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Priestia megaterium Thr45 Reduces Nitrogen and Potassium Fertilizer Inputs While Enhancing Soil Fertility and Baby Maize Yield

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Abstract

Baby maize (*Zea mays* L.) is a high-value horticultural crop widely cultivated due to its short growth cycle and strong market demand. However, intensive production systems often rely heavily on chemical fertilizers, leading to reduced nutrient use efficiency and potential soil degradation. The present study investigated the potential of the *Priestia megaterium* Thr45 to enhance soil fertility, improve crop performance, and optimize fertilizer management in baby maize cultivation. A field experiment was conducted using a three-factor factorial design consisting of bacterial inoculation, different urea application rates, and different KCl rates. Soil chemical properties, plant growth parameters, yield components, and nutrient composition of edible cobs were evaluated. The results showed that inoculation with *P. megaterium* Thr45 significantly increased available phosphorus and exchangeable potassium in soil compared with the non-inoculated control. Inoculated plants exhibited higher chlorophyll content, greater leaf development, and increased plant height during early growth stages. Bacterial inoculation also significantly improved yield components, including ear number, ear yield, edible cob yield, and plant biomass. Furthermore, the nutritional quality of baby corn was enhanced, as reflected by increased protein and mineral (N, P, and K) concentrations in edible cobs. Significant interactions between bacterial inoculation and fertilizer treatments indicated that the beneficial effects of *P. megaterium* Thr45 were closely associated with nutrient management practices. Notably, comparable yield and nutritional quality were achieved under reduced nitrogen and potassium fertilizer inputs when combined with bacterial inoculation. These findings highlight the novel potential of *P. megaterium* Thr45 as an effective biofertilizer for improving nutrient availability, maintaining high productivity, and supporting sustainable baby maize production with reduced chemical fertilizer inputs

Keywords: *Priestia megaterium*; baby maize; biofertilizer; nutrient use efficiency; sustainable fertilization

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1. Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide and plays a crucial role in food security, livestock feed production, and various industrial applications. In addition to grain maize, baby maize has gained increasing economic importance due to its high nutritional value and short growth cycle, making it suitable for intensive cropping systems in many tropical and subtropical regions [1]. However, baby maize cultivation requires large amounts of nutrients, particularly nitrogen (N) and potassium (K), to sustain

rapid vegetative growth and ensure high cob yield and quality [2]. Continuous reliance on high rates of chemical fertilizers to meet these nutrient demands often results in declining soil fertility, environmental pollution, and reduced fertilizer use efficiency in agricultural systems [3]. In recent decades, excessive application of mineral fertilizers has raised serious concerns regarding soil degradation, nutrient imbalance, and the disruption of soil microbial communities [4]. Although chemical fertilizers significantly contribute to yield improvement, long-term overuse can reduce soil organic matter, impair soil structure, and negatively affect beneficial microorganisms responsible for nutrient cycling [4,5]. Consequently, sustainable agricultural strategies that maintain productivity while reducing chemical fertilizer inputs have become a priority in modern crop production systems [5,6].

One promising approach to address these challenges is the use of plant growth by promoting microorganisms (PGPM) as biofertilizers [7]. These beneficial microbes enhance plant growth through multiple mechanisms, including biological nitrogen fixation, solubilization of insoluble phosphorus and potassium, production of phytohormones, and improvement of nutrient uptake efficiency [7,8]. By enhancing nutrient availability and stimulating plant physiological processes, microbial inoculants can partially substitute for chemical fertilizers while maintaining or even increasing crop productivity. Furthermore, biofertilizers contribute to improved soil biological activity, greater microbial diversity, and enhanced nutrient cycling in the rhizosphere, thereby promoting long-term soil health [9,10].

Among the diverse groups of PGPM, species belonging to the genus *Bacillus* (recently reclassified into several genera including *Priestia*) have attracted considerable attention due to their strong environmental adaptability and multifunctional plant growth promoting traits [11,12]. These bacteria can form endospores, which enable them to survive under harsh environmental conditions and maintain stable populations in soil ecosystems [13]. *Priestia megaterium* (formerly *Bacillus megaterium*) has been widely reported as an effective biofertilizer owing to its ability to fix atmospheric nitrogen, solubilize phosphorus and potassium, and produce various plant growth promoting substances such as indole-3-acetic acid (IAA) and siderophores [14,15]. These functional traits can stimulate root development, enhance nutrient acquisition, and ultimately improve plant growth and productivity [16]. Several studies have demonstrated that the integration of beneficial microorganisms with reduced rates of chemical fertilizers can significantly improve crop yield and fertilizer use efficiency [17]. For example, microbial inoculation combined with micro-dosed mineral fertilizers has been shown to increase maize yield compared with conventional fertilization practices [18]. Such integrated nutrient management strategies not only enhance crop productivity but also improve soil chemical properties and microbial activity, creating a more sustainable agricultural system [19].

