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The effectiveness of *Bacillus*-coated NPK fertilizer on broccoli growth, nutrient status, rhizosphere *Bacillus* population, yield, and flower quality

Abstract. Efforts to increase the availability of macronutrients in soil have relied on inorganic fertilization, particularly NPK fertilizers. However, global challenges in the fertilizer raw material supply chain, including price fluctuations and availability, are driving the need for more efficient and sustainable fertilizer alternatives. The field experiment was conducted in Baruajak, Lembang District, West Java, Indonesia, to evaluate the effectiveness of *Bacillus*-coated NPK fertilizer on broccoli (*Brassica oleracea* var. *italica*) growth, nutrient status, rhizosphere *Bacillus* population, yield, and flower quality. The experiment used a randomized complete block design with 15 fertilizer treatments and three replications. Treatments consisted of two coated NPK formulations, Formula C (0.4% *Bacillus* consortium + 0.2% zeolite) and Formula G (0.2% *Bacillus* consortium + 0.4% zeolite), applied once or twice at 100%, 75%, and 50% of the recommended NPK dose, and conventional NPK fertilizer at the same dose levels. The recommended NPK dose for broccoli was 300 kg ha^{-1}. Plant growth, chlorophyll content, shoot biomass, nutrient concentration and uptake, soil nutrient status, rhizosphere *Bacillus* population, flower yield, flower diameter, and vitamin B3 and K contents were observed. The results showed that *Bacillus*-coated NPK fertilizer generally improved vegetative growth compared with conventional NPK fertilizer. Formula G applied once at 100% recommended NPK dosage produced the highest flower weight and diameter, while Formula C applied once at 75% resulted in the highest vitamin B3 and vitamin K contents. The coated NPK fertilizer maintained shoot N, P, and K concentrations comparable to those of conventional NPK and showed potential to partially or fully replace conventional NPK in broccoli cultivation.

Keywords: *Bacillus* · *Brassica oleracea* var. *italica* · Plant growth · Coated NPK · Sustainable fertilizer alternatives

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Introduction

Broccoli (*Brassica oleracea* var. *italica*) is an important vegetable crop with high nutritional value, particularly as a source of vitamins and minerals. In intensive vegetable production areas such as Lembang, broccoli cultivation commonly depends on regular application of inorganic NPK fertilizer to maintain plant growth and yield. However, continuous use of inorganic fertilizers without balancing them with organic materials can also reduce soil quality, including organic matter levels, base saturation, and long-term crop yields (Niu et al., 2022).

One approach to improve fertilizer efficiency is the use of NPK fertilizer coated or enriched with beneficial microorganisms such as *Bacillus*. Several *Bacillus* species are known to support plant growth by solubilizing nutrients, producing growth-promoting compounds, and enhancing rhizosphere biological activity. Souza et al., (2023) reported that the application of Bacillus increased the production components and yield of common beans, P content in leaves, P accumulation, number of pods per plant, and dry matter yield. Bacillus, as a phosphate-solubilizing bacteria (PSB), improved soil health indicators, reduced soilborne diseases, and promoted tomato growth (Abdallah et al., 2026). Other studies showed that Bacillus, a dominant genus in PSB, produces various antibiotics, including bacillomycin, rhizomycin, and actinomycin (Khoshru et al., 2023).

Although the potential of *Bacillus* as a plant growth promoter agent (PGPR) has been widely researched in horticultural commodities, the effectiveness of biological NPK fertilizer formulation in the field is greatly influenced by the dynamics of the soil environment, frequency of application, and the suitability of application doses (Sharma et al., 2019). In Brassicaceae family plants, such as broccoli, that have a rapid vegetative growth phase and high macronutrient requirements, nutrient release from microbial-coated NPK fertilizers must be in sync with the plant's needs (Li et al., 2021). Without proper dosage and application frequency, bacterial colonization in the rhizosphere is often suboptimal due to competition with soil-native microbes or nutrient leaching caused by high rainfall in highland areas such as Lembang (Moeskops et al., 2012). Determining optimal balancing formulations and efficient application intervals is important to ensure the sustainability of nutrient supply while maintaining the viability of soil bacterial populations.

Therefore, integrating *Bacillus* with NPK fertilizer may improve nutrient availability and plant performance while reducing the amount of inorganic fertilizer applied (Hindersah et al., 2025). This study aimed to evaluate the effectiveness of *Bacillus*-coated NPK fertilizer with different formulations, application frequencies, and dose levels on growth, nutrient uptake, rhizosphere *Bacillus* population, yield, and flower quality of broccoli under field conditions.

Materials and Methods

Preparation of *Bacillus*-coated NPK fertilizer. The final *Bacillus* population in the coated fertilizer was approximately 10^8 CFU ml^{-1}. *Bacillus*-coated NPK fertilizer was prepared by applying a Bacillus-based coating formulation containing a *Bacillus* consortium and zeolite onto the NPK granules. The coated granules were homogenized using a spinning mixing bowl for 5 min to ensure uniform distribution of the coating material over the granule surface. The coated fertilizer was subsequently used according to the experimental treatments.

