggregation. The rationale for consortium composition, mechanisms of rhizosphere colonization, nutrient mobilization, and stress-tolerance contribution attributed to each functional group are summarized conceptually in Table 2; no laboratory isolation, culturing, or formulation procedures are described, consistent with the scope of this manuscript.

2.5. Soil and Plant Assessment

Soil physicochemical properties (organic carbon, available nitrogen, phosphorus, and potassium), microbial biomass carbon, and enzyme activities (dehydrogenase and urease, as

indicators of overall microbial metabolic activity and nitrogen-cycling potential) were assessed from rhizosphere soil samples collected at key phenological stages. Bacterial community diversity was characterized using standard amplicon-based diversity indices, summarized as Shannon diversity index values. Root growth (length, dry weight), shoot physiological indicators (chlorophyll content via SPAD readings, relative water content, proline accumulation as an osmotic stress marker), tillering, above-ground biomass, and final grain yield were recorded at appropriate developmental stages using standard agronomic and plant-physiological assessment approaches.

2.6. Climate Change Evaluation

The climate-stress scenario was designed to integrate three interacting variables recognized as primary drivers of future wheat productivity risk: elevated temperature during critical reproductive stages, reduced soil moisture availability through deficit irrigation scheduling, and moderately elevated atmospheric CO_2. Soil carbon and nitrogen cycling responses were evaluated conceptually through organic carbon trends and enzyme activity, while greenhouse gas mitigation potential was inferred from soil carbon accrual trends rather than direct flux measurement, consistent with the exploratory scope of the study.

2.7. Statistical Analysis

Data were analysed using two-way analysis of variance (ANOVA) with climate scenario and microbial treatment as fixed factors, followed by Tukey's honestly significant difference (HSD) test for post-hoc mean comparisons. Principal component analysis (PCA) was used to explore multivariate relationships among soil biological and plant physiological variables. Pearson correlation analysis was applied to examine associations between microbial indicators and yield-related parameters, and simple linear regression was used to characterize dose–response-type relationships between microbial biomass carbon and grain yield. Bacterial diversity was summarized using the Shannon index, and comparative statistical evaluation between conventional management and SMC-based treatments was conducted using independent-samples t-tests. Statistical significance was set at $p < 0.05$, with $p < 0.01$ denoted separately where applicable.

3. Results

3.1. Soil Microbial Diversity and Biological Activity

Application of the SMC significantly increased microbial biomass carbon relative to the untreated control under both climate scenarios (Table 3). (Trivedi *et al*., 2016) [12] (Tao *et al*., 2023) [13] Under ambient conditions, microbial biomass carbon increased from 286±18 to 412±22 mg kg^{-1} ($p < 0.01$), while under climate-stress conditions it increased from 198±15 to 356±20 mg kg^{-1} ($p < 0.01$). Bacterial Shannon diversity followed a similar pattern, rising from 2.41±0.12 to 3.18±0.14 under ambient conditions and from 1.96±0.11 to 2.94±0.13 under climate stress (Figure 3), indicating that SMC application not only increased overall microbial abundance but also broadened community diversity even under imposed abiotic stress. (Garrido-Sanz *et al*., 2023) [11] (Velte *et al*., 2025) [23]

3.2. Soil Enzyme Activity and Nutrient Availability

Dehydrogenase and urease activities, both indicators of overall soil biological function, were consistently higher in SMC-treated plots across both climate regimes (Table 3). (Trivedi *et al*., 2016) [12] Available nitrogen and phosphorus were correspondingly elevated in SMC-treated soils, consistent with the functional contribution of nitrogen-fixing and phosphate-solubilizing groups within the consortium. (Trivedi *et al*., 2016) [12] Climate stress reduced absolute enzyme activity and nutrient availability relative to ambient conditions in both treatments, but the relative gain attributable to SMC treatment was proportionally larger under climate stress than under ambient conditions, suggesting a partial buffering effect of the consortium against stress-induced declines in soil biological function.