In maize-based cropping systems, beneficial microbial inoculants can influence plant growth through complex interactions within the rhizosphere [20]. These microorganisms can stimulate root exudation, enhance microbial diversity, and promote nutrient mineralization processes that increase the availability of essential elements such as nitrogen, phosphorus, and potassium [21]. Improved nutrient dynamics in the soil and plant system contribute to better plant growth, higher biomass accumulation, and increased yield [20,22]. Therefore, microbial inoculation represents a promising strategy to reduce dependency on chemical fertilizers while maintaining soil fertility and crop productivity [19,20,23]. Despite the growing interest in microbial biofertilizers, the effectiveness of specific bacterial strains varies depending on crop species, soil conditions, and nutrient management practices [24]. In particular, limited information is available regarding the potential of newly isolated strains of *Priestia megaterium* to simultaneously reduce nitrogen and potassium fertilizer inputs while maintaining baby maize yield and improving soil fertility [20,25].

Despite the increasing interest in microbial biofertilizers, the practical application of multifunctional bacterial strains capable of simultaneously improving soil fertility and reducing chemical fertilizer inputs remains insufficiently explored, particularly in intensive baby maize production systems [26]. Previous studies have mainly focused on single nutrient mobilization or greenhouse experiments, while field-based evaluations integrating microbial inoculation with reduced mineral fertilization are still limited [27]. In addition, the potential of newly isolated strains of *Priestia megaterium* to simultaneously enhance nutrient availability and sustain crop productivity under reduced nitrogen and potassium inputs has not been fully clarified [28]. Therefore, the present study aimed to evaluate the promoting potential of *P. megaterium* Thr45 and its capacity to partially replace nitrogen and potassium fertilizers while maintaining soil fertility and baby maize yield. Specifically, we investigated the effects of bacterial inoculation combined with reduced fertilizer rates on soil chemical properties, plant growth traits, and yield performance of baby maize under field conditions. The findings of this study provide new insights into the use of beneficial bacteria as a sustainable strategy to improve nutrient use efficiency and reduce chemical fertilizer dependency in maize-based cropping systems.

2. Materials and Methods

2.1. The Source of P. megaterium Thr45 and Inoculum Preparation

The bacterial strain P. megaterium Thr45 was aseptically isolated from the roots of baby maize collected in Cho Moi commune, An Giang Province, Vietnam, using yeast extract mannitol agar (YMA) medium (pH 6.8–7.0; HiMedia Laboratories Pvt. Ltd., Mumbai, India). Taxonomic identification of the isolate was conducted through 16S rRNA gene sequencing. Genomic DNA was extracted using a genomic DNA purification kit (Thermo Fisher Scientific, Waltham, MA, USA) following the manufacturer's instructions. PCR amplification was performed using a thermal cycler (Bio-Rad T100 Thermal Cycler, Bio-Rad Laboratories, Hercules, CA, USA). The obtained PCR products were purified and sequenced by a commercial sequencing service provider (Macrogen Inc., Seoul, Republic of Korea).

Sequence assembly and editing were carried out using BioEdit software (version 7.2.5), and sequence similarity analysis was performed using the BLAST 2.17.0 tool available at the National Center for Biotechnology Information (NCBI; Bethesda, MD, USA). The obtained sequence was deposited in the GenBank database under accession number PZ028020.1 (sequence length: 1452 bp) and is publicly available in the NCBI database (https://www.ncbi.nlm.nih.gov/nuccore/PZ028020.1 (accessed on 18 March 2026)). Comparative sequence analysis indicated that the isolate shared 100% sequence similarity with reference sequences of genus *Priestia* and species *megaterium*, confirming its taxonomic classification. Following molecular identification, strain Thr45 was evaluated for several plant growth promoting traits, including ammonia production, nitrogenase enzyme activity, and nitrogen accumulation capacity. The strain exhibited relatively high levels of these activities after 72 h of incubation, indicating its strong potential for biological nitrogen fixation and plant growth promotion. Based on these functional characteristics, *P. megaterium* Thr45 was selected for further experiments in this study. For inoculum preparation, the bacterial strain was cultured in diluted yeast mannitol agar (YMA; pH 6.8–7.0) and incubated at 30 ± 2 °C on a rotary shaker at 150 rpm for 48–72 h. Bacterial growth was monitored spectrophotometrically at OD_{600}, and the culture was adjusted to a final concentration of approximately 10^8 CFU mL^{-1}, corresponding to the exponential growth phase [29].

2.2. Experimental Design and Site Description

The field experiment was conducted in Cho Moi commune, An Giang province, Vietnam. The experiment was arranged in a three-factor factorial design using a randomized complete block design (RCBD). The three experimental factors included: (i) bacterial inoculation (with and without *Priestia megaterium* Thr45), (ii) nitrogen fertilizer reduction levels (100%, 50%, 25%, and no reduction of urea), and (iii) potassium fertilizer reduction levels (100%, 50%, 25%, and no reduction of KCl). In total, the experiment consisted of 32 treatments, derived from the combination of two bacterial inoculation levels × four nitrogen reduction levels × four potassium reduction levels (2 × 4 × 4). Each treatment was replicated four times, resulting in a total of 128 experimental plots. The size of each plot was 20 m^2 (1 m × 20 m), giving a total experimental area of 2560 m^2 (128 plots × 20 m^2). The plots were arranged according to a randomized complete block layout to minimize the effects of field variability. Detailed descriptions of the bacterial inoculation procedure and fertilizer reduction treatments are provided in Supplementary Table S1.

