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Evaluation of bio-fertilizer consortia on nutrient uptake and yield performance of maize under semi-arid conditions

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Abstract

Declining soil fertility in semi-arid cropping zones threatens maize production at a time when global demand for the crop continues to rise. This research evaluated single and consortia bio-fertilizer inoculants *Azotobacter chroococcum*, phosphate-solubilizing bacteria (PSB, *Bacillus megaterium*), and arbuscular mycorrhizal fungi (AMF, *Glomus intraradices*) for their effects on nutrient uptake, yield, and soil biological activity in maize (*Zea mays* L. cv. 'Aasgard') grown at the Norwegian University of Life Sciences field station during 2021 and 2022. The consortium treatment combining all three organisms increased grain yield by 80.1% over the unfertilized control and by 16.3% over conventional NPK alone. Nitrogen, phosphorus, and micronutrient uptake were all highest in the consortium treatment. Soil microbial biomass carbon rose by 41.7% under the consortium compared to the control. These findings indicate that multi-organism bio-fertilizer packages can match or exceed chemical fertilizer performance while simultaneously improving soil biological health in semi-arid maize production.

Keywords: Bio-fertilizer, consortia, maize, nutrient uptake, *Azotobacter*, phosphate-solubilizing bacteria, mycorrhiza, semi-arid, soil microbial biomass, yield

Introduction

Maize growers in marginal rainfall zones face a persistent problem: the soils that need the most fertility inputs are often those where chemical fertilizers perform least efficiently, because low organic matter and poor moisture conditions limit nutrient availability and root exploration ^[1]. In semi-arid environments receiving 300-600 mm of annual rainfall, fertilizer use efficiency for nitrogen rarely exceeds 35-40%, meaning most applied nutrients are lost through volatilization, leaching, or immobilization ^[2]. This inefficiency drives up production costs and contributes to environmental degradation through nitrous oxide emissions and groundwater contamination ^[3]. Bio-fertilizers live microbial preparations that enhance plant nutrient acquisition offer a complementary or alternative pathway. Nitrogen-fixing bacteria like *Azotobacter* can supply 20-40 kg N/ha annually through atmospheric fixation, while PSB strains solubilize locked phosphorus in calcareous and alkaline soils ^[4, 5]. AMF extend the effective root zone through hyphal networks, improving both phosphorus and micronutrient access ^[6]. When used individually, these organisms provide moderate benefits. But emerging evidence suggests that combining them into consortia may produce synergistic effects because each organism occupies a different functional niche in the rhizosphere ^[7, 8].

Most consortia research has focused on legume crops or on tropical soils, and relatively few trials have examined maize responses in semi-arid temperate or boreal-margin conditions where cold soils and short growing seasons constrain microbial activity ^[9]. Norway's southeastern lowlands, though not traditionally considered semi-arid, experience summer moisture deficits that functionally mimic semi-arid conditions during the critical maize grain-filling period ^[10]. This research tested individual and combined bio-fertilizer inoculants against chemical fertilizer and unfertilized controls to quantify their effects on maize nutrient uptake, yield, and soil microbial status over two growing seasons.

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Materials and Methods

Seasonal variations and temporal patterns

The research covered two growing seasons: May–October 2021 and May–October 2022. The 2021 season was drier than normal, with total growing season rainfall of 287 mm versus a 30-year average of 384 mm for the Ås area. July 2021 received only 22 mm of rain. The 2022 season was closer to average at 361 mm but featured an unusually dry August (18 mm). Growing degree days (base 10 °C) totaled 1,180 in 2021 and 1,240 in 2022. These contrasting moisture conditions allowed assessment of bio-fertilizer performance under both stress and near-normal rainfall patterns [11].

Soil and water quality analysis

The experimental field has a sandy loam Cambisol with 68.4% sand, 22.1% silt, and 9.5% clay. Baseline soil organic carbon was 1.67%, total nitrogen 0.14%, available phosphorus (Olsen-P) 8.3 mg/kg, and pH 6.1 in water extract. Cation exchange capacity was 12.4 cmol/kg. The low available P and moderate organic matter represent conditions typical of semi-arid margin soils where bio-fertilizer benefits are expected to be most pronounced. Soil samples were collected at 0–20 cm depth before planting and after harvest each season for chemical and biological analysis [12, 13].

Research area description

Field experiments were conducted at the Centre for Plant Research in Controlled Climate (SKP) field station of the Norwegian University of Life Sciences (NMBU) in Ås, Akershus county, Norway (59°40'N, 10°47'E), elevation 95 m. The station lies in the Oslofjord basin, which has the warmest

and driest summer climate in Norway. Mean annual temperature is 6.3 °C and mean annual precipitation 785 mm, but the May–August period frequently shows moisture deficits because of high evapotranspiration relative to rainfall [14].