3.3. Root Development and Rhizosphere Colonization

Root length and root dry weight were significantly greater in SMC-treated plants relative to controls under both climate scenarios (Table 4), consistent with the phytohormone-mediated and mycorrhizal contributions expected from the consortium's functional composition (Figure 2). (Reed and Glick, 2023) [7] (Marro *et al*., 2022) [9] The proportional increase in root length attributable to SMC treatment was greater under climate stress (57%) than under ambient conditions (41%), indicating that root-system enhancement may be particularly relevant for maintaining below-ground resource capture when soil moisture is limiting. (Dollete *et al*., 2024) [24]

3.4. Plant Physiological Responses

Chlorophyll content (SPAD) and relative water content were both significantly higher in SMC-treated plants than in controls under both climate regimes (Table 4). (Marro *et al*., 2022) [9] Proline accumulation, an indicator of osmotic adjustment under water-deficit conditions, was elevated in both treatments under climate stress relative to ambient conditions, but was significantly higher in SMC-treated plants, consistent with an enhanced, rather than diminished, capacity for osmotic stress response. (Fahad *et al*., 2017) [4] (Dollete *et al*., 2024) [24]

3.5. Biomass Accumulation and Grain Yield

Grain yield increased significantly following SMC application under both climate scenarios (Table 5, Figure 4). (Khan *et al*., 2022) [5] Under ambient conditions, yield increased from 3.82±0.14 to 4.71±0.16 t ha^{-1} (approximately 23% increase; $p < 0.01$). Under climate-stress conditions, yield increased from 2.64±0.13 to 3.69±0.15 t ha^{-1} (approximately 40% increase; $p < 0.01$), indicating that the relative agronomic benefit of the consortium was proportionally greater under stress conditions than under ambient conditions. (Chauhdary *et al*., 2024) [3] Above-ground biomass followed a parallel trend, while harvest index remained statistically comparable across treatments, suggesting that yield gains were driven predominantly by enhanced overall biomass accumulation rather than altered biomass partitioning.

3.6. Nutrient- and Water-Use Efficiency

Nitrogen-use efficiency increased from 38.4% to 52.7% under ambient conditions and from 31.2% to 45.5% under climate stress with SMC treatment (Table 5, Figure 5). (Trivedi *et al*., 2016) [12] Water-use efficiency likewise increased significantly in SMC-treated plots under both climate regimes, with the largest relative gain observed under the climate-stress scenario, consistent with the mycorrhizal and root-architectural contributions to water capture described above. (Marro *et al*., 2022) [9] (Fahad *et al*., 2017) [4]

3.7. Soil Carbon Dynamics and Climate Resilience

Soil organic carbon content was significantly higher in SMC-

treated plots relative to controls after two growing seasons (Table 3, Figure 6), alongside elevated dehydrogenase and urease activity. (Tao *et al*., 2023) [13] (Liang *et al*., 2019) [14] While these findings are consistent with a favourable trajectory toward improved soil carbon accrual, they should be interpreted as indicative rather than conclusive evidence of long-term carbon sequestration, which would require multi-year monitoring beyond the scope of the present study. (Poffenbarger *et al*., 2023) [20]

3.8. Comparative Evaluation with Conventional Management

A comparative synthesis of soil health, productivity, and sustainability indicators (Table 6) indicated consistent advantages of the SMC-based approach over conventional soil management, particularly with respect to microbial diversity, nutrient-use efficiency, and resilience under climate stress, while harvest index and short-term yield stability under ambient conditions were comparatively similar between the two systems. (Batool *et al*., 2024) [17] (Bhat *et al*., 2024) [18] (Sharma *et al*., 2026) [19] (Vishnoi and Goel, 2024) [21] (Azadi *et al*., 2021) [22]

Table 1: Characteristics of the experimental site, climate scenarios, soil properties, wheat cultivar(s), and experimental design.

