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Research Article

Integration of *Paenibacillus alvei* AK6SR into Compost-Plus Growing Media Improves Shallot (*Allium cepa* L.) Growth Performance

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ABSTRACT

Compost is widely used as an organic soil amendment, however most commercial compost products are not enriched with functional microorganisms. This study aimed to develop a Compost-Plus formulation inoculated with Paenibacillus alvei AK6SR, a bacterium with phosphate-solubilizing ability, nitrogen-fixation potential, and indole compound production, and to evaluate its effects on the growth and yield of shallot (Allium cepa L.). The Compost-Plus formulation consisted of 90% compost, 10% tapioca flour, and 20% water. A completely randomized design was applied with five treatments: K0 (without compost), K1 (5% Compost-Plus), K2 (10% Compost-Plus), K3 (15% Compost-Plus), and K4 (20% Compost-Plus), based on 8 kg of soil per experimental unit, with five replications. Bacterial viability and moisture content were measured over a two-month period. Shallot growth parameters observed included plant height, number of bulb tillers, and bulb dry weight. The Compost-Plus formulation effectively maintained and increased the viability of P. alvei AK6SR during eight weeks of storage, reaching 13.41 log CFU mL $^{-1}$ with a moisture content of 55.02 ± 0.97%. Application of 10% Compost Plus resulted in optimal shallot performance, with a plant height of 34.72 cm, 10.6 tillers per clump, and bulb dry weight of 20.6 g. These findings demonstrate the potential of P. alvei enriched Compost Plus as a functional organic amendment for sustainable crop production.

Keywords: biofertilizer, Compost plus, Paenibacillus alvei AK6SR, plant growth-promoting bacteria, shallot

ABSTRAK

Kompos banyak digunakan sebagai amelioran tanah organik, namun sebagian besar produk kompos komersial belum diperkaya dengan mikroorganisme fungsional. Penelitian ini bertujuan untuk mengembangkan formulasi Compost Plus yang diinokulasi dengan Paenibacillus alvei AK6SR, yaitu bakteri yang memiliki kemampuan melarutkan fosfat, potensi fiksasi nitrogen, serta memproduksi senyawa indol, serta mengevaluasi pengaruhnya terhadap pertumbuhan dan hasil tanaman bawang merah (Allium cepa L.). Formulasi Compost Plus terdiri atas 90% kompos, 10% tepung tapioka, dan 20% air. Percobaan disusun menggunakan Rancangan Acak Lengkap dengan lima perlakuan, yaitu K0 (tanpa kompos), K1 (5% Compost Plus), K2 (10% Compost Plus), K3 (15% Compost Plus), dan K4 (20% Compost Plus), berdasarkan bobot tanah 8 kg per satuan percobaan, dengan lima ulangan. Viabilitas bakteri dan kadar air diukur selama dua bulan. Parameter pertumbuhan tanaman bawang merah diamati yaitu tinggi tanaman, jumlah anakan umbi dan berat kering umbi. Formulasi Compost Plus mampu mempertahankan dan meningkatkan viabilitas P. alvei AK6SR selama delapan minggu penyimpanan, dengan viabilitas mencapai 13,41 log CFU mL $^{-1}$ dan kadar air kompos sebesar 55,02 ± 0,97%. Pemberian 10% Compost Plus menghasilkan pertumbuhan bawang merah yang optimal, dengan tinggi tanaman 34,72 cm, jumlah anakan rata-rata 10,6 per rumpun, serta bobot umbi kering angin sebesar 20,6 g. Hasil penelitian ini menunjukkan bahwa Compost Plus yang diperkaya P. alvei AK6SR berpotensi sebagai amelioran organik fungsional untuk mendukung produksi tanaman yang berkelanjutan.

Keywords: *bakteri pemacu pertumbuhan tanaman, bawang merah, Compost Plus, Paenibacillus alvei AK6SR, pupuk hayati,*

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1. Introduction

Growing media play a fundamental role in determining crop growth and productivity, as their physical, chemical, and biological properties directly influence root activity and plant growth responses (Li et al., 2024). In solid-based cultivation systems, soil remains the primary growing medium, with its suitability largely dependent on soil type and fertility status. Ultisols (red yellow podzolic soils), which are widely distributed in tropical regions, are extensively used for horticultural production. However, their agricultural potential is often constrained by low pH, low organic matter content, high nutrient leaching, and elevated aluminum and iron concentrations, resulting in limited nutrient availability particularly phosphorus under acidic conditions (Idwar et al., 2025).