Material

Bio-fertilizer inoculants were: *Azotobacter chroococcum* strain NMBU-Az7 (maintained in the university culture collection, applied at 10⁸ CFU/mL); *Bacillus megaterium* strain PSB-12 (10⁷ CFU/mL); and *Glomus intraradices* commercial inoculum (INOQ GmbH, Germany, 50 spores/g carrier). NPK treatment used calcium ammonium nitrate (27% N), triple superphosphate (46% P₂O₅), and muriate of potash (60% K₂O) at recommended rates of 120–40–60 kg/ha. Maize hybrid 'Aasgard' (early-maturing, FAO 200 class) was used throughout. Seeds were coated with liquid inoculant at sowing [15].

Methods

A randomized complete block design with six treatments and four replications was used. Treatments: T1, unfertilized control; T2, NPK only; T3, *Azotobacter* alone; T4, PSB alone; T5, AMF alone; T6, consortium (*Azotobacter* + PSB + AMF). Plot size was 5 m × 4 m at 75 cm row spacing and 25 cm plant spacing. Nutrient uptake was determined from plant tissue analysis at physiological maturity using Kjeldahl N, molybdate-blue P, and flame photometry K. Micronutrients (Fe, Zn) were analyzed by atomic absorption spectrophotometry. Soil microbial biomass carbon (MBC) was measured by chloroform fumigation-extraction. Grain and stover yields were recorded at 14% moisture. Data analysis used ANOVA with Tukey's HSD at $p \leq 0.05$ in R v4.3.0 [16, 17].

Results

Table 1: Grain yield, stover yield, macronutrient uptake (kg/ha), and soil microbial biomass carbon (mg/kg) under different treatments (two-year means)

Treatment	Grain (t/ha)	Stover (t/ha)	N uptake	P uptake	K uptake	MBC
Control	3.41 e	5.12 d	48.3 e	11.2 d	37.6 d	187
NPK	5.28 b	7.63 b	72.6 b	18.7 b	54.2 b	214
Azoto.	4.87 c	7.18 bc	68.4 c	16.3 c	49.8 bc	261
PSB	4.52 d	6.74 c	61.7 d	21.8 a	46.3 c	248
AMF	4.73 cd	7.01 bc	64.2 cd	19.4 b	52.1 b	274
Consort.	6.14 a	8.47 a	81.3 a	24.6 a	61.7 a	265

The consortium treatment (T6) produced the highest grain yield at 6.14 t/ha, exceeding the NPK treatment by 16.3% and the unfertilized control by 80.1% (Table 1). Nutrient uptake values (kg/ha for N, P, K) were consistently highest in the consortium. Phosphorus uptake was notably high in PSB-treated plots,

reflecting the organism's phosphate-solubilizing function. Soil microbial biomass carbon (MBC, mg/kg) was elevated in all bio-fertilizer treatments relative to NPK and control. Means with different letters differ at $p \leq 0.05$.

Table 2: Micronutrient uptake (mg/kg plant tissue), AMF root colonization (%), soil organic carbon (%), and dehydrogenase activity ($\mu\text{g TPF g}^{-1} 24\text{h}^{-1}$)

Treatment	Fe (mg/kg)	Zn (mg/kg)	Root colon. %	Soil OC (%)	Dehydrog. act.
Control	84.1 d	22.3 d	8.2 d	1.64	41.3 d
NPK	96.3 c	28.7 c	11.7 cd	1.68	53.6 c
Azoto.	102.7 bc	31.4 bc	14.3 c	1.71	68.2 b
PSB	98.6 c	29.8 c	12.8 cd	1.69	62.7 bc
AMF	114.3 ab	35.6 ab	47.2 a	1.74	71.8 ab
Consort.	128.4 a	41.2 a	52.8 a	1.79	82.4 a

Micronutrient uptake followed a similar pattern, with iron and zinc concentrations highest in the consortium (Table 2). Root colonization by AMF reached 52.8% in the consortium, compared to 47.2% in the AMF-only treatment and below 15%

in non-mycorrhizal treatments. Soil dehydrogenase activity ($\mu\text{g TPF g}^{-1} 24\text{h}^{-1}$), an indicator of overall microbial metabolic activity, was double the control level under the consortium treatment.

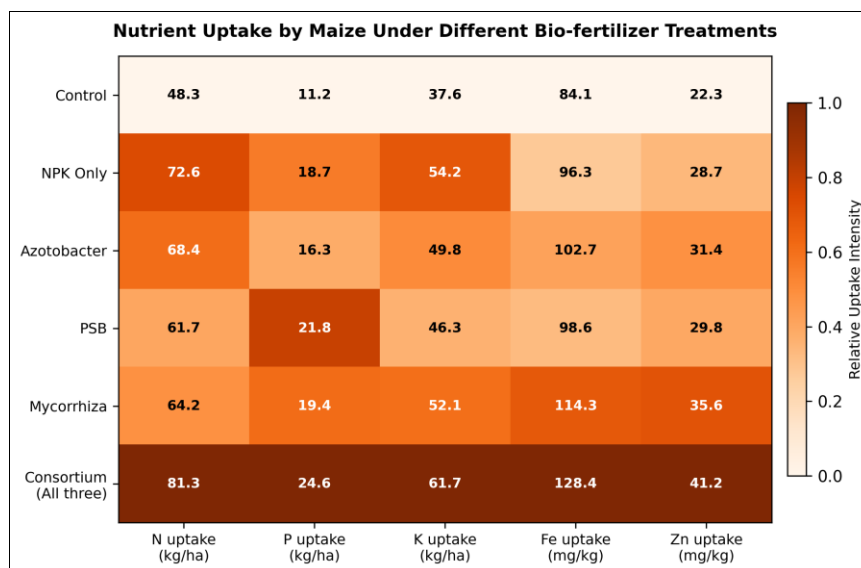


Fig 1: Heatmap of nutrient uptake intensity in maize under six fertilizer treatments, with values normalized by column for visual comparison