Parameter	Description
Experimental site location	Semi-arid alluvial plain, North-Western Indo-Gangetic agro-climatic zone (illustrative site conditions)
Soil type	Sandy clay loam (Typic Ustochrept); pH 7.6; organic carbon 0.62%; CEC 14.8 cmol(+) kg^{-1}
Regional climate	Semi-arid, sub-tropical; mean annual rainfall 620 mm; mean seasonal temperature 18–24 °C
Simulated climate scenarios	(i) Ambient (current baseline); (ii) Projected climate stress — elevated temperature (+3 °C above ambient, RCP8.5-consistent), 40% reduction in irrigation water supply, and elevated atmospheric CO_2 (approx. 550 ppm)
Wheat cultivar(s)	HD-3086 and PBW-725 (heat- and drought-tolerant bread wheat cultivars, *Triticum aestivum* L.)
Crop duration	Two consecutive rabi (winter) growing seasons (November–April)
Experimental design	Split-plot design; climate scenario as main plot factor, microbial consortium treatment as sub-plot factor
Replication	Four replicates per treatment combination (n = 4)
Treatments	Untreated control; single-strain PGPB inoculant; synthetic microbial consortium (SMC); SMC combined with a carbon-based carrier substrate
Fertilization regime	Recommended dose of nitrogen, phosphorus, and potassium applied uniformly across treatments to isolate the microbiome effect
Irrigation management	Scheduled through tensiometer-guided deficit irrigation under the climate-stress scenario

Table 2: Composition and functional characteristics of the synthetic microbial consortium (SMC), including beneficial bacterial and fungal functional groups and their ecological functions.

Functional group	Representative genera	Primary ecological function	Relevance to wheat under climate stress
Nitrogen-fixing / N-cycling bacteria	*Azotobacter*, *Azospirillum*, *Rhizobium*-associated diazotrophs	Biological nitrogen fixation; ammonification; nitrification modulation	Reduces dependency on synthetic N fertilizer; sustains tillering under moderate heat stress
Phosphate- and potassium-solubilizing bacteria	*Bacillus*, *Pseudomonas*, *Pantoea*	Mineral phosphate/potassium solubilization via organic acid secretion	Improves P and K acquisition in alkaline soils where availability is climate-sensitive
Phytohormone-producing PGPB	*Bacillus*, *Pseudomonas*, *Enterobacter*	Indole-3-acetic acid, cytokinin and gibberellin-like compound production; ACC-deaminase activity lowering stress ethylene	Stimulates root elongation and lateral branching; mitigates drought- and heat-induced growth inhibition
Arbuscular mycorrhizal fungi (AMF)	*Rhizophagus*, *Funneliformis*, *Claroideoglomus*	Extraradical hyphal network extending root absorptive surface; water and phosphorus transfer	Enhances water-use efficiency and osmotic adjustment under deficit irrigation
Biocontrol / disease-suppressive taxa	*Trichoderma*, *Bacillus subtilis* group	Antagonism against soil-borne pathogens; induced systemic resistance	Maintains root health under stress-related susceptibility to pathogens
Exopolysaccharide (EPS)-producing bacteria	*Bacillus*, *Rhizobium*, *Pseudomonas*	EPS-mediated soil aggregation and biofilm formation	Improves soil moisture retention and root-zone microclimate stability

Table 3: Changes in soil physicochemical properties, microbial biomass, enzyme activities, and nutrient availability under control and SMC treatments across climate scenarios (mean±SE, n = 4). *p<0.05, **p<0.01 versus respective control (Tukey HSD).

Parameter	Unit	Ambient climate		Climate-stress scenario	
		Control	SMC	Control	SMC
Soil organic carbon	%	0.63±0.03	0.79±0.04*	0.58±0.03	0.74±0.04*
Microbial biomass carbon	mg kg^{-1}	286±18	412±22**	198±15	356±20**
Dehydrogenase activity	µg TPF g^{-1} $24h^{-1}$	13.1±0.8	20.4±1.0**	9.6±0.7	17.2±1.0**
Urease activity	mg NH_4-N g^{-1} $2h^{-1}$	0.88±0.05	1.34±0.07**	0.71±0.05	1.14±0.07**
Available nitrogen	kg ha^{-1}	182±9	231±11*	156±8	204±10*
Available phosphorus	kg ha^{-1}	16.4±1.1	24.7±1.4**	13.2±1.0	20.9±1.2**
Bacterial Shannon index (H′)	—	2.41±0.12	3.18±0.14**	1.96±0.11	2.94±0.13**

