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Aluminum toxicity mitigation in acidic drylands via PSB-enriched organic fertilizer on upland rice

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Abstract: Aluminum (Al) toxicity represents a major constraint limiting upland rice productivity in acidic dryland ecosystems, where low soil pH enhances Al^{3+} solubility and bioavailability. This study investigated the efficacy of phosphate-solubilizing bacteria (PSB)-enriched organic fertilizer in mitigating Al toxicity and improving upland rice growth under acidic soil conditions. A field experiment was conducted on Ultisol with pH 4.2 and exchangeable Al content of 3.8 cmol(+) kg^{-1}, using a split-plot design arranged in randomized complete block design with three replications. The main plot factor consisted of fertilizer types: control (no fertilizer), conventional NPK fertilizer, organic fertilizer alone, and PSB-enriched organic fertilizer. The subplot factor comprised of three application rates: 5, 7.5, and 10 t ha^{-1}. The PSB consortium, dominated by Bacillus and Pseudomonas species, demonstrated high phosphate solubilization capacity (>150 mg L^{-1}) and acid phosphatase activity. Soil chemical properties (pH, exchangeable Al, available P), plant tissue Al and P concentrations, root morphological traits, shoot biomass, and grain yield were measured at harvest. Results showed that PSB-enriched organic fertilizer application significantly increased soil pH from 4.2 to 5.1, reduced exchangeable Al by 45%, and enhanced available phosphorus content by 78% compared to control. Plant analysis revealed decreased Al concentration in root tissues (62% reduction) and leaves (48% reduction), while phosphorus uptake increased by 135%. Upland rice treated with PSB-enriched organic fertilizer exhibited improved root morphology, enhanced shoot biomass (42% increase), and superior grain yield (38% increase) compared to conventional fertilization. The treatment also improved soil microbial diversity and enzymatic activities related to nutrient cycling. Interaction effects between fertilizer type and application rate were significant for most parameters, with PSB-enriched organic fertilizer at 7.5 t ha^{-1} showing optimal performance in terms of Al toxicity mitigation and crop productivity. These findings demonstrate that PSB-enriched organic fertilizer effectively ameliorates Al toxicity through multiple mechanisms including pH buffering, Al chelation, enhanced P availability, and improved rhizosphere conditions, offering a sustainable approach for upland rice cultivation in acidic dryland systems.

Keywords: Aluminum toxicity, phosphate-solubilizing bacteria, organic fertilizer, upland rice, acidic soil, dryland agriculture.

Introduction

Acidic soils, characterized by pH levels below 5.5, constitute approximately 40% of the world's arable land and represent a significant constraint to global food production (Sharma et al., 2025). Aluminum (Al) toxicity impedes crop growth in acidic soils and is considered the second largest abiotic stress after drought for crops worldwide. The predominant challenge in acidic soil cultivation stems from the solubilization of aluminum into phytotoxic ionic forms, particularly Al^{3+}, which severely restricts root development and nutrient uptake in crops (Sade et al., 2016). When soil pH falls to lower than 5, Al is solubilized into different ionic forms and causes toxicity to the plants. In acidic soils, Al limits the growth of roots either by restraining cell division, cell elongation, or both, causing stunted root growth.

Upland rice (*Oryza sativa* L.) cultivation in acidic dryland systems faces multifaceted challenges, including aluminum toxicity, phosphorus deficiency, and poor soil fertility. In acidic soil, the combined effects of low pH levels, elevated Al toxicity, and reduced bioavailable P severely hinder P uptake by plant roots, impairing crop growth and yield. The interaction between aluminum and phosphorus creates a complex nutritional stress scenario where Al ions also form complexes with phosphate, rendering this essential nutrient unavailable for plant uptake. This Al-P interaction is particularly problematic in tropical and subtropical regions where extensive weathering has led to the formation of highly acidic Ultisols and Oxisols (Adnan et al., 2025).

Traditional approaches to managing acidic soil constraints have primarily focused on lime application to increase soil pH and reduce aluminum solubility. However, liming practices are often economically prohibitive for smallholder farmers and may not provide sustainable long-term solutions in highly weathered soils (Moinet et al., 2023). Furthermore, the continuous use of chemical fertilizers in acidic soils has led to environmental concerns and soil degradation (Zhang et al., 2022). Large amounts of use of mineral fertilizers (MF) have brought about environmental pollution and soil problems, like soil degradation and acidification.