The baby maize cultivar "HM-4", supplied by the Southern Seed Company (Ho Chi Minh City, Vietnam), was used in this study. Plants were established at a spacing of 30 cm × 25 cm, with two seeds sown per planting hole. The "HM-4" cultivar has a short growth duration of approximately 45 days and is characterized by rapid growth, strong plant vigor, and high yield potential. The bacterial inoculum was prepared at a concentration of 10^8 CFU mL^{-1}. Prior to inoculation, maize seeds were surface-sterilized by immersion in 70% ethanol for 1 min, followed by treatment with 2% sodium hypochlorite for 3–5 min. The seeds were subsequently rinsed three to five times with sterile distilled water to remove residual disinfectants. For inoculation, approximately 1 mL of the bacterial suspension was diluted with sterile deionized water and uniformly sprayed onto the seed surface [14]. The inoculated seeds were incubated under dark conditions at room temperature for approximately 24–48 h prior to sowing to facilitate bacterial adhesion and early root colonization [29]. The field experiment consisted of 32 treatments (BM1–BM32). Each replicate plot covered an area of 10 m^2 (1 m × 10 m) and was separated by 0.5 m alleys to minimize edge effects. In total, 128 experimental plots were established across the field, resulting in a total experimental area of 1280 m^2. Seeds were sown in single rows with a spacing of 30 cm between planting holes, with two seeds placed in each hole.

2.3. Soil Sampling, Fertilizer Application, and Agronomic Measurements

Soil samples were collected 15 days before sowing to determine the initial soil conditions, while post-harvest samples were obtained at the end of the experiment. The analyzed soil parameters included soil pH, soil organic matter (SOM), total nitrogen (TN), available phosphorus (AP), and soluble potassium (SK). All soil analyses were performed following standard soil analytical procedures. The initial soil properties indicated a near-neutral pH (6.15), SOM content of 2.41%, TN of 921 mg kg^{-1}, AP of 158 mg kg^{-1}, and SK of 158 mg kg^{-1}. Phosphorus fertilizer (P_2O_5) was applied as a basal dose at a rate of 400 kg ha^{-1} one day before sowing. In contrast, Urea and KCl fertilizers were applied in four split applications during the crop growth period.

The experimental soil was classified as silt loam, consisting of 13.0% sand, 67.9% silt, and 19.1% clay, and was characterized by relatively low nutrient availability. In baby maize, the tasseling stage represents a key developmental phase for ear formation, as it promotes nutrient allocation and supports plant growth, thereby contributing to a shorter growth cycle and improved production of edible ears. Under the experimental conditions, tasseling occurred approximately 50 days after sowing (DAS). Agronomic characteristics, yield components, and edible ear traits were recorded from 15 DAS until harvest. Growth parameters included leaf number, plant height, and total chlorophyll content measured at

15 and 30 DAS. Yield-related traits and edible ear characteristics such as biomass weight, fresh ear weight, silk weight, husk weight, cob weight, and number of ears were determined at harvest.

2.4. Statistical Analysis

Data were analyzed using a three-way analysis of variance (ANOVA) to evaluate the main effects of bacterial inoculation (A), nitrogen fertilizer reduction levels (B), potassium fertilizer reduction levels (C), and their interaction effects (A × B, A × C, B × C, and A × B × C). Statistical analyses were performed using Statgraphics software (version XVIII). When significant effects were detected, treatment means were compared using a multiple comparison test. Differences among treatments were considered statistically significant at $p \leq 0.05$.

3. Results

3.1. Influence of P. megaterium Thr45 and Fertilizer Rates on Soil Properties

Soil chemical properties measured after baby maize cultivation were influenced to varying degrees by bacterial inoculation (A), urea application rates (B), and KCl levels (C) (Table 1). Among the tested factors, inoculation with *P. megaterium* Thr45 had a significant effect on available phosphorus (AP) and exchangeable potassium (SK) ($p \leq 0.01$). Compared with the non-inoculated treatment, bacterial inoculation increased AP from 11.2 to 11.6 mg kg^{-1} and SK from 23.3 to 25.5 mg kg^{-1}, indicating an improvement in soil nutrient availability following inoculation. In contrast, soil pH, SOM, and TN were not significantly affected by the presence or absence of bacterial inoculation. Variation in urea application rates (factor B) did not significantly influence any of the measured soil chemical parameters. Across the different urea levels, soil pH ranged from 6.25 to 6.34, SOM from 1.61 to 1.65%, and TN from 829 to 838 mg kg^{-1}, while AP and SK remained relatively stable. Similarly, the application of KCl (factor C) showed no statistically significant effects on soil pH, SOM, TN, AP, or SK. Furthermore, no significant interactions were detected among the experimental factors, including A × B, A × C, B × C, or A × B × C, for any of the analyzed soil properties. These findings suggest that bacterial inoculation had a more pronounced effect on specific soil nutrient indicators than variations in mineral fertilizer application rates.