Experimental Site and Soil Characteristics. The field experiment was conducted in Baruajak, Lembang District, West Java, Indonesia. Prior to the experiment, soil chemical properties and cattle manure used in the field trial were analyzed. The soil at the experimental site had a slightly acidic pH of 5.9 in H_2O and 5.0 in KCl. The soil contained high organic carbon, total nitrogen, available phosphorus, and potassium. Soil organic C was 5.40%, total N was 0.50%, C/N ratio was 11, P_2O_5 extracted by HCl 25% was 1161.73 mg 100 g^{-1}, Olsen P was 1112.7 mg kg^{-1} P, K_2O extracted by HCl 25% was 186.73 mg 100 g^{-1}, and cation exchange capacity was 30.46 cmol kg^{-1}. The cattle manure used in the experiment had 33.53% organic C, a C/N ratio of 18, a moisture content of 22.34%, a pH of 6.21, 1.8% N, 1.2% P_2O_5, and 3.71% K_2O.

Experimental Design and Treatments. The experiment was arranged in a randomized complete block design with 15 fertilizer treatments and three replications, resulting in 45 experimental plots. The treatments consisted of combinations of fertilizer formulation, application frequency, and fertilizer dose. Two

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Bacillus-coated NPK formulations were tested, namely Formula C (0.4% *Bacillus* consortium + 0.2% zeolite) and Formula G (0.2% *Bacillus* consortium + 0.4% zeolite). Each formula was applied either once and twice. Conventional NPK fertilizer was used as the farmer-control treatment. Each fertilizer type was applied at three dose levels: 100%, 75%, and 50% of the recommended NPK dose. The recommended NPK dose for broccoli was 300 kg ha^{-1}. Based on plant population and plot size, the fertilizer doses per plant were 5.0 g plant^{-1} for 100%, 3.75 g plant^{-1} for 75%, and 2.5 g plant^{-1} for 50% of the recommendation. The treatment combinations were as follows:

Code	Fertilizer treatment
A	Formula C, one application, 100% dose
B	Formula C, one application, 75% dose
C	Formula C, one application, 50% dose
D	Formula C, two applications, 100% dose
E	Formula C, two applications, 75% dose
F	Formula C, two applications, 50% dose
G	Formula G, one application, 100% dose
H	Formula G, one application, 75% dose
I	Formula G, one application, 50% dose
J	Formula G, two applications, 100% dose
K	Formula G, two applications, 75% dose
L	Formula G, two applications, 50% dose
M	Conventional NPK, 100% dose
N	Conventional NPK, 75% dose
O	Conventional NPK, 50% dose

Plot Size and Fertilizer Application. Each broccoli plot measured 1.0 m × 1.3 m. The planting distance was 50 cm × 50 cm, resulting in six plants per plot. Fertilizer was applied one week after transplanting. For treatments with two applications, the dose was split, with the second application given 1 week after the first.

Observed Parameters. Plant growth parameters, including plant height, number of leaves, and leaf length, were evaluated at 2 and 4 weeks after transplanting. Plant height was measured from the soil surface to the apical growing point using a ruler, the number of fully expanded leaves was counted, and leaf length was measured from the leaf base to the leaf tip. Chlorophyll content was measured on the third fully expanded leaf at 4 weeks after transplanting using a chlorophyll meter, and the results were expressed as chlorophyll content index (CCI). Fresh and dry shoot weights were determined at 4 weeks after transplanting. Shoots were harvested and weighed to determine fresh weight and subsequently oven-dried at 60°C until constant weight to determine dry weight.