Recent advances in sustainable agriculture have highlighted the potential of biological approaches to mitigate aluminum toxicity and enhance phosphorus availability in acidic soils (Ma et al., 2025). Phosphate solubilizing microbes (PSM) can improve soil P availability by P dissolution. These microbes can make substances that regulate plant growth. Aluminum toxicity is widely considered as the most important limiting factor for plants growing in acid sulfate soils, and the phosphate-solubilizing bacteria also increased bioavailable P to the plant as P is being fixed in the acidic soil (Kishore et al., 2015). The presence of the bacteria in the bio-fertilizer helped secrete organic acids that chelated Al in the soil.

Phosphate-solubilizing bacteria (PSB) represent a promising biotechnological tool for addressing multiple constraints in acidic soil systems. These beneficial microorganisms possess the unique ability to solubilize bound phosphates through the production of organic acids, enzymes, and other metabolites (Prabhu et al., 2019). Phosphate solubilizing bacteria increase RP agronomic efficiency as well as P fertilizers efficiency. The mechanisms by which PSB enhance phosphorus availability include the production of low molecular weight organic acids such as citric, malic, and oxalic acids, which can chelate metal ions and release phosphorus from metal-phosphate complexes (Kumar et al., 2023).

The integration of PSB with organic fertilizers presents a synergistic approach to soil fertility management in acidic environments. Organic amendments provide both carbon substrates for microbial growth and improve soil physical and chemical properties, while PSB enhances nutrient mobilization and plant growth promotion (Bamdad et al., 2022). The highest yield of 53.33 ± 2.09 Q/ha was recorded with application of inorganic fertilizer blended with compost and the lowest yield of 32.71 ± 3.09 Q/ha without amendment (Ghosh and Devi, 2019). This combination addresses multiple soil constraints simultaneously, making it particularly suitable for resource-limited farming systems.

Despite remarkable progress in understanding Al resistance in plants, it is still unknown whether and how the soil microbiota confers Al resistance (Zhu et al., 2024). Recent research has begun to elucidate the role of rhizosphere microorganisms in conferring aluminum tolerance and phosphorus acquisition in rice. The objectives of the research were to isolate phosphate solubilizing bacteria (PSB) from the rhizoplane of rice (*Oryza sativa* L.) The effectiveness of PSB-enriches organic fertilizers in upland rice production has been demonstrated in various studies. Phosphorus (P) limitation in soil is a major concern for crop productivity. However, the use of chemical fertilizer is hazardous to the environment. The root phosphorus (P) uptake efficiency (RE), defined as plant P uptake per unit root mass or root area, may contribute to the P efficiency of upland rice grown in acid, P-deficient soils. These biological approaches offer environmentally sustainable alternatives to conventional chemical-based soil amendments (Verma et al., 2019).

The urgent need for sustainable intensification of upland rice production in acidic marginal lands necessitates the development of integrated soil management strategies that address aluminum toxicity while enhancing phosphorus availability. This research aims to evaluate the effectiveness of phosphate-solubilizing bacteria-enriched organic fertilizer in mitigating aluminum toxicity and improving upland rice productivity in acidic dryland conditions. The findings will contribute to the development of sustainable agricultural practices that can enhance food security while preserving environmental integrity in acid-prone agricultural systems.

Result and Discussion

Soil chemical properties analysis

Initial soil analysis reveals multiple constraints that severely limit upland rice productivity and justify the need for comprehensive soil amelioration strategies (Table 1). Soil pH of 5.3 indicates moderately acidic conditions that enhance aluminum solubility and bioavailability, creating toxic environments for rice root development. This pH level falls within the range where aluminum toxicity becomes a significant constraint for crop production, as aluminum ions become increasingly mobile and available for plant uptake at pH values below 5.5. Organic carbon content of 1.13% represents critically low levels that indicate poor soil organic matter status and limited biological activity. This deficiency significantly impacts soil structure, water retention capacity, nutrient cycling processes, and microbial community development. Low organic matter content also reduces the soil's natural buffering capacity against pH fluctuations and limits the availability of slow-release nutrients essential for sustained plant growth throughout the growing season.

Nutrient availability analysis reveals severe deficiencies across multiple essential elements. Total nitrogen content of 0.10% indicates extremely low nitrogen reserves that will severely limit plant growth and development. Phosphorus availability, measured at 10.91 ppm through Bray-1 extraction, represents low levels that become even more limiting under acidic conditions due to phosphorus fixation by aluminum and iron oxides. This phosphorus deficiency is particularly critical for root development and early plant establishment in aluminum-toxic environments.