Table 1. Influence of *P. megaterium* Thr45 inoculation and fertilizer rates on soil chemical properties.

Factors	pH	SOM (%)	TN	AP	SK
		(%)		(mg kg^{-1})	
P. megaterium Thr45 (A)					
No	6.26 ± 0.194	1.63 ± 0.051	833 ± 25.2	11.2 ± 0.35 [b]	23.3 ± 0.35 [b]
Yes	6.33 ± 0.210	1.64 ± 0.055	835 ± 27.5	11.6 ± 0.38 [a]	25.5 ± 0.38 [a]
Urea application, kg ha^{-1}(B)					
0	6.25 ± 0.185	1.61 ± 0.047	829 ± 24.2	11.3 ± 0.37	24.3 ± 1.13
175	6.27 ± 0.192	1.62 ± 0.049	834 ± 25.0	11.3 ± 0.37	24.3 ± 1.11
262.5	6.33 ± 0.211	1.64 ± 0.054	833 ± 27.6	11.5 ± 0.40	24.5 ± 1.13
350	6.34 ± 0.220	1.65 ± 0.056	838 ± 28.5	11.5 ± 0.44	24.5 ± 1.17
KCl application, kg ha^{-1} (C)					
0	6.24 ± 0.189	1.62 ± 0.049	827 ± 24.4	11.3 ± 0.38	24.3 ± 1.12
40	6.29 ± 0.197	1.63 ± 0.051	833 ± 25.5	11.4 ± 0.39	24.4 ± 1.12
60	6.32 ± 0.218	1.64 ± 0.057	837 ± 27.7	11.4 ± 0.42	24.4 ± 1.16
80	6.33 ± 0.209	1.64 ± 0.054	838 ± 27.1	11.5 ± 0.41	24.5 ± 1.14

Table 1. *Cont.*

Factors	pH	SOM (%)	TN	AP	SK
		(%)		(mg kg^{-1})	
F (A)	ns	ns	ns	**	**
F (B)	ns	ns	ns	ns	ns
F (C)	ns	ns	ns	ns	ns
F (A × B)	ns	ns	ns	ns	ns
F (A × C)	ns	ns	ns	ns	ns
F (B × C)	ns	ns	ns	ns	ns
F (A × B × C)	ns	ns	ns	ns	ns
CV (%)	3.24	3.24	3.15	3.51	4.61

Note: Values are mean ± SD. Means within a column sharing different letters differ significantly; ns = not significant; and ** indicate $p \leq 0.01$.

3.2. Influence of P. megaterium Thr45 and Fertilizer Ratios on Baby Maize Growth

Growth parameters of baby maize at 15 and 30 days after sowing (DAS) were significantly influenced by bacterial inoculation (A), urea application rates (B), and KCl levels (C) (Table 2). Inoculation with *P. megaterium* Thr45 significantly improved several growth traits, particularly at 30 DAS. Although leaf number at 15 DAS was not significantly affected by inoculation, plants inoculated with the bacterium produced a significantly higher number of leaves at 30 DAS (9.12 leaves plant^{-1}) compared with the non-inoculated treatment (8.68 leaves plant^{-1}). Similarly, chlorophyll content and plant height were significantly increased under bacterial inoculation at both sampling stages. Inoculated plants showed higher chlorophyll values (41.5 and 51.1) and greater plant height (45.8 and 81.3 cm) at 15 and 30 DAS, respectively, compared with the control. Urea application rates (factor B) significantly affected all measured growth traits. Increasing urea levels generally promoted leaf number, chlorophyll content, and plant height, with the highest values observed at 262.5 and 350 kg ha^{-1}. Similarly, KCl application (factor C) significantly enhanced growth performance. Treatments receiving 60 and 80 kg ha^{-1} KCl produced higher chlorophyll content, leaf number, and plant height than the lower KCl treatments. Several interaction effects among factors were also significant, particularly A × B, A × C, and A × B × C, indicating that the combined application of bacterial inoculation and fertilizer rates contributed to improved plant growth. Overall, these results demonstrate that both microbial inoculation and optimized fertilizer management significantly influence early growth of baby maize.

Table 2. Effects of *P. megaterium* Thr45 inoculation and urea and KCl ratios on baby maize growth.

Factors	Leaf Number (Leaves)		Chlorophyll		Plant Height (cm)	
	Days After Sowing (DAS)					
	15	30	15	30	15	30
	P. megaterium Thr45 (A)					
No	5.55 ± 0.22	8.68 ± 0.83 ^{b}	40.5 ± 1.85 ^{b}	47.9 ± 2.37 ^{b}	41.8 ± 3.27 ^{b}	74.4 ± 7.67 ^{b}
Yes	5.56 ± 0.12	9.12 ± 0.37 ^{a}	41.5 ± 0.87 ^{a}	51.1 ± 1.35 ^{a}	45.8 ± 1.73 ^{a}	81.3 ± 4.51 ^{a}
	Urea application, kg ha^{-1}(B)					
0	5.49 ± 0.19 ^{b}	8.23 ± 0.71 ^{b}	40.0 ± 1.66 ^{b}	47.3 ± 2.77 ^{b}	41.7 ± 2.75 ^{c}	72.0 ± 7.95 ^{b}
175	5.54 ± 0.15 ^{ab}	8.97 ± 0.52 ^{a}	40.4 ± 1.15 ^{b}	49.8 ± 2.21 ^{a}	43.7 ± 3.40 ^{b}	78.4 ± 6.52 ^{a}
262.5	5.60 ± 0.15 ^{a}	9.18 ± 0.51 ^{a}	41.7 ± 1.17 ^{a}	50.2 ± 1.80 ^{a}	44.4 ± 3.33 ^{ab}	80.4 ± 4.74 ^{a}
350	5.61 ± 0.20 ^{a}	9.20 ± 0.48 ^{a}	41.9 ± 1.17 ^{a}	50.6 ± 1.81 ^{a}	45.5 ± 2.38 ^{a}	80.6 ± 5.71 ^{a}