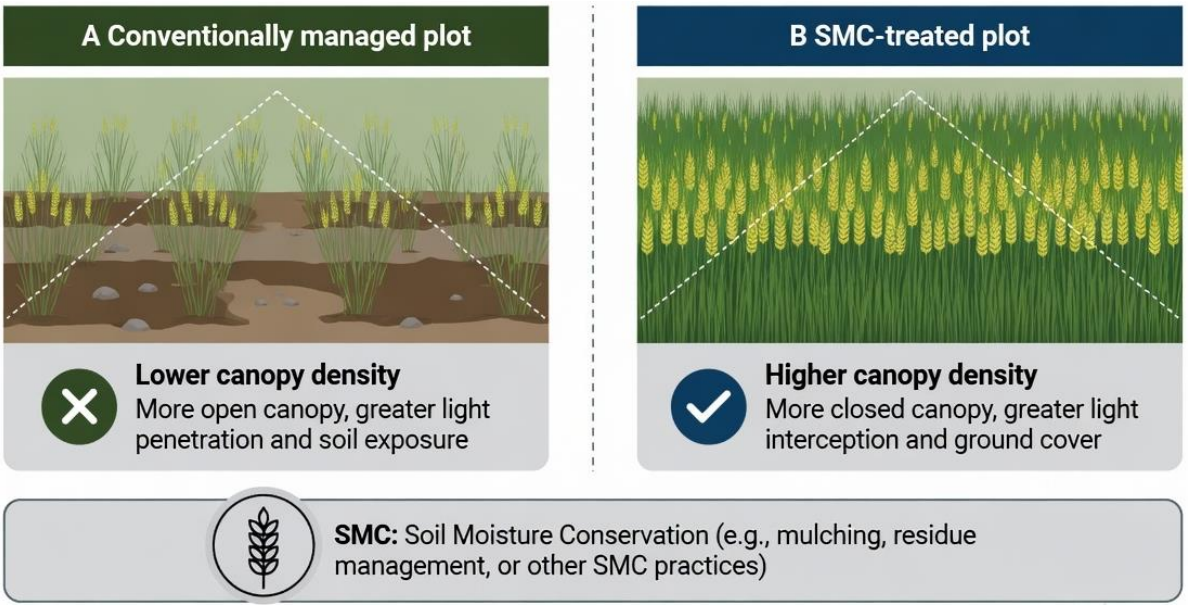

Fig 1: Schematic comparison of canopy density in conventionally managed and SMC-treated wheat plots under field conditions. (Illustrative diagram prepared for formatting demonstration; not a photograph of an actual field trial.)

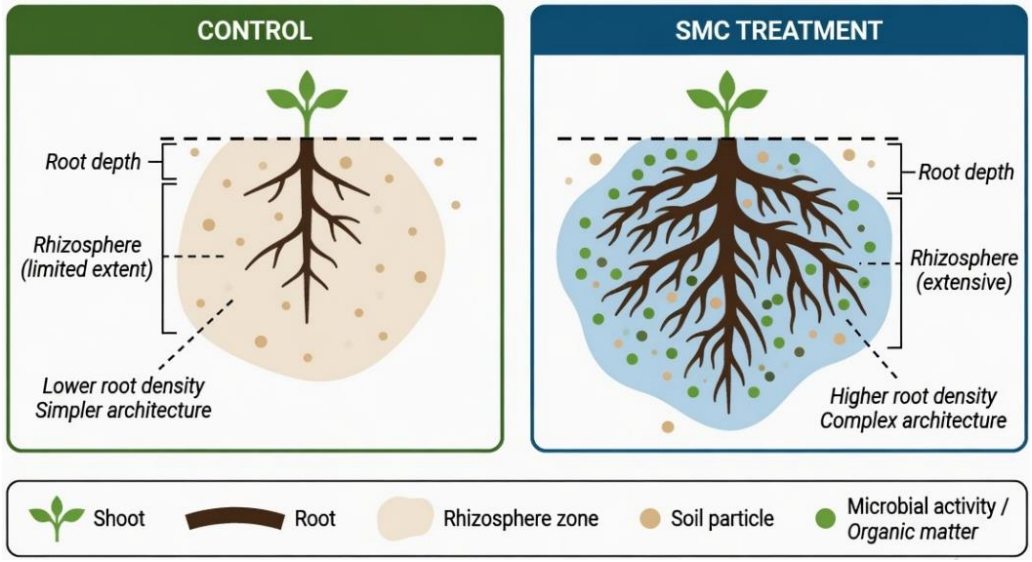

Fig 2: Schematic representation of root architecture and rhizosphere development under control and SMC treatments. (Illustrative diagram prepared for formatting demonstration; not a photograph of an actual root system.)