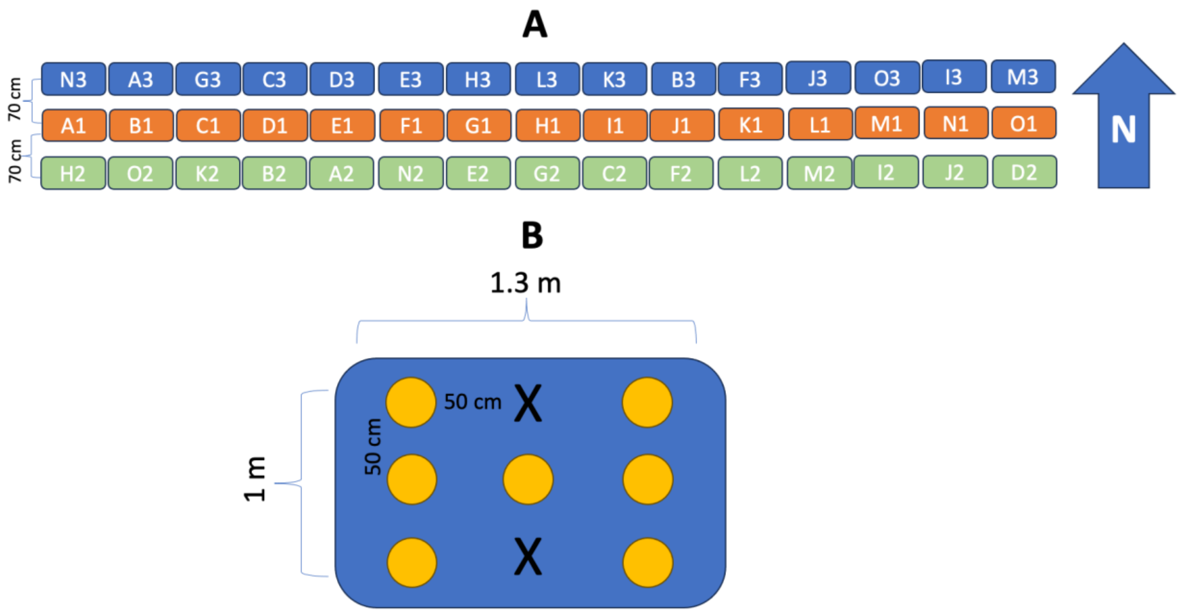

Figure 1. (A) Layout of treatment and repetition in the field experiment, (B) sampling points marked with the letter 'X'

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Shoot N, P, and K concentrations and nutrient uptake were determined to evaluate plant nutrient status. Soil N, P, and K were also determined at 4 weeks after transplanting. Rhizosphere *Bacillus* populations were quantified using the serial dilution and plate count method on tryptic soy agar (TSA). Vegetative cells and heat-resistant spores were enumerated separately. For spore enumeration, samples were heat-treated at 80°C for 20 min before serial dilution and plating. At harvest, flower weight, flower diameter, vitamin B3 content, and vitamin K content were determined. Two plants from each plot, representing approximately 33% of the plant population, were selected as observation samples.

Statistical Analysis. All data were analyzed using analysis of variance with Fisher's test at $p < 0.05$. When treatment effects were significant, mean separation was performed using Duncan's Multiple Range Test at $p < 0.05$. Statistical analysis was conducted using IBM SPSS Statistics version 24.

Results and Discussion

Vegetative Growth of Broccoli. The application of *Bacillus*-coated NPK fertilizer significantly affected broccoli vegetative growth. At 2 weeks after transplanting, plant height ranged from 28.67 to 37.33 cm. The 50% conventional NPK treatment (O) had the lowest numerical mean plant height (28.67 cm), whereas Formula C applied once at 75% of the recommended NPK dose (B) had the highest mean (37.33 cm) (Table 1). This shows that Bacillus-coated NPK had a greater effect on increasing broccoli growth. This is in line with research conducted by Hindersah et al., (2025), which showed that Bacillus-coated NPK improved broccoli growth on Inceptisols. One application of formula C with NPK 75% increased up to 28.7% compare with the conventional NPK 75% dose. This shows that the Bacillus-coated NPK can increase plant growth. The addition of *Bacillus* consortium to NPK can improve nutrient availability, thereby increasing plant growth.

At 4 weeks after transplanting, the highest numerical mean plant height was observed in Formula G applied once at 75% and twice at 100% of the recommended NPK dose, with both treatments reaching 55.67 cm (Table 1). These values were significantly higher than those observed under conventional NPK fertilizer applied at 100%, 75%, and 50% of the recommended dose, which produced plant heights of 50.33, 49.33, and 49.67 cm, respectively.

Table 1. Height of broccoli plants with various coated NPK fertilizer treatments

Treatments	Plant Height (cm)	
	2 WAP	4 WAP
A: Formula C, one application, 100% dose	36.00 ef	53.67abc
B: Formula C, one application, 75% dose	37.33 f	50.33 ab
C: Formula C, one application, 50% dose	34.67 def	50.33 ab
D: Formula C, two applications, 100% dose	34.00 cdef	55.00 bc
E: Formula C, two applications, 75% dose	33.33 bcdef	53.67 abc
F: Formula C, two applications, 50% dose	34.00 cdef	50.67 ab
G: Formula G, one application, 100% dose	32.33 abcde	54.00 abc
H: Formula G, one application, 75% dose	34.00 cdef	55.67 c
I: Formula G, one application, 50% dose	34.00 cdef	52.33 abc
J: Formula G, two applications, 100% dose	30.67 abcd	55.67 c
K: Formula G, two applications, 75% dose	31.67 abcde	53.00 abc
L: Formula G, two applications, 50% dose	32.33 abcde	52.00 abc
M: Conventional NPK, 100% dose	29.67 abc	50.33 ab
N: Conventional NPK, 75% dose	29.00 ab	49.33 a
O: Conventional NPK, 50% dose	28.67 a	49.67a

Note: Mean values followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test at $p < 0.05$.

These values were higher than those observed in conventional NPK treatments, particularly NPK at 75% and 50%, which produced plant heights of 49.33 cm and 49.67 cm, respectively. The improvement in plant height indicates that *Bacillus*-coated NPK fertilizer may enhance nutrient availability during early vegetative growth. The presence of *Bacillus* in the fertilizer coating may enhance nutrient mobilization in the rhizosphere, especially under highland vegetable production conditions where nutrient demand is relatively high. Also, *Bacillus* may increase soil enzyme activity (alkaline phosphatase, acid phosphatase, urease, and β-glucosidase), organic acid production, and phytohormone levels (zeatin, gibberellin, and kinetin) (Kumar et al., 2021; Risanti et al., 2025), thereby promoting higher vegetative growth of the plants.