Improving the productivity of Ultisols requires integrated soil management strategies that enhance soil quality while reducing dependence on chemical inputs. Compost application has been widely recognized as an effective approach to improve soil structure, increase organic matter content, and promote gradual nutrient release (Oyebiyi et al., 2026). Nevertheless, most commercially available compost products are not enriched with functional microorganisms, limiting their capacity to enhance soil biological activity and nutrient cycling. Recent advances in agricultural microbiology have demonstrated that functional microbes, including phosphate-solubilizing and nitrogen-fixing bacteria, can enhance nutrient availability and promote plant growth, particularly in acidic soils where phosphorus immobilization by aluminum and iron is prevalent (Silva et al., 2023; Timofeeva et al., 2023).

The integration of functional microorganisms into compost-based amendments represents a promising strategy for developing multifunctional growing media. Among these, *Paenibacillus* spp. have been widely reported to exhibit plant growth-promoting traits, including phosphate solubilization, nitrogen fixation, and phytohormone production (Liu et al., 2019). *Paenibacillus alvei* AK6SR is a functionally characterized strain with such properties (Purwaningsih et al., 2023). However, information regarding its viability during storage when formulated within compost matrices and its effectiveness when applied to Ultisol-based growing media remains limited. Ensuring microbial survival during storage is a critical factor determining the effectiveness of biofertilizer-based products under field conditions (Kanishka et al., 2025).

Shallot (*Allium cepa* L.) is a high-value horticultural crop with consistent demand and significant economic importance in many regions. Productivity of shallot is highly sensitive to soil fertility and nutrient availability, particularly phosphorus, during early growth stages (Hartono et al., 2024). Given the widespread use of microbe-enriched composts, a critical gap remains in understanding how the viability of specific functional bacterial strains during storage influences their agronomic effectiveness after application, particularly in marginal soils such as Ultisols. To address this gap, the present study developed a Compost Plus prototype enriched with *Paenibacillus alvei* AK6SR, systematically evaluated bacterial viability during storage, and assessed its effects on the growth and yield of shallot cultivated on Ultisol soil. This integrated approach provides application-oriented evidence that supports the development of more reliable and biologically effective compost based amendments for sustainable shallot production.

2. Method

2.1. Isolate Selection

The isolate exhibiting the highest cell viability was subsequently selected for the formulation of Compost Plus. To obtain the highest bacterial cell viability, four plant growth-promoting rhizobacteria (PGPR) isolates from the culture collection of Dr. Purwaningsih (1=*Paenibacillus alvei* AP6SR, 2=*Paenibacillus alvei* AP4SR, 3=B*acillus cereus* RH8SR, 4=*Bacillus cereus* RH10SR) were cultivated in Tryptic Soy Broth (TSB) and incubated in a shaker incubator at 150 rpm for 48 and 72 h at room temperature (Purwaningsih et al., 2023). Cell viability after 48 and 72 h of incubation was determined using the total plate count (TPC) method.

2.2. Formulation of the "Compost Plus" and cell viability after storage

Based on preliminary tests, the Compost Plus formulation consisted of 90% compost, 10% tapioca flour, and 20% water. The compost was finely ground using a dry blender and mixed with 10% (w/w) tapioca flour as a binder. The mixture was then sprayed with water at 20% (v/w), molded, and air-dried at 36 °C for 2 days until the moisture content reached <10%. This formulation was subsequently used for Compost Plus production. Compost Plus was produced at a larger scale for (i) evaluation of cell viability during storage and (ii) plant application. During production, water was replaced with Tryptic Soy Broth (TSB) containing bacterial cultures. The resulting product was not dried. Compost samples for viability testing were packed in aluminum foil, sealed, and stored under airtight conditions. Bacterial viability were monitored monthly for a period of up to eight weeks. Moisture content was measured after eight weeks of storage. Cell viability after storage was determined using the total plate count (TPC) method. The ability of bacteria to attach to the compost matrix during a two-month storage period was evaluated using scanning electron microscopy (SEM).

2.2. Greenhouse Evaluation of the "Compost Plus" on Shallot (*Allium cepa* L.)

The application of Compost Plus to shallot (*Allium cepa* L.) was conducted under greenhouse conditions. The soil used in this study was Podzolic Red Yellow soil (PMK), with 8 kg of soil placed in each polybag. The experiment was arranged in a completely randomized design with five replications. The treatments consisted of Compost Plus formulations applied at four dosage levels: K0 = 0% Compost Plus, K1 = 5% Compost Plus, K2 = 10% Compost Plus, K3 = 15% Compost Plus, and K4 = 20% Compost Plus. Plant growth parameters of shallot (*Allium cepa* L.), including plant height, number of tillers, and bulb dry weight, were recorded.