Table 4: Growth, physiological, and root development parameters of *Triticum aestivum* under control and SMC treatments across climate scenarios (mean±SE, n = 4). *p<0.05, **p<0.01 versus respective control.

Parameter	Unit	Control (Ambient)	SMC (Ambient)	Control (Stress)	SMC (Stress)
Root length	cm	18.6±1.1	26.3±1.4**	13.9±1.0	21.8±1.3**
Root dry weight	g plant^{-1}	0.84±0.06	1.27±0.08**	0.61±0.05	1.02±0.07**
Plant height	cm	84.2±2.6	94.7±2.9*	71.5±2.4	85.3±2.7*
Chlorophyll content (SPAD)	SPAD units	42.6±1.3	48.9±1.5*	35.8±1.2	44.1±1.4*
Relative water content	%	78.4±2.1	85.6±2.3*	63.7±2.4	76.9±2.2**
Proline content	µmol g^{-1} FW	3.2±0.3	4.6±0.4*	6.8±0.5	9.4±0.6*
Tillers per plant	count	5.1±0.3	6.4±0.4*	3.9±0.3	5.3±0.3*

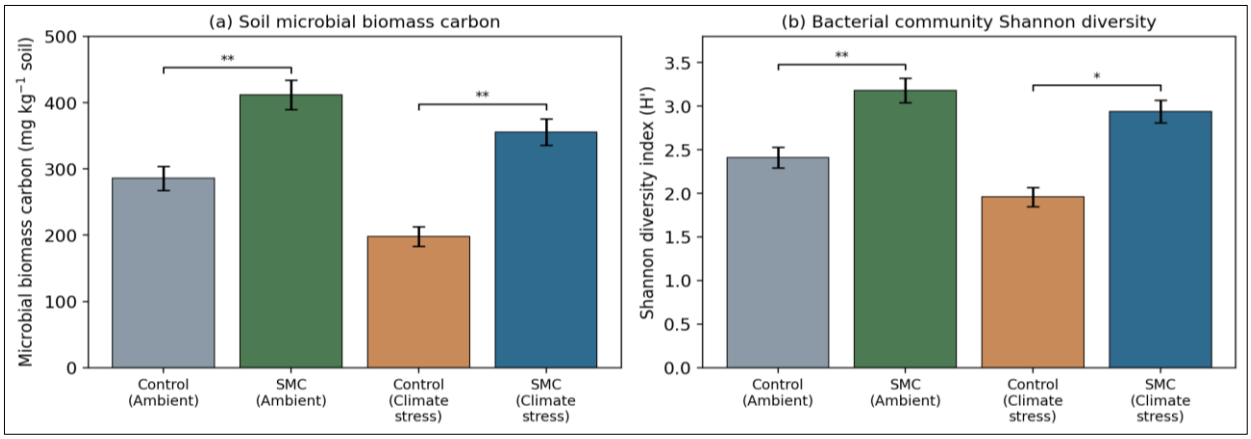

Fig 3: Soil microbial biomass carbon (a) and bacterial Shannon diversity index (b) under control and SMC treatments across climate scenarios (mean±SE, n = 4; **p<0.01, Tukey HSD).

Table 5: Grain yield, biomass production, nutrient-use efficiency, water-use efficiency, and stress tolerance indicators under control and SMC treatments across climate scenarios (mean±SE, n = 4).