Leaf Growth and Chlorophyll Content. The number of leaves and leaf length also responded to fertilizer treatment. At 4 weeks after transplanting, the highest number of leaves was recorded in Formula G applied twice at 50% dose, with 13.67 leaves per plant. Formula C, applied once at 100%, and Formula G, applied twice at 100%, also produced relatively high leaf numbers, with 13.00 leaves per plant (Table 2).

Leaf length at 4 weeks after transplanting was highest in Formula G applied twice at 75% dose, reaching 28.33 cm. Conventional NPK at 100% produced the shortest leaf length, with 21.67 cm. This suggests that coated NPK fertilizer improved leaf expansion compared with conventional NPK. Chlorophyll content was also influenced by treatment. The highest chlorophyll content was observed in Formula G applied once at 100% dose, with 16.43 CCI. This value was higher than that of conventional NPK at 100%, which produced only 6.83 CCI. According to Kulkova et al., (2023), after application of *Bacillus* the photosynthetic pigment content was enhanced, as well as an increase in chlorophyll a, chlorophyll b, and carotenoids. This enhancement in chlorophyll accumulation may reflect improved nitrogen uptake and utilization, thereby increasing the photosynthetic capacity of broccoli leaves.

Overall, Formula C and Formula G at different doses and application frequencies tended to increase plant height, leaf number, leaf length, and chlorophyll content compared with conventional NPK at the recommended dose.

Table 2. Leaf Number, Leaf Length, and Chlorophyll Index of Broccoli Plants at 2 and 4 WAP with Various Treatments of *Bacillus*-coated NPK Fertilizer

Treatments	Number of leaves		Leaf lengths (cm)		Chlorophyll (cci) (4 WAP)
	2 WAP	4 WAP	2 WAP	4 WAP	
A: Formula C, one application, 100% dose	8.67 ab	13.00 bc	23.33 cd	27.00 bc	8.33 ab
B: Formula C, one application, 75% dose	8.00 ab	11.67 abc	26.00 d	26.33 abc	9.13 ab
C: Formula C, one application, 50% dose	9.00 ab	12.00 abc	23.00 cd	26.67 abc	11.03 ab
D: Formula C, two applications, 100% dose	7.33 ab	11.33 abc	22.00 bc	25.67 abc	10.76 ab
E: Formula C, two applications, 75% dose	7.00 a	10.00 ab	20.67 abc	27.00 bc	9.76 ab
F: Formula C, two applications, 50% dose	8.33 ab	11.67 abc	22.00 bc	27.00 bc	11.86 b
G: Formula G, one application, 100% dose	11.33 c	10.33 ab	20.67 abc	24.33 abc	16.43 c
H: Formula G, one application, 75% dose	7.67 ab	11.67 abc	21.67 bc	27.00 bc	9.53 ab
I: Formula G, one application, 50% dose	9.67 ab	12.33 abc	23.00 cd	24.67 abc	7.10 a
J: Formula G, two applications, 100% dose	6.67 a	13.00 bc	21.67 bc	27.00 bc	11.46 ab
K: Formula G, two applications, 75% dose	8.67 ab	9.33a	21.67 bc	28.33 c	8.67 ab
L: Formula G, two applications, 50% dose	10.33 ab	13.67 c	21.00 abc	27.00 bc	12.90 bc
M: Conventional NPK, 100% dose	9.00 ab	11.33 abc	18.33 a	21.67 a	6.83 a
N: Conventional NPK, 75% dose	10.33 ab	11.67 abc	19.33 ab	23.33 abc	9.90 ab
O: Conventional NPK, 50% dose	7.67 ab	9.67 a	19.33 ab	23.00 ab	9.16 ab

Note: Mean values followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test at $p < 0.05$.

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Shoot Biomass. Shoot fresh weight at 4 weeks after transplanting was significantly affected by fertilizer treatment, while shoot dry weight was not significantly different among treatments. The highest shoot fresh weight was obtained from Formula G applied once at 50% dose, with 293.07 g plant^{-1}. This treatment produced a higher fresh weight than conventional NPK at 50%, which only reached 107.03 g plant^{-1}.

Formula G applied twice at 100% also produced high shoot fresh weight, with 257.29 g plant^{-1}. In general, *Bacillus*-coated NPK fertilizer was able to produce shoot biomass comparable to or higher than conventional NPK fertilizer. This result indicates that coated NPK fertilizer may improve fertilizer efficiency and support vegetative biomass accumulation even at reduced dose levels. Similar findings have been reported by Kumari et al., (2023), who demonstrated that *Bacillus*-based biofertilizers enhance nutrient availability and stimulate plant growth through the production of phytohormones and other plant growth-promoting metabolites. Likewise, Backer et al., (2018) reported that plant growth-promoting bacteria can improve nutrient use efficiency and increase crop biomass production under various cultivation conditions. The absence of significant differences in shoot dry weight suggests that the treatments affected fresh biomass more strongly than structural dry matter accumulation at the vegetative stage. Differences in water content, leaf expansion, and tissue succulence may have contributed to the variation in fresh weight.