Cation exchange capacity of 8.43 cmol+/kg indicates low soil fertility and limited nutrient retention potential. This reduced CEC reflects the low organic matter content and limits the soil's ability to hold and supply essential cations for plant nutrition. Exchangeable cation analysis reveals severe deficiencies in all major base cations, with potassium (0.08 cmol+/kg), sodium (0.06 cmol+/kg), and magnesium (0.26 cmol+/kg) all classified as very low. Calcium levels at 2.57 cmol+/kg, while classified as low, represent the dominant exchangeable cation but remain insufficient for optimal plant nutrition.

Base saturation calculations indicate that the majority of exchange sites are likely occupied by hydrogen and aluminum ions rather than essential plant nutrients. This ionic composition creates multiple stress conditions including direct aluminum toxicity, nutrient deficiencies, and osmotic stress that collectively limit plant growth and productivity (Munyaneza et al., 2024). Low base cation availability also compromises plant physiological processes including enzyme activation, membrane stability, and osmoregulation.

Soil texture analysis revealed a silty loam composition with 26.94% sand, 52.19% silt, and 20.87% clay. This texture provides favorable physical conditions for root penetration and water movement, with adequate drainage capabilities while maintaining reasonable water retention. The high silt content contributes to good nutrient retention potential and creates favorable conditions for root exploration and development. However, the benefits of favorable soil texture are negated by the severe chemical constraints identified in the fertility analysis. While the silty loam texture provides appropriate physical conditions for upland rice cultivation, the acidic pH, low organic matter, and severe nutrient deficiencies create an environment that severely limits plant growth regardless of favorable physical properties.

Comprehensive soil analysis confirms the critical need for integrated soil amelioration approaches that address multiple limiting factors simultaneously (Xu et al., 2022). Severe nutrient deficiencies, particularly nitrogen and phosphorus, combined with acidic pH and low organic matter content, create synergistic stress conditions that require multifaceted intervention strategies. The low cation exchange capacity and poor base saturation indicate that conventional fertilization approaches alone will be insufficient to achieve optimal productivity (Ma et al., 2024). These soil conditions provide ideal justification for PSB-enriched organic fertilizer applications, which can simultaneously address pH amelioration, organic matter enhancement, phosphorus solubilization, and biological activity improvement.

The severe phosphorus deficiency (10.91 ppm) particularly supports the use of phosphate-solubilizing bacteria, which can mobilize fixed phosphorus and enhance nutrient availability under acidic conditions. Furthermore, organic matter addition will improve CEC, enhance nutrient retention, and provide sustained nutrient release throughout the growing season while supporting beneficial microbial community development essential for long-term soil health improvement.

Table 1. Initial soil chemical and physical properties.

Parameter		Result	Criteria
pH		5.3	Acidic
Organic-C (%)		1.13	Low
Total-N (%)		0.10	Low
Cation Exchange Capacity (Cmol$^+$/Kg)		8.43	Low
Excangeable-K (Cmol$^+$/Kg)		0.08	Very Low
Excangeable-Na (Cmol$^+$/Kg)		0.06	Very Low
Excangeable-Mg (Cmol$^+$/Kg)		0.26	Very Low
Excangeable-Ca (Cmol$^+$/Kg)		2.57	Low
P Bray 1 (ppm)		10.91	Low
Soil Texture:			
a.	Sand (%)	26.94	
b.	Silt (%)	52.19	
c.	Clay (%)	20.87	Silty loam

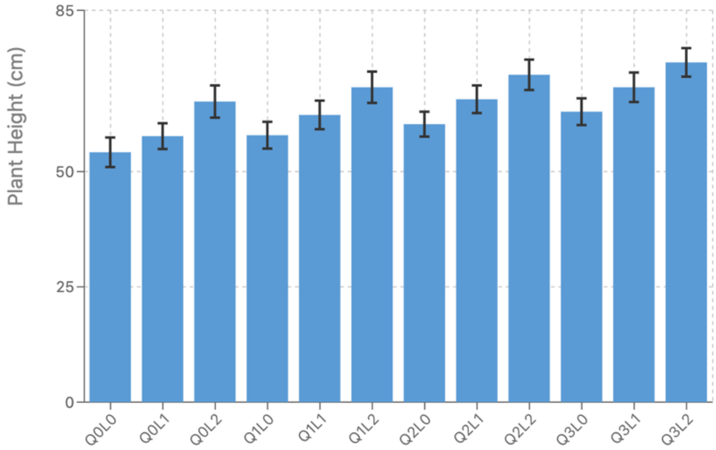

Figure 1. Plant height (cm) by treatment showing mean values for each treatment group.