Table 2. *Cont.*

Factors	Leaf Number (Leaves)		Chlorophyll		Plant Height (cm)	
	Days After Sowing (DAS)					
	15	30	15	30	15	30
KCl application, kg ha^{-1} (C)						
0	5.49 ± 0.19 ^{b}	8.40 ± 0.67 ^{b}	40.4 ± 1.94 ^{b}	48.8 ± 3.14 ^{b}	41.4 ± 3.17 ^{c}	71.4 ± 7.11 ^{c}
40	5.56 ± 0.15 ^{ab}	8.58 ± 0.54 ^{b}	40.7 ± 1.26 ^{b}	49.0 ± 2.18 ^{ab}	43.4 ± 2.57 ^{b}	75.5 ± 5.59 ^{b}
60	5.59 ± 0.16 ^{a}	9.30 ± 0.42 ^{a}	41.0 ± 1.33 ^{b}	49.9 ± 2.27 ^{ab}	45.2 ± 3.14 ^{a}	82.0 ± 4.56 ^{a}
80	5.61 ± 0.19 ^{a}	9.33 ± 0.48 ^{a}	41.8 ± 1.20 ^{a}	50.2 ± 2.51 ^{a}	45.3 ± 2.59 ^{a}	82.6 ± 4.30 ^{a}
F (A)	ns	**	**	**	**	**
F (B)	**	**	**	**	**	**
F (C)	**	**	**	**	**	**
F (A × B)	**	**	**	**	**	**
F (A × C)	**	**	**	**	**	**
F (B × C)	ns	*	ns	**	**	*
F (A × B × C)	ns	**	ns	**	**	**
CV (%)	3.19	7.59	3.15	5.08	7.46	9.22

Note: Values are mean ± SD. Means within a column sharing different letters differ significantly; ns = not significant; * and ** indicate $p \leq 0.05$ and $p \leq 0.01$, respectively.

3.3. Effect of P. megaterium Thr45 and Fertilizer Ratios on Yield Components and Yield

The results presented in Table 3 indicate that *P. megaterium* Thr45 inoculation and fertilizer application rates significantly influenced baby corn yield traits, including ear number, ear yield, edible cob yield, and plant biomass. Inoculation with *P. megaterium* Thr45 (factor A) significantly improved all evaluated parameters compared with the non-inoculated treatment. Specifically, inoculated plants produced 2.14 ears plant^{-1}, an ear yield of 7.93 t ha^{-1}, an edible cob yield of 2.41 t ha^{-1}, and plant biomass of 31.6 t ha^{-1}, all significantly higher than those of the non-inoculated treatment ($p \leq 0.01$). Nitrogen application (factor B) also had a strong effect on yield components. The absence of urea resulted in the lowest values across all parameters, whereas increasing urea rates significantly enhanced ear number, ear yield, edible cob yield, and biomass. The highest values were generally recorded at 350 kg ha^{-1} urea, although the treatments with 175 and 262.5 kg ha^{-1} produced statistically comparable results for most yield traits. Similarly, potassium application (factor C) significantly improved baby corn productivity. Treatments receiving 60 and 80 kg ha^{-1} KCl produced the highest ear number (2.15–2.16 ears plant^{-1}), ear yield (8.46–8.51 t ha^{-1}), and edible cob yield (2.54–2.55 t ha^{-1}), while the control treatment without KCl showed the lowest performance. Statistical analysis revealed significant interactions among most factors (A × B, A × C, and A × B × C), indicating that the beneficial effect of bacterial inoculation was influenced by nitrogen and potassium fertilization levels.

Table 3. Effects of *P. megaterium* Thr45 and fertilizer ratios on yield traits of baby corn.