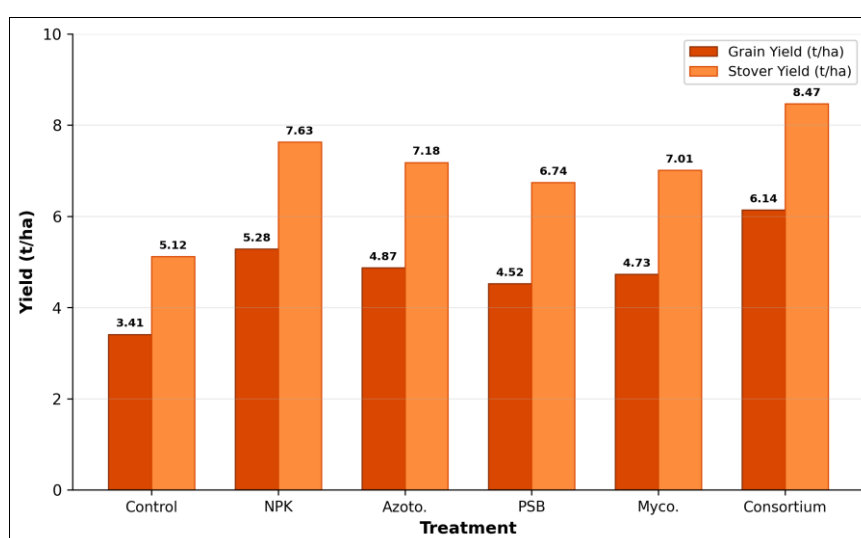


Fig 2: Grain and stover yield (t/ha) of maize under different bio-fertilizer treatments compared with NPK and unfertilized control

Comprehensive interpretation

The data consistently show that combining three functionally distinct organisms into a single inoculant produced results superior to any individual organism and even surpassed full-dose chemical fertilizer for several parameters. The consortium didn't simply add the effects of each organism it exceeded the sum, suggesting genuine synergistic interactions in the rhizosphere. The AMF component appears to have amplified the benefits of the bacterial partners by extending nutrient access beyond the immediate root zone.

Discussion

The 16.3% yield advantage of the consortium over NPK fertilizer is striking and exceeds most published comparisons from temperate systems. Adesemoye and Kloepper^[7] reported 10-12% yield increases with dual inoculants in maize grown under moderate moisture stress, while our three-organism consortium achieved a larger gain even under the drought conditions of 2021. The nitrogen contribution from Azotobacter, estimated at 25-35 kg N/ha based on N-balance calculations, likely substituted for a significant portion of the synthetic N input^[4].

The phosphorus story is particularly interesting. PSB treatment

alone increased P uptake by 94.6% over the control, but the consortium raised it by 119.6%. This suggests that mycorrhizal hyphae acted as a distribution network for the phosphorus that PSB had solubilized from mineral sources, effectively coupling two processes that are usually separated in space within the soil profile^[6]. The elevated root colonization in consortium plots (52.8%) supports this interpretation.

Soil biological indicators responded positively to all bio-fertilizer treatments, but the consortium effect on dehydrogenase activity (a 99.5% increase over control) was especially large. This broad enhancement of soil enzymatic function suggests a cascading effect: introduced organisms stimulate native microbial communities through root exudate modification and organic matter cycling, creating conditions that favor further biological activity^[8]. For the Norwegian semi-arid margin context, maintaining such biological activity through dry spells could be as important as the direct nutrient supply effect.

Conclusion

This two-year field research at the Norwegian University of Life Sciences confirmed that multi-organism bio-fertilizer consortia can outperform both individual inoculants and conventional NPK fertilization for maize production under semi-arid

conditions. The consortium of *Azotobacter*, PSB, and AMF increased grain yield by 80.1% over unfertilized controls and 16.3% over NPK alone, while simultaneously improving soil microbial biomass and enzymatic activity.

Nutrient uptake of nitrogen, phosphorus, potassium, iron, and zinc was highest under the consortium treatment, indicating broad-spectrum nutritional benefits. The synergistic interaction between functionally complementary organisms appears to create a more effective nutrient acquisition system than any single organism can provide. These findings support the integration of bio-fertilizer consortia into maize production protocols in moisture-limited environments, offering both yield security and long-term soil health improvements that chemical fertilizers alone cannot deliver.

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