Shoot Nutrient Concentration and Uptake. Fertilizer treatments significantly affected shoot K concentration and P and K uptake, but did not significantly affect shoot N and P concentrations. Shoot N concentration ranged from 4.01% to 5.03%, which was within the sufficient range for broccoli. Shoot K concentration ranged from 2.92% to 5.01%, while shoot P concentration was relatively high across treatments.

The highest shoot N concentration was observed with Formula G applied twice at 50% dose, at 5.03%. The highest K concentration was observed in conventional NPK at 75%, with a concentration of 5.01%. Meanwhile, the highest N uptake was also recorded in Formula G applied twice at 50%, reaching 1.04 g plant^{-1}. For P uptake, Formula G applied at 100% once showed the highest value (0.52 g plant^{-1}), although several treatments were statistically comparable. The highest K uptake was observed in Formula G applied once at 50%, with 1.01 g plant^{-1}. These results show that no single treatment consistently produced the highest uptake of all three macronutrients. However, *Bacillus*-coated NPK fertilizer generally maintained shoot N, P, and K concentrations and uptake levels comparable to those of conventional NPK. Besides, studies on the application of Bacillus to vegetables found that it can increase plant phosphate and nitrogen levels, produce organic acids, lower soil pH, and make P more soluble and available to plants.

Table 3. Fresh and dry weight of broccoli plant at 4 WAP with various treatments of *Bacillus*-coated NPK fertilizer

Treatments	Fresh weight (g)	Dry weight (g)
A: Formula C, one application, 100% dose	136.31 ab	12.49
B: Formula C, one application, 75% dose	208.57 ab	15.99
C: Formula C, one application, 50% dose	180.39 ab	14.06
D: Formula C, two applications, 100% dose	221 ab	15.91
E: Formula C, two applications, 75% dose	235.62 ab	16.99
F: Formula C, two applications, 50% dose	121.21 a	10.38
G: Formula G, one application, 100% dose	124.26 a	13.30
H: Formula G, one application, 75% dose	146.83 ab	12.45
I: Formula G, one application, 50% dose	293.07 b	20.74
J: Formula G, two applications, 100% dose	257.29 ab	20.01
K: Formula G, two applications, 75% dose	159.15 ab	14.31
L: Formula G, two applications, 50% dose	178.51 ab	20.84
M: Conventional NPK, 100% dose	166.61 ab	13.03
N: Conventional NPK, 75% dose	156.51 ab	13.74
O: Conventional NPK, 50% dose	107.03 a	8.66

Note: Mean values followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test at $p < 0.05$.

Table 4. Nutrients (Nitrogen, Phosphorus and Potassium) levels and absorption of broccoli leaves with various treatments of *Bacillus*-coated NPK fertilizer

Treatments	Nutrient Levels (%)			Nutrient Absorption (g/plant)		
	Nitrogen	Phosphorus	Potassium	Nitrogen	Phosphorus	Potassium
A: Formula C, one application, 100% dose	4.97 ab	3.67 a	3.46 abc	0.60 ab	0.30 ab	0.44 abc
B: Formula C, one application, 75% dose	4.25 ab	3.57 a	3.76 abc	0.67 ab	0.32 ab	0.60 abc
C: Formula C, one application, 50% dose	4.08 ab	3.48 a	3.31 abc	0.56 ab	0.38 abc	0.47 abc
D: Formula C, two applications, 100% dose	4.01 a	3.57 a	3.92 abcd	0.63 ab	0.38abc	0.62 abc
E: Formula C, two applications, 75% dose	4.29 ab	3.06 a	3.87 abcd	0.74 ab	0.30 ab	0.64 abc
F: Formula C, two applications, 50% dose	4.77 ab	3.34 a	2.92 a	0.48 ab	0.39 abc	0.29 a
G: Formula G, one application, 100% dose	4.19 ab	3.18 a	3.17 ab	0.58 ab	0.52 c	0.38 ab
H: Formula G, one application, 75% dose	4.35 ab	3.37 a	4.22 bcd	0.52 ab	0.32 ab	0.55 abc
I: Formula G, one application, 50% dose	4.37 ab	3.42 a	4.47 cd	0.85 ab	0.24 a	1.01 c
J: Formula G, two applications, 100% dose	4.39 ab	3.13 a	4.01 abcd	0.88 ab	0.36 ab	0.77 abc
K: Formula G, two applications, 75% dose	4.82 ab	3.42 a	4.45 cd	0.66 ab	0.29 ab	0.64 abc
L: Formula G, two applications, 50% dose	5.03 b	3.36 a	4.40 cd	1.04 b	0.43 bc	0.92 bc
M: Conventional NPK, 100% dose	4.60 ab	3.57 a	3.72 abc	0.57 ab	0.24 a	0.45 abc
N: Conventional NPK, 75% dose	4.74 ab	3.64 a	5.01 d	0.67 ab	0.35 ab	0.66 abc
O: Conventional NPK, 50% dose	4.77 ab	3.21 a	3.68 abc	0.41 a	0.29 ab	0.33 a

Note: Mean values followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test at $p < 0.05$.