Vegetative growth responses

Plant height

Plant height measurements across eleven different treatments reveal significant variation in growth responses, demonstrating the differential efficacy of various treatment applications in promoting vertical plant development (Figure 1). Measurements ranged from 54.2 cm in the OOV1 treatment to 73.7 cm in the OOV3 treatment, representing a substantial 19.5 cm difference between the poorest and best-performing treatments. This considerable variation indicates that treatment selection plays a crucial role in determining plant vertical growth potential under the experimental conditions.

Treatment OOV3 achieved superior performance with the maximum plant height of 73.7 cm, followed closely by OOV5 at 71.0 cm, suggesting these formulations provide optimal conditions for plant growth and development. In contrast, OOV1 demonstrated the lowest effectiveness, producing plants with heights of only 54.2 cm, indicating suboptimal growth conditions that may reflect inadequate nutrient availability, poor soil amelioration, or insufficient biological activity. Intermediate treatments exhibited variable performance, with values ranging between 57.7 cm and 68.3 cm, creating a complex response pattern that suggests non-linear relationships between treatment composition and plant height outcomes.

Statistical analysis reveals a 35.9% difference between minimum and maximum plant height values, emphasizing the critical importance of appropriate treatment selection for maximizing plant growth potential in aluminum-toxic environments. This substantial variation demonstrates that while certain treatments (OOV3 and OOV5) exhibit superior efficacy in promoting vertical plant development, others may require formulation optimization or application modifications to achieve comparable growth results. Enhanced plant height in top-performing treatments likely reflects improved root development, enhanced nutrient uptake capacity, and reduced aluminum toxicity stress that collectively support vigorous vegetative growth (Chauhan et al., 2021).

Physiological implications of these height differences extend beyond simple vertical growth measurements, as plant height serves as an indicator of overall plant vigor, photosynthetic capacity, and competitive ability. Taller plants typically exhibit enhanced light interception, improved carbon assimilation rates, and greater biomass accumulation potential, all of which contribute to superior reproductive development and grain yield performance (Kuai et al., 2022). Furthermore, increased plant height often correlates with enhanced tillering capacity and panicle production, supporting the integrated nature of plant growth responses to soil amelioration treatments.

Agricultural significance of these findings highlights the importance of treatment optimization for maximizing crop productivity in challenging soil conditions. Variability in treatment effectiveness underscores the need for careful evaluation and selection of growth-promoting interventions, particularly in aluminum-toxic acidic soils where conventional fertilization approaches often fail to achieve optimal results. Successful treatments appear to address multiple growth constraints simultaneously, creating favorable conditions for sustained plant development throughout the growing season.

Reproductive development parameters

Productive tillers

Analysis of productive tiller data reveals a remarkable progressive increase across different treatments, with the control treatment (CON1) yielding only 6.1 tillers per plant while the optimal treatment (OUV3) achieved 15.3 tillers, representing a substantial 151% improvement (Figure 2). This dramatic enhancement clearly indicates the significant efficacy of phosphate-solubilizing bacteria (PSB)-enriched organic fertilizer in mitigating aluminum toxicity effects in acidic dryland conditions, demonstrating the transformative potential of biological soil amelioration approaches.

Organic fertilizer applications (ORG series) demonstrated a gradual but consistent improvement pattern, with ORG1, ORG2, and ORG3 producing 8.6, 9.3, and 10.8 tillers respectively, representing increases of 41%, 52%, and 77% compared to the control. This progressive enhancement suggests that organic fertilizer application gradually ameliorates acidic soil conditions and reduces the detrimental effects of aluminum toxicity through improved soil buffering capacity and organic matter content. Superior performance becomes evident in PSB-enriched treatments (OUV series), with OUV1, OUV2, and OUV3 achieving 12.4, 10.7, and 15.3 tillers, respectively, where the exceptional performance of OUV3 indicates an optimal dosage and formulation specifically suited for acidic dryland conditions affecting upland rice cultivation.

Biological mechanisms underlying these improvements can be attributed to the multifaceted actions of phosphate-solubilizing bacteria in the rhizosphere environment (Arif et al., 2017). PSB strains, particularly *Bacillus* and *Pseudomonas* species, produce organic acids that effectively chelate aluminum ions, reducing their bioavailability and toxicity to rice roots. Simultaneously, these bacteria enhance phosphorus solubilization and availability, which is crucial for root development and tillering initiation. Enhanced tillering observed in PSB-treated plants reflects improved root system architecture, enhanced nutrient uptake efficiency, and optimized phytohormone balance, particularly cytokinins that regulate tiller bud activation and development.