3. Result

3.1. Selection of Isolates and Incubation Duration for Maximum Viability

Four plant growth–promoting rhizobacteria (PGPR) isolates were cultivated in Tryptic Soy Broth (TSB) for 48 and 72 h. Cell viability at each incubation period was determined using the total plate count (TPC) method. The TPC results are presented in Table 1. Among the four isolates, Isolate 1 exhibited the highest cell density compared with the other isolates and was therefore selected for Compost Plus production. Isolate 1 was identified as *Paenibacillus alvei* AK6SR. The highest cell viability was obtained after 72 h of incubation in a shaker incubator; consequently, bacterial inoculum preparation for the Compost Plus formulation was conducted using *P. alvei* AK6SR incubated for 72 h. The Compost Plus formulation supplemented with *P. alvei* AK6SR culture is shown in Fig 1.

Table 1. Cell viability after 48 h and 72 h incubation in a shaker incubator at 150 rpm

Isolate*	Cell Viability (CFU/mL)	
	48 h	72 h
1	87×10^{10}	62×10^{11}
2	30×10^{9}	67×10^{10}
3	78×10^{9}	54×10^{10}
4	60×10^{8}	45×10^{11}

*1=*Paenibacillus alvei* AP6SR, 2=*Paenibacillus alvei* AP4SR, 3=B*acillus cereus* RH8SR, 4=*Bacillus cereus* RH10SR

Figure 1. Compost Plus: compost enriched with *Paenibacillus alvei* AK6SR

3.2. Cell Viability after Storage

The results of the cell viability assessment during eight weeks of storage are presented in Fig 2. Isolate 1 (*Paenibacillus alvei* AK6SR) exhibited a progressive increase in cell viability throughout the storage period, reaching its highest level at week eight. Cell viability at week 0 was 12.70 log CFU mL^{-1}, while after eight weeks of storage it increased by 5.8% to 13.41 log CFU mL^{-1}. These results indicate that the compost matrix provided a suitable substrate to support the survival and continued growth of *P. alvei* AK6SR during storage.

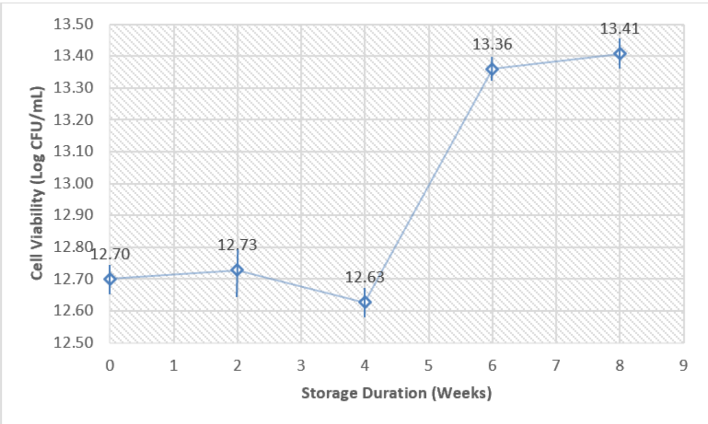

Figure 2. Cell viability curve of *Paenibacillus alvei* AK6SR in compost during eight weeks of storage

SEM analysis (Fig. 3) showed the presence of rod-shaped *Paenibacillus alvei* AK6SR cells attached to the compost substrate at 10,000× magnification. The average moisture content of Compost Plus during eight weeks of storage was 55.02 ± 0.97% (Table 2).