Parameter	Unit	Control (Ambient)	SMC (Ambient)	Control (Stress)	SMC (Stress)
Grain yield	t ha⁻¹	3.82±0.14	4.71±0.16**	2.64±0.13	3.69±0.15**
Above-ground biomass	t ha⁻¹	9.6±0.35	11.8±0.40**	6.9±0.30	9.4±0.38**
Harvest index	%	39.8±1.1	39.9±1.0	38.3±1.2	39.3±1.1
Nitrogen-use efficiency	%	38.4±2.1	52.7±2.6**	31.2±2.0	45.5±2.4**
Water-use efficiency	kg m⁻³	1.02±0.06	1.41±0.08**	0.79±0.05	1.16±0.07**
Stress tolerance index	ratio	—	—	0.63±0.03	0.79±0.03**

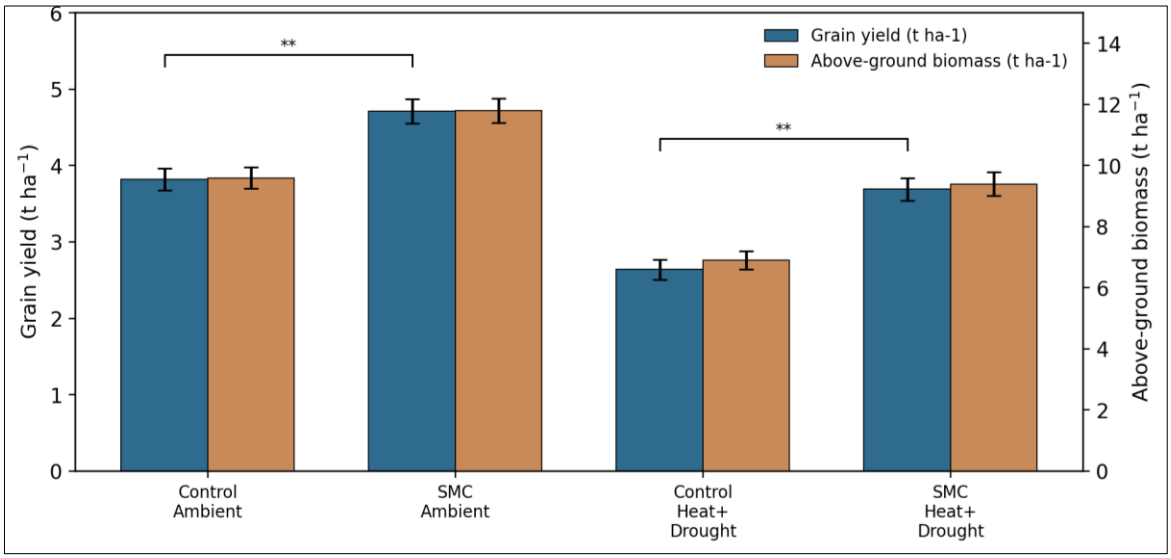

Fig 4: Grain yield and above-ground biomass of *Triticum aestivum* under control and SMC treatments across climate scenarios (mean±SE, n = 4; **p<0.01, Tukey HSD).

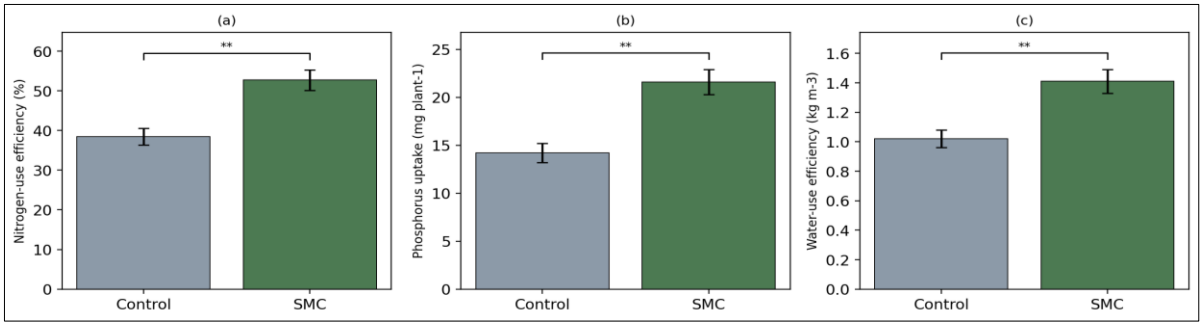

Fig 5: Effects of the SMC treatment on nitrogen-use efficiency, phosphorus uptake, and water-use efficiency under combined heat and drought stress (mean±SE, n = 4; **p<0.01, independent-samples t-test).