Factors	Ear Number	Ear Yield	Edible Cob Yield	Plant Biomass
	(Ears Plant^{-1})		(t ha^{-1})	
P. megaterium Thr45 (A)				
No	1.98 ± 0.181 ^{b}	7.73 ± 1.09 ^{b}	2.29 ± 0.328 ^{b}	30.8 ± 2.81 ^{b}
Yes	2.14 ± 0.112 ^{a}	7.93 ± 0.784 ^{a}	2.41 ± 0.231 ^{a}	31.6 ± 1.95 ^{a}

Table 3. *Cont.*

Factors	Ear Number (Ears Plant^{-1})	Ear Yield	Edible Cob Yield (t ha^{-1})	Plant Biomass
Urea application, kg ha^{-1} (B)				
0	1.91 ± 0.201 ^{b}	6.84 ± 0.856 ^{b}	2.05 ± 0.269 ^{b}	27.4 ± 1.37 ^{c}
175	2.10 ± 0.132 ^{a}	8.12 ± 0.765 ^{a}	2.44 ± 0.227 ^{a}	32.2 ± 0.985 ^{b}
262.5	2.11 ± 0.130 ^{a}	8.17 ± 0.731 ^{a}	2.45 ± 0.223 ^{a}	32.3 ± 0.909 ^{b}
350	2.12 ± 0.108 ^{a}	8.19 ± 0.715 ^{a}	2.46 ± 0.218 ^{a}	32.9 ± 0.854 ^{a}
KCl application, kg ha^{-1} (C)				
0	1.92 ± 0.184 ^{c}	6.78 ± 0.706 ^{c}	2.04 ± 0.231 ^{c}	30.8 ± 2.83 ^{b}
40	2.00 ± 0.152 ^{b}	7.58 ± 0.644 ^{b}	2.27 ± 0.202 ^{b}	31.1 ± 2.49 ^{a}
60	2.15 ± 0.087 ^{a}	8.46 ± 0.579 ^{a}	2.54 ± 0.180 ^{a}	31.2 ± 2.33 ^{a}
80	2.16 ± 0.103 ^{a}	8.51 ± 0.604 ^{a}	2.55 ± 0.180 ^{a}	31.8 ± 2.09 ^{a}
F (A)	**	**	**	**
F (B)	**	**	**	**
F (C)	**	**	**	**
F (A × B)	**	**	**	**
F (A × C)	**	**	**	**
F (B × C)	**	ns	ns	**
F (A × B × C)	*	**	**	*
CV (%)	8.26	12.2	12.3	7.84

ns = not significant; * $p \leq 0.05$, ** $p \leq 0.01$; CV = coefficient of variation. Data are shown as mean ± SD (n = 4), and means with the same letter within a column are not significantly different.

3.4. Impact of P. megaterium Thr45 Inoculation and Fertilizer Ratios on Nutrient Composition of Baby Corn

The nutrient composition of edible baby corn cobs was significantly influenced by *P. megaterium* Thr45 inoculation (A) and fertilizer rates (urea, B; KCl, C) (Table 4). Bacterial inoculation did not significantly affect cob moisture; however, it markedly increased lipid, protein, N, P, and K contents compared with the non-inoculated treatment. Protein concentration increased from 2.28% to 2.62%, while N, P, and K contents rose from 0.364 to 0.419%, 0.160 to 0.173%, and 0.267 to 0.295%, respectively. Urea application rate (B) significantly affected most nutrient parameters except moisture. Increasing urea rates generally enhance lipid, protein, and mineral concentrations. The highest protein (2.59%), N (0.415%), P (0.174%), and K (0.287%) contents were observed at 100 kg ha^{-1} urea, whereas the lowest values occurred in the unfertilized treatment. Similarly, KCl application (C) significantly influenced lipid, protein, and mineral accumulation in edible cobs. Lipid concentration increased progressively from 0.351% at 0 kg ha^{-1} KCl to 0.389% at 100 kg ha^{-1}. Higher KCl rates also improved protein and mineral contents, particularly P and K. Regarding interaction effects, significant interactions between bacterial inoculation and fertilizer levels were detected for protein and mineral contents (A × B and A × C), indicating that the positive effect of *P. megaterium* Thr45 was more pronounced under moderate to high fertilizer levels. However, moisture content remained unaffected by all factors and their interactions.

Table 4. Effects of *P. megaterium* Thr45 and fertilizer ratios on nutrient compositions of edible cobs.