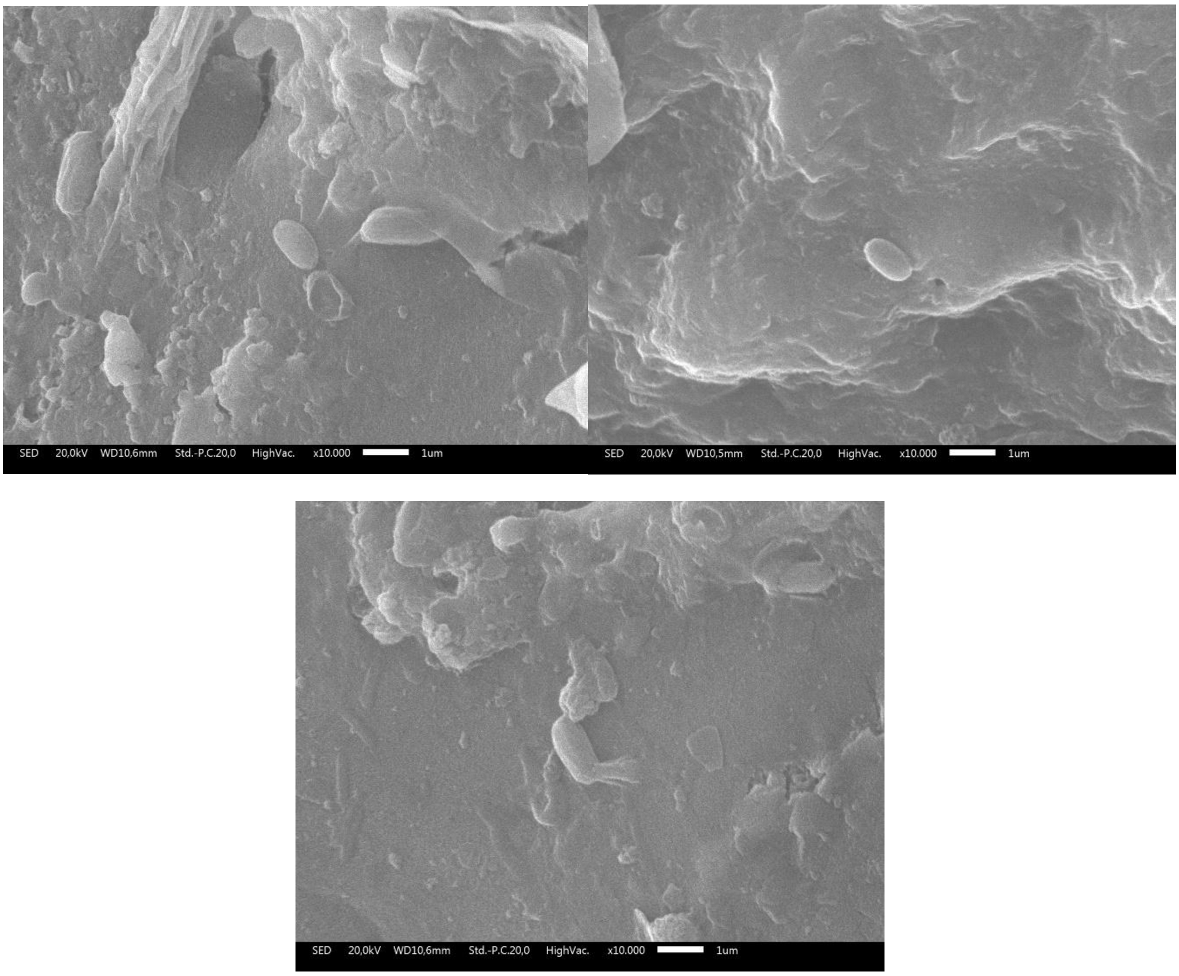

Figure 3. Scanning electron micrograph of Compost Plus supplemented with *Paenibacillus alvei* AK6SR at 10,000× magnification.

Table 2. Moisture content of Compost Plus during eight weeks of storage.

Parameter	Value (%)
Moisture content	55.02 ± 0.97

3.3. Greenhouse Evaluation of the "Compost Plus" on Shallot (*Allium cepa* L.)

Application of compost significantly affected the growth and yield of shallot. Results of the honestly significant difference (HSD) test (Table 3) indicated that Compost Plus application significantly increased plant height and bulb dry weight (HSD test, $p \leq 0.05$). In addition, Compost Plus applied at rates of 10% and 15% significantly enhanced the number of tillers per clump compared with the control (Table 3; Fig. 4). Application of 10% Compost Plus resulted in optimal shallot performance, with a plant height of 34.72 cm, 10.6 tillers per clump, and bulb dry weight of 20.6 g.

Table 3. Effect of Compost Plus on the Growth and Yield of Shallot (*Allium cepa* L.)

Treatment	Plant Height (cm)	Number of Tillers per Clump (unit/plant))	Bulb Dry Weight (g)
0% Compost Plus	11,6[a]	7,2[a]	6,4[a]
5% Compost Plus	25,0[ab]	8,0[a]	14,2[b]
10% Compost Plus	34,72[b]	10,6[b]	20,6[b]
15% Compost Plus	26,0[ab]	10,5[b]	17,43[b]
20% Compost Plus	20,4[ab]	8,42[a]	12,6[ab]

*Values followed by the same letter within the same column are not significantly different at the 5% HSD test level.