Table 5. Soil Nutrients (Nitrogen, Phosphorus and Potassium) levels with various treatments of *Bacillus*-coated NPK fertilizer

Treatments	Nutrient levels (%)		
	Nitrogen	Phosphorus	Potassium
A: Formula C, one application, 100% dose	0.48 ab	1.89 e	0.09 abc
B: Formula C, one application, 75% dose	0.49 ab	1.23 abc	0.10 abc
C: Formula C, one application, 50% dose	0.54 ab	1.49 cd	0.09 abc
D: Formula C, two applications, 100% dose	0.48 ab	1.39 bcd	0.12 bc
E: Formula C, two applications, 75% dose	0.63 b	1.65 de	0.13 c
F: Formula C, two applications, 50% dose	0.35 ab	1.35 bcd	0.11 abc
G: Formula G, one application, 100% dose	0.56 ab	1.35 bcd	0.08 a
H: Formula G, one application, 75% dose	0.44 ab	1.34 bcd	0.10 abc
I: Formula G, one application, 50% dose	0.26 a	1.04 ab	0.08 a
J: Formula G, two applications, 100% dose	0.49 ab	1.10 abc	0.10 abc
K: Formula G, two applications, 75% dose	0.57 ab	1.33 bcd	0.10 abc
L: Formula G, two applications, 50% dose	0.51 ab	1.11 abc	0.09 abc
M: Conventional NPK, 100% dose	0.55 ab	0.99 ab	0.09 ab
N: Conventional NPK, 75% dose	0.46 ab	1.30 bcd	0.10 abc
O: Conventional NPK, 50% dose	0.44 ab	0.89 a	0.09 abc

Note: Mean values followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test at $p < 0.05$.

And also, bacillus can enhance soil nitrogen levels by accelerating the mineralization of organic nitrogen into ammonium nitrogen, thereby increasing soil and plant ammonium nitrogen levels (Fitriatin et al., 2025; Kang et al., 2019; Ren et al., 2025; Venancio et al., 2019). This supports the potential use of coated NPK fertilizer as an alternative to conventional NPK in broccoli cultivation.

Soil N, P, and K Status at 4 Weeks After Transplanting. Soil nutrient status at 4 weeks after transplanting was influenced by fertilizer treatment. Soil total N ranged from 0.26% to 0.63%. The highest soil N content was observed with Formula C applied twice at 75% dose, while the lowest was recorded with Formula G applied once at 50% dose. However, many treatments did not differ significantly from conventional NPK at 100%. Soil P content ranged from 0.89% to 1.89%. Formula C, applied once at 100%, produced the highest soil P content, while conventional NPK at 50% produced the lowest. Soil K content ranged from 0.08% to 0.13%, with Formula C applied twice at 75% producing the highest value.

Application of formula C can increase nitrogen and potassium levels in broccoli planting

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soil, because *Bacillus* can enhance organic nitrogen and solubilize soil potassium by producing organic acids through mineralization (Elekhtyar, 2015; Saxena et al., 2020). In general, soils receiving *Bacillus*-coated NPK fertilizer had nutrient contents comparable to soils receiving conventional NPK at the recommended dose. This indicates that coated NPK did not reduce soil nutrient availability during the vegetative phase and may help maintain nutrient status even when applied at lower doses.

Rhizosphere *Bacillus* Population. The population of *Bacillus* in the broccoli rhizosphere varied among fertilizer treatments. Spore populations ranged from 15.83 × 10^3 to 26.33 × 10^3 CFU g^{-1}, while vegetative cell populations ranged from 123.33 × 10^5 to 270.00 × 10^5 CFU g^{-1}. The highest spore population was observed in Formula G applied once at 100% and conventional NPK at 100%, both with 26.33 × 10^3 CFU g^{-1}. The highest vegetative cell population was recorded in Formula C applied twice at 50%, with 270.00 × 10^5 CFU g^{-1}.