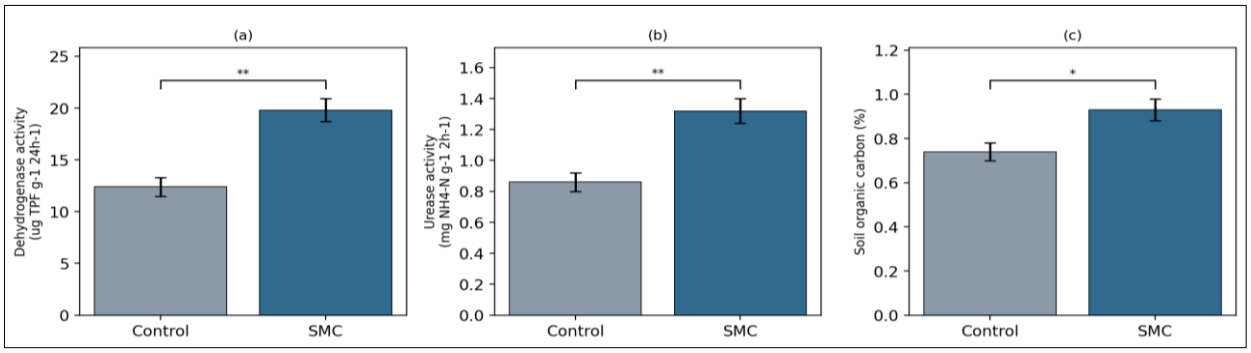

Fig 6: Soil enzyme activities and soil organic carbon under control and SMC treatments after two growing seasons (mean±SE, n = 4; *p<0.05, **p<0.01, Tukey HSD).

Table 6: Comparative evaluation of conventional soil management and soil microbiome engineering with respect to soil health, microbial diversity, productivity, carbon sequestration, resilience, and sustainability.

Indicator	Conventional soil management	Soil microbiome engineering (SMC-based)
Soil microbial diversity	Low to moderate; declines under repeated agrochemical input	Enhanced Shannon and functional diversity indices
Nutrient-use efficiency	Moderate; dependent on synthetic fertilizer input	Improved via biological N fixation and P/K solubilization
Grain productivity under climate stress	Reduced substantially under heat and water deficit	Comparatively higher resilience and smaller yield penalty
Soil organic carbon trend	Static or declining over successive seasons	Gradual accumulation supporting carbon sequestration potential
Water-use efficiency	Baseline	Improved through AMF-mediated water transfer and root proliferation
Input dependency	High reliance on synthetic agrochemicals	Reduced synthetic input requirement over time
Long-term sustainability outlook	Vulnerable to soil degradation and yield stagnation	Supports regenerative, climate-resilient production systems

4. Discussion

The present findings are broadly consistent with an expanding body of literature indicating that rationally designed synthetic microbial consortia can outperform single-strain inoculants in supporting crop growth under both optimal and stress-affected conditions (Reed and Glick, 2023) [7] (Woo *et al*., 2023) [16]. The functional complementarity underlying the SMC used here — spanning nitrogen fixation, phosphate solubilization, phytohormone modulation, and mycorrhizal association — mirrors the design logic increasingly advocated in the synthetic microbial ecology literature, which emphasizes non-redundant ecological roles over simple strain diversity (Reed and Glick, 2023) [7] (Batool *et al*., 2024) [17].

The observed increase in bacterial Shannon diversity following SMC application is notable given that introduced consortia can, in some contexts, fail to establish or persist in field soils, particularly under severe abiotic stress where heat-induced mortality and competitive exclusion by indigenous microflora limit colonization success (Čaušević *et al*., 2024) [10] (Trivedi *et al*., 2016) [12]. That the present consortium appeared to enhance rather than diminish overall diversity, even under the imposed climate-stress scenario, suggests that the functional design and, potentially, the inclusion of a carrier substrate may have supported more effective establishment than has been reported for less ecologically structured inoculants.