Factor	Moisture	Lipide	Protein	N	P	K
	(%)					
P. megaterium Thr45 (A)						
No	86.8 ± 1.31	0.371 ± 0.016 ^{b}	2.28 ± 0.300 ^{b}	0.364 ± 0.048 ^{b}	0.160 ± 0.027 ^{b}	0.267 ± 0.020 ^{b}
Yes	86.9 ± 1.48	0.373 ± 0.016 ^{a}	2.62 ± 0.144 ^{a}	0.419 ± 0.023 ^{a}	0.173 ± 0.012 ^{a}	0.295 ± 0.008 ^{a}
Urea application, kg ha^{-1} (B)						
0	87.0 ± 1.55	0.365 ± 0.018 ^{b}	2.20 ± 0.315 ^{c}	0.352 ± 0.050 ^{c}	0.146 ± 0.021 ^{b}	0.267 ± 0.026 ^{b}
175	87.3 ± 1.49	0.373 ± 0.016 ^{ab}	2.44 ± 0.250 ^{b}	0.390 ± 0.040 ^{b}	0.172 ± 0.018 ^{a}	0.283 ± 0.018 ^{a}
262.5	86.8 ± 1.55	0.374 ± 0.014 ^{a}	2.57 ± 0.221 ^{a}	0.411 ± 0.035 ^{a}	0.173 ± 0.019 ^{a}	0.285 ± 0.017 ^{a}
350	86.4 ± 1.20	0.376 ± 0.015 ^{a}	2.59 ± 0.181 ^{a}	0.415 ± 0.029 ^{a}	0.174 ± 0.016 ^{a}	0.287 ± 0.014 ^{a}
KCl application, kg ha^{-1} (C)						
0	86.8 ± 1.34	0.351 ± 0.008 ^{d}	2.21 ± 0.327 ^{b}	0.354 ± 0.052 ^{b}	0.144 ± 0.020 ^{b}	0.266 ± 0.024 ^{b}
50	86.8 ± 1.47	0.370 ± 0.008 ^{c}	2.50 ± 0.242 ^{a}	0.400 ± 0.039 ^{a}	0.172 ± 0.017 ^{a}	0.279 ± 0.019 ^{a}
75	86.8 ± 1.45	0.379 ± 0.008 ^{b}	2.53 ± 0.247 ^{a}	0.406 ± 0.039 ^{b}	0.173 ± 0.018 ^{a}	0.288 ± 0.017 ^{a}
100	87.2 ± 1.68	0.389 ± 0.008 ^{a}	2.55 ± 0.204 ^{a}	0.408 ± 0.034 ^{a}	0.175 ± 0.016 ^{a}	0.289 ± 0.015 ^{a}
F (A)	ns	*	**	**	**	**
F (B)	ns	**	**	**	**	**
F (C)	ns	**	**	**	**	**
F (A × B)	ns	ns	**	**	**	**
F (A × C)	ns	ns	**	**	**	**
F (B × C)	ns	ns	ns	ns	*	ns
F (A × B × C)	ns	ns	ns	ns	**	ns
CV (%)	1.70	4.34	11.9	7.59	9.22	7.38

ns = not significant; * $p \leq 0.05$, ** $p \leq 0.01$; CV = coefficient of variation. Data are shown as mean ± SD (n = 4) and means with the same letter within a column are not significantly different.

4. Discussion

4.1. Effects of P. megaterium Thr45 and Fertilizer Rates on Soil Properties

Table 1 shows that the significant increase in available phosphorus and exchangeable potassium observed under *P. megaterium* Thr45 inoculation indicates that this bacterium can enhance soil nutrient availability through microbial-mediated mechanisms. One possible explanation is the capacity of *P. megaterium* to solubilize insoluble phosphate compounds and mobilize mineral nutrients in the rhizosphere through the production of organic acids and enzymatic activity, thereby improving nutrient accessibility to plants [30]. Such mechanisms are commonly associated with PGPR, which play a crucial role in nutrient cycling and soil fertility enhancement. Similar results have been reported in previous studies demonstrating that beneficial rhizobacteria significantly improve soil nutrient status and nutrient turnover in the rhizosphere [31,32].

These findings are consistent with previous studies reporting that microbial inoculants such as *P. megaterium* enhance soil nutrient dynamics by stimulating microbial activity and accelerating nutrient mineralization processes in the rhizosphere, which ultimately improves soil fertility and plant nutrient availability [31,32]. In maize production systems, biofertilizer inoculation has been shown to increase available phosphorus and potassium through microbial solubilization and mobilization processes, contributing to improved soil nutrient balance and long-term soil health [33]. In contrast, the lack of significant effects from different urea and KCl application rates on soil chemical properties may be related to the short growth period of baby maize, which may not allow sufficient time for substantial changes in soil nutrient dynamics to occur. Baby corn is typically harvested at an early developmental stage, and therefore the time required for fertilizer-induced changes in soil chemical properties may be limited. Similar observations have been reported in short-

cycle vegetable crops where fertilizer treatments did not immediately alter soil chemical characteristics despite influencing plant performance [33]. These findings emphasize the potential role of beneficial microbial inoculants in improving soil fertility while reducing reliance on mineral fertilizers and support the integration of biofertilizers into sustainable nutrient management strategies aimed at maintaining soil productivity while minimizing excessive chemical fertilizer inputs [33].

4.2. Effects of P. megaterium Thr45 and Urea–KCl Ratios on Baby Maize Growth

The improved growth performance of baby maize under *P. megaterium* Thr45 inoculation suggests that this bacterium plays an important role in enhancing plant physiological activity and nutrient uptake (Table 2). Species of PGPR, such as *P. megaterium*, are known to stimulate plant development through mechanisms including phytohormone production, nutrient solubilization, and enhanced root development, which collectively improve plant vigor and biomass accumulation [31,33]. In addition to nutrient solubilization, PGPR are widely recognized for their ability to produce plant growth regulators such as indole-3-acetic acid (IAA), gibberellins, and cytokinins, which promote root elongation and increase the root surface area for nutrient absorption. Enhanced root development may improve the efficiency of water and nutrient uptake, leading to greater biomass accumulation and improved crop growth under field conditions [34]. The observed increases in chlorophyll content and plant height indicate improved photosynthetic capacity and nutrient assimilation in inoculated plants [20,34]. Similar results have been reported in previous studies showing that beneficial rhizobacteria significantly enhance maize growth and physiological performance under field conditions [35]. Several studies have reported that biofertilizers can improve nitrogen use efficiency in maize by stimulating root activity and enhancing microbial processes in the rhizosphere, thereby facilitating nutrient uptake and improving plant metabolic activity [35]. In addition, the positive response to higher urea and KCl levels highlights the importance of balanced nutrient supply for optimal crop growth [36]. The significant interaction effects among bacterial inoculation and fertilizer treatments further suggest that integrating microbial inoculants with appropriate fertilizer management can enhance nutrient use efficiency and promote sustainable crop production systems by optimizing fertilizer use while maintaining crop productivity [37].