Table 6. Bacterial population in broccoli Rhizosphere at 4 WAP with various treatments of *Bacillus*-coated NPK fertilizer

Treatments	Bacterial Population (CFU/g)	
	Spore cell (x 10^3)	Vegetative cell (x 10^5)
A: Formula C, one application, 100% dose	23.00 ab	185.00 abc
B: Formula C, one application, 75% dose	19.67 ab	123.33 a
C: Formula C, one application, 50% dose	19.00 ab	170.00 ab
D: Formula C, two applications, 100% dose	18.67 ab	176.67 abc
E: Formula C, two applications, 75% dose	22.33 ab	160.00 ab
F: Formula C, two applications, 50% dose	22.16 ab	270.00 c
G: Formula G, one application, 100% dose	26.33 b	236.67 bc
H: Formula G, one application, 75% dose	22.33 ab	163.33 ab
I: Formula G, one application, 50% dose	15.83 a	213.33 abc
J: Formula G, two applications, 100% dose	17.00 a	178.33 abc
K: Formula G, two applications, 75% dose	18.16 ab	245.00 bc
L: Formula G, two applications, 50% dose	21.00 ab	165.00 ab
M: Conventional NPK, 100% dose	26.33 b	218.33 abc
N: Conventional NPK, 75% dose	16.00 a	195.00 abc
O: Conventional NPK, 50% dose	17.33 a	165.00 ab

Note: Mean values followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test at $p < 0.05$.

Table 7. Fresh weight and diameter of broccoli flower with various treatments of *Bacillus*-coated NPK fertilizer

Treatments	Flower Weight (g)	Diameter Flowers (cm)
A: Formula C, one application, 100% dose	146.09 abc	12.67 ab
B: Formula C, one application, 75% dose	128.16 ab	12.63 ab
C: Formula C, one application, 50% dose	226.25 abcd	17.50 abcd
D: Formula C, two applications, 100% dose	150.69 abc	13.13 ab
E: Formula C, two applications, 75% dose	121.45 ab	15.33 abc
F: Formula C, two applications, 50% dose	99.51 a	12.23 ab
G: Formula G, one application, 100% dose	424.63 e	22.83 d
H: Formula G, one application, 75% dose	249.53 abcde	17.33 abcd
I: Formula G, one application, 50% dose	305.36 bcde	20.33 cd
J: Formula G, two applications, 100% dose	322.62 cde	18.67 bcd
K: Formula G, two applications, 75% dose	355.27 de	20.40 cd
L: Formula G, two applications, 50% dose	252.39 abcde	18.83 cd
M: Conventional NPK, 100% dose	94.28 a	13.30 ab
N: Conventional NPK, 75% dose	113.70 a	12.83 ab
O: Conventional NPK, 50% dose	97.51 a	11.83 a

Note: Mean values followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test at $p < 0.05$.

Although *Bacillus*-coated NPK was expected to increase rhizosphere *Bacillus* populations, the results showed that populations in coated NPK treatments were often comparable to those in conventional NPK treatments. Bacillus can play a role in enhancing microbial activity in the rhizosphere and help in the restoration of soil structure and function, because bacillus can play a key role in increasing carbon supply in soil when organic resources are abundant for microbial energy sources in the soil (Daraz et al., 2021; Fierer et al., 2007). Therefore, the contribution of coated *Bacillus* to the total rhizosphere population can be caused by the fertilizer formula G.

Broccoli Flower Yield. Broccoli flower yield was significantly affected by fertilizer treatment. The highest flower weight was obtained from Formula G applied once at 100% dose, reaching 424.63 g plant^{-1}. This treatment also produced the largest flower diameter, 22.83 cm. Several Formula G treatments produced relatively high flower weights, including twice-applied Formula G at 75% with 355.27 g plant^{-1}, twice-applied Formula G at 100% with 322.62 g plant^{-1}, and once-applied Formula G at 50% with 305.36 g plant^{-1}. In contrast, conventional NPK treatments produced lower flower weights, ranging from 94.28 to 113.70 g plant^{-1}.

The superior yield performance of Formula G suggests that this formulation was more effective than Formula C and conventional NPK in supporting the transition from vegetative growth to flower development. The improved flower weight and diameter may be related to better nutrient uptake, higher chlorophyll content, and more favorable plant growth during the vegetative stage. A study by Salsabila et al., (2024) found that the application of Bacillus can improve broccoli productivity during the generative phase. Therefore, the formula C and G containing the inoculant bacillus can produce phytohormones, such as cytokinins, which play a role in plant growth processes, including photosynthesis, chloroplast development, and cell division, and also increase shoot growth. And phytohormone gibberellin plays a role in expansion through cell growth (Binenbaum et al., 2018; Li et al., 2021; Ma et al., 2025).