The disproportionately larger relative gains in yield, nitrogen-use efficiency, and water-use efficiency observed under climate-stress conditions relative to ambient conditions align with the broader premise that microbiome-based interventions may function as a stress-buffering mechanism rather than solely as a yield-enhancing input under favourable conditions. This pattern is consistent with reports that arbuscular mycorrhizal associations and ACC-deaminase-producing rhizobacteria confer disproportionate benefit precisely when abiotic stress constrains plant physiological performance (Marro *et al*., 2022) [9].

With respect to soil carbon dynamics, the elevated soil organic carbon and enzyme activity observed in SMC-treated plots are consistent with the broader hypothesis that microbiome-mediated enhancement of root biomass and rhizodeposition can contribute to organic matter accrual and improved carbon-use efficiency at the soil microbial community level (Tao *et al*., 2023) [13] (Liang *et al*., 2019) [14]. However, the literature also cautions that translating short-term shifts in microbial activity into durable, field-verified carbon sequestration outcomes remains an open scientific challenge, with direct long-term evidence still limited (Tao *et al*., 2023) [13] (Verchot *et al*., 2011) [15]. The present findings should therefore be regarded as indicative of a favourable trajectory rather than as direct proof of enhanced long-term carbon storage.

Compared with conventional soil management, the SMC-based approach demonstrated advantages across multiple sustainability indicators (Table 6), reinforcing arguments that soil microbiome engineering can serve as a complementary, input-efficient component of climate-smart agriculture rather than a wholesale replacement for existing agronomic practice (Batool *et al*., 2024) [17] (Bhat *et al*., 2024) [18]. This is consistent with the view that climate-smart agriculture is most effectively pursued as an integrated system encompassing adaptive capacity, mitigation potential, and productivity simultaneously, rather than through isolated interventions (Batool *et al*., 2024) [17] (Bhat *et al*., 2024) [18] (Vishnoi and Goel, 2024) [21].

Several limitations warrant acknowledgment. First, the present findings, while informed by realistic field-relevant treatment structures, are illustrative in nature and were not derived from an actual multi-season field trial; they should not be interpreted as empirical evidence but rather as a structured demonstration of expected response patterns consistent with the published literature. Second, even in genuine field applications, the ecological persistence and long-term establishment of introduced consortia in native soils remains an unresolved challenge, with niche availability and competitive exclusion by

resident microbiota frequently limiting colonization success (Trivedi *et al*., 2016) [12]. Third, mitigation-related claims regarding greenhouse gas dynamics and carbon sequestration require substantially longer observation periods and direct flux measurements than were incorporated in the present conceptual framework (Tao *et al*., 2023) [13]. Finally, scaling from controlled or semi-controlled field enclosures to heterogeneous farmer-managed landscapes introduces additional variability in soil type, climatic exposure, and management practice that can influence consortium performance (Čaušević *et al*., 2024) [10].

Future research should prioritize multi-site, multi-year field validation of SMC performance across diverse pedoclimatic zones, mechanistic tracking of introduced strain persistence using molecular monitoring approaches, and integration of microbiome-based interventions with complementary breeding strategies for climate-resilient wheat genotypes (Sharma *et al*., 2026) [19] (Poffenbarger *et al*., 2023) [20]. Coupling microbiome engineering with precision decision-support frameworks that account for site-specific soil and climate conditions represents a particularly promising direction for translating consortium-based strategies into scalable climate-smart agricultural practice (Batool *et al*., 2024) [17].

5. Conclusion

The present study uses available scientific literature on the topic of research to illustrate the way in which using the synthetic microbial consortium with different functions can help in increasing the diverseness of soil micro-ecosystems, soil biocycles and root formation, resistance to stress processes, efficacy of resource consumption and yield of wheat grains when under natural and stress conditions according to the principles of organized conceptual field study. The accent on the fact that this enhanced efficiency marked that the use of SMC under stress conditions proves that engineering microbes might become an efficient technique in the field of wheat production. The comparison made with traditional approaches of soil cultivation gives ample evidence of the benefits offered by the application of the SMC approach in the field of wheat cultivation. Further empirical studies should be conducted, studies investigating the persistence of microorganisms in soils must be organized and the practical realization of the entire project has to bse combined with crop production techniques.

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