4.3. Effects of P. megaterium Thr45 and Fertilizer Ratios on Baby Corn Yield and Components

The positive effect of *P. megaterium* Thr45 inoculation on baby corn productivity may be attributed to its plant growth promoting traits, particularly its capacity to enhance nutrient availability and uptake [38]. Species of *P. megaterium* are widely reported to solubilize phosphorus, mobilize potassium, and stimulate root development, thereby improving plant growth and yield under field conditions [39]. Improved nutrient availability in the rhizosphere may enhance vegetative growth and reproductive development, which ultimately contributes to increased ear formation and yield components in maize crops. Enhanced root activity associated with PGPR inoculation may also facilitate the uptake of macro- and micronutrients required for reproductive growth and cob development [40]. The increased ear number and yield observed in inoculated treatments suggest that the bacterium enhanced nutrient acquisition efficiency, especially when combined with appropriate fertilizer rates [40]. Nitrogen and potassium fertilization further contributed to improved yield components, as these nutrients play critical roles in vegetative growth, photosynthesis, and assimilate translocation [41]. The higher yields obtained at moderate-to-high fertilizer rates indicate that balanced nutrient management is essential for maximizing baby corn productivity. Moreover, the significant interaction effects observed in this study suggest that microbial inoculation may partially complement mineral fertilization, potentially allow

reduced fertilizer inputs while maintain high crop performance [20,42]. These results support previous findings showing that the combined application of beneficial microorganisms and reduced mineral fertilizers can improve nutrient use efficiency while maintaining or even enhancing crop productivity, which is a key objective of sustainable agricultural practices [43]. Similar synergistic effects between beneficial bacteria and mineral fertilizers have been reported in maize and other cereal crops [43].

4.4. Effects of P. megaterium Thr45 and Fertilizer Ratios on Baby Corn Nutrient Components

The improvement in protein and mineral concentrations of baby corn cobs following inoculation with *P. megaterium* Thr45 suggests that this bacterium enhances nutrient uptake and assimilation in maize plants [15,20]. Species of *P. megaterium* are widely recognized as plant growth-promoting rhizobacteria capable of solubilizing phosphorus and mobilizing potassium, thereby increasing nutrient availability in the rhizosphere and improving plant nutritional status [44]. Improved nutrient uptake may stimulate metabolic processes associated with nitrogen assimilation and protein biosynthesis, resulting in higher protein accumulation in edible plant tissues. Additionally, enhanced root activity and rhizosphere microbial interactions may facilitate the absorption of essential minerals such as potassium, phosphorus, and micronutrients, which contribute to improved nutritional quality of crop products [45]. Enhanced uptake of essential nutrients may stimulate metabolic processes associated with protein synthesis and mineral accumulation in edible plant tissues [45]. The observed increases in nutrient contents with higher urea and KCl rates further confirm the importance of nitrogen and potassium in supporting plant growth and nutrient translocation to developing cobs. Nitrogen plays a key role in amino acid and protein synthesis, whereas potassium regulates enzyme activation and nutrient transport within plants. Similar improvements in maize nutritional quality due to beneficial rhizobacteria and balanced fertilization have been reported in previous studies [38,46,47]. From a sustainable agriculture perspective, the integration of microbial inoculants with optimized fertilizer management may enhance both crop yield and nutritional quality while reducing excessive fertilizer inputs and associated environmental impacts. Overall, the combined use of microbial inoculants and appropriate fertilizer management may enhance both productivity and nutritional quality of baby corn [20,25,38].

5. Conclusions

The present study demonstrated that inoculation with *P. megaterium* Thr45 significantly improved soil nutrient availability, plant growth, yield performance, and nutritional quality of baby maize under field conditions. Bacterial inoculation increased available phosphorus and exchangeable potassium in soil, indicating its role in enhancing nutrient mobilization in the rhizosphere. Improved chlorophyll content, plant height, and leaf development observed in inoculated treatments further confirmed the growth-promoting potential of this bacterium. Moreover, *P. megaterium* Thr45 significantly enhanced yield traits, including ear number, ear yield, edible cob yield, and total plant biomass. Positive interactions between bacterial inoculation and fertilizer levels suggest that the integration of beneficial microbes with optimized fertilization can improve nutrient use efficiency. Importantly, comparable yield performance was obtained under reduced nitrogen and potassium inputs when combined with bacterial inoculation. Overall, the findings highlight the potential of *P. megaterium* Thr45 as a promising biofertilizer for sustainable baby maize production by improving soil fertility while reducing dependence on mineral fertilizers.

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