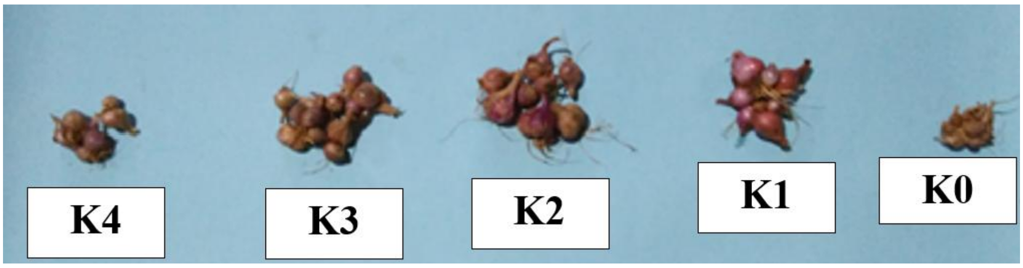

Figure 4. Comparison of Total Shallot Bulb Yield under Different Compost Plus Treatments. K0 (without compost), K1 (5% Compost-Plus), K2 (10% Compost-Plus), K3 (15% Compost-Plus), and K4 (20% Compost-Plus)

4. Discussion

The present study demonstrates that selection of an effective plant growth–promoting rhizobacteria (PGPR) strain and optimization of incubation conditions are essential steps in the development of microbial-based soil amendments. Among four isolates cultured in Tryptic Soy Broth (TSB), *Paenibacillus alvei* AK6SR (Isolate 1) consistently exhibited the highest cell density at both 48 and 72 h, with 72 h of agitated incubation yielding the greatest viable cell counts (Table 1). This finding aligns with established evidence that prolonged aerobic incubation under agitation enhances oxygen transfer and metabolic activity, thereby improving microbial biomass and viability prior to formulation (Pereira et al., 2024). Consequently, a 72-h incubation period was selected for inoculum preparation in the Compost Plus formulation (Fig. 1).

The viability of *P. alvei* AK6SR not only remained stable but progressively increased over eight weeks of storage within the compost matrix (Fig. 2), indicating that the organic carrier provided a supportive microhabitat for survival. Compost and other organic carriers are known to maintain moisture, nutrient availability, and physical protection, all of which contribute to sustained microbial viability over extended storage periods (Raju et al., 2025).

SEM imaging confirmed physical adherence of rod-shaped *P. alvei* cells to the compost substrate (Fig. 3), while the measured moisture content (55.02 ± 0.97%; Table 2) falls within ranges reported to support microbial persistence without significant desiccation stress.

The incorporation of *P. alvei* AK6SR into compost (Compost Plus) translated into measurable agronomic benefits when applied to shallot (*Allium cepa* L.). Compost Plus significantly increased plant height and bulb dry weight, and application rates of 10% and 15% notably enhanced tiller formation relative to the untreated control (Table 3; Fig. 4). These results are consistent with multiple reports demonstrating that PGPR strains can improve plant performance through enhanced nutrient availability and root development, particularly in soils with inherently low fertility, by mechanisms including nitrogen fixation, phosphate solubilization, and phytohormone production (Asriatno et al., 2023; Erdiandini et al., 2025; Ndlazi et al., 2026; Rio et al., 2024). The optimal shallot performance at 10% Compost Plus (plant height = 34.72 cm, 10.6 tillers per clump, bulb weight = 20.6 g) underscores the importance of balancing microbial input and organic carrier volume to optimize plant responses, as excessive organic amendment can lead to nutrient immobilization or physical impediments to root growth in some contexts (Oyebiyi et al., 2026).

Overall, the data illustrate that a well-selected and properly incubated PGPR strain integrated into an organic carrier can persist through storage and exert positive influences on crop growth. The sustained viability of *P. alvei* AK6SR and the agronomic benefits observed in shallot suggest that Compost Plus may serve as an effective soil amendment in systems that require both improved microbial function and organic matter enrichment. However, further investigation across soil types and environmental conditions is recommended to refine dosage recommendations and to elucidate underlying microbial–plant interactions under field conditions.

5. Conlusion

The present study confirms that *Paenibacillus alvei* AK6SR is a suitable functional inoculant for Compost Plus formulation, exhibiting high cell viability after 72 h of incubation and sustained survival during eight weeks of storage within the compost matrix. The carrier provided favorable physical conditions, as indicated by stable moisture content and effective bacterial attachment, supporting microbial persistence. Application of Compost

Plus significantly enhanced shallot growth and yield, with the 10% application rate producing optimal plant height, tiller number, and bulb dry weight. These results demonstrate that combining organic compost with a viable PGPR inoculum can improve microbial delivery efficiency and crop performance. Compost Plus enriched with *P. alvei* AK6SR therefore shows potential as a bio-based amendment for shallot cultivation, warranting further validation under field conditions.

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