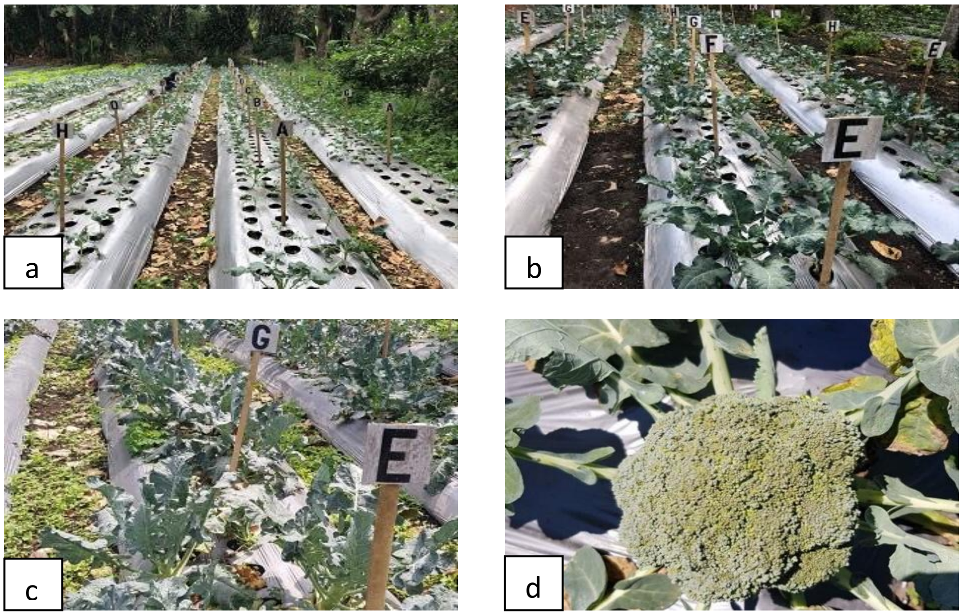

Figure 2. Broccoli plants at 1 WAP (a), 2 WAP (b), 4 WAP (c), and broccoli flowers at harvest (d)

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Table 8. Vitamin B3 and vitamin K levels in broccoli flowers with various treatments of *Bacillus*-coated NPK fertilizer

Treatments	Vitamin B3 (g/100)	Vitamin K (µg/100)
A: Formula C, one application, 100% dose	1.24 bc	119.10 ab
B: Formula C, one application, 75% dose	1.31 c	125.05 b
C: Formula C, one application, 50% dose	1.03 abc	110.71 ab
D: Formula C, two applications, 100% dose	0.99 abc	112.05 ab
E: Formula C, two applications, 75% dose	1.15 abc	116.13 ab
F: Formula C, two applications, 50% dose	1.14 abc	115.61 ab
G: Formula G, one application, 100% dose	0.76 a	100.94 a
H: Formula G, one application, 75% dose	1.08 abc	114.22 ab
I: Formula G, one application, 50% dose	1.15 abc	103.79 a
J: Formula G, two applications, 100% dose	0.96 abc	102.11 a
K: Formula G, two applications, 75% dose	0.83 ab	104.18 ab
L: Formula G, two applications, 50% dose	0.98 abc	105.78 ab
M: Conventional NPK, 100% dose	1.17 abc	117.45 ab
N: Conventional NPK, 75% dose	1.23 bc	119.11 ab
O: Conventional NPK, 50% dose	1.11 abc	115.34 ab

Note: Mean values followed by the same letter within the same column are not significantly different according to Duncan's Multiple Range Test at $p < 0.05$.

Flower Quality: Vitamin B3 and Vitamin K. Fertilizer treatment also affected vitamin B3 and vitamin K contents in broccoli flowers. The highest vitamin B3 content was observed in Formula C applied once at 75% dose, with 1.31 g 100 g^{-1}. The same treatment also produced the highest vitamin K content, reaching 125.05 µg 100 g^{-1}. In contrast, Formula G, applied at 100%, produced the highest flower yield but had lower vitamin B3 and vitamin K contents, at 0.76 g 100 g^{-1} and 100.94 µg 100 g^{-1}, respectively. This finding suggests a trade-off between biomass production and nutrient concentration, commonly referred to as the dilution effect, in which rapid plant growth can reduce the concentration of certain nutrients and bioactive compounds in plant tissues (Jarrell & Beverly, 1981). Similar observations have been reported in vegetable crops, where increased biomass production was not always accompanied by proportional increases in vitamin concentration (Davis et al., 2004).

The enhanced vitamin content observed under Formula C may also be associated with improved nutrient uptake and metabolic activity promoted by *Bacillus* spp. Plant growth-promoting *Bacillus* are known to increase nutrient availability, stimulate phytohormone production, and enhance plant physiological processes that contribute to the synthesis of secondary metabolites and vitamins (Backer et al., 2018). Furthermore, broccoli is recognized as an important dietary source of vitamin K and B-complex vitamins, and their accumulation is influenced by nutrient management practices and plant physiological status during growth (Singh et al., 2007).

The results suggest a possible trade-off between yield and certain quality attributes. Formula G was more effective in increasing flower biomass and diameter, while Formula C, at 75% with one application, appeared more favourable for vitamin accumulation. Therefore, the selection of a fertilizer treatment may depend on the production objective, whether yield quantity or nutritional quality.

Conclusion

The application of Bacillus-coated NPK fertilizer Formula C (0.4% Bacillus consortium + 0.2% zeolite) and Formula G (0.2% Bacillus consortium + 0.4% zeolite) improved vegetative growth and bacterial population compared with conventional NPK fertilizer. Formula G applied once at 100% produced the highest flower weight and diameter, while Formula C applied once at 75% resulted in the highest vitamin B3 and vitamin K contents. The coated NPK fertilizer was able to maintain shoot N, P, and K concentrations comparable to conventional NPK and showed potential to partially or fully replace conventional NPK fertilizer in broccoli cultivation

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