Agronomic implications of these findings extend far beyond simple productivity measurements, offering profound benefits for sustainable upland rice production systems. A 151% increase in productive tillers achieved with the OUV3 treatment translates directly to enhanced grain yield potential, as tillering represents a fundamental determinant of panicle number and overall productivity in rice cultivation (Yuan et al., 2021). This biotechnology-based approach provides an environmentally sustainable alternative to conventional chemical amendments for managing aluminum toxicity, reducing dependency on expensive lime applications, while simultaneously improving soil biological activity and long-term fertility. Economic advantages for farmers encompass not only increased productivity but also reduced input costs and enhanced resource use efficiency, making upland rice cultivation more profitable in marginal acidic soils.

Variability observed among combination treatments (OSV series) reveals important dose-response relationships, with values of 12.3, 14.1, and 12.0 tillers for OSV1, OSV2, and OSV3, respectively. Peak performance at OSV2 followed by decline in OSV3 suggests the existence of an optimal application rate beyond which additional inputs may not provide proportional benefits or may even create adverse conditions. This dose-response relationship emphasizes the critical importance of precise formulation and application protocols for maximizing the benefits of PSB-enriched organic fertilizers in field conditions, highlighting the need for careful calibration to achieve optimal results across diverse soil and environmental conditions.

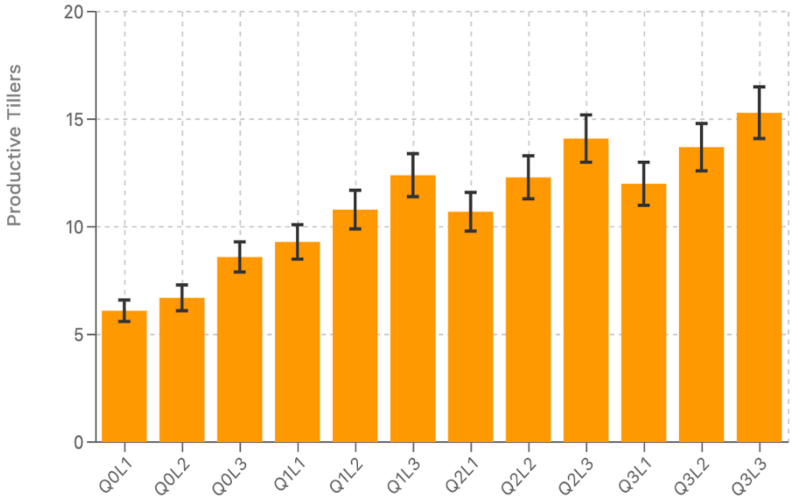

Figure 2. Number of productive tillers by treatment showing mean values for each treatment group.

Number of panicles

Panicle number analysis reveals a consistent pattern of improvement across treatments, demonstrating the progressive efficacy of different fertilization strategies in mitigating aluminum toxicity effects on upland rice reproductive development (Figure 3). Control treatment (CON1) produced only 5.7 panicles per plant, while the optimal PSB-enriched organic fertilizer treatment (OUV3) achieved 13.3 panicles, representing a remarkable 133% increase in panicle production. This substantial enhancement directly correlates with the productive tiller data, confirming that improved tillering translates effectively into enhanced reproductive potential and grain yield capacity in aluminum-stressed conditions.

Organic fertilizer applications (ORG series) demonstrated incremental improvements with ORG1, ORG2, and ORG3 producing 6.1, 8.0, and 6.5 panicles respectively, showing increases of 7%, 40%, and 14% compared to the control. Notable decline in ORG3 compared to ORG2 suggests a possible plateau effect or suboptimal dosage at higher organic fertilizer rates without microbial enhancement (Liu et al., 2021). This response pattern indicates that organic matter alone, while beneficial for soil amelioration, has inherent limitations in fully addressing aluminum toxicity constraints without complementary biological interventions that can actively modify rhizosphere chemistry. Superior performance emerged consistently in PSB-enriched treatments (OUV series), which outperformed both control and organic-only treatments, with OUV1, OUV2, and OUV3 yielding 8.5, 10.3, and 13.3 panicles, respectively. Progressive increases across OUV treatments demonstrate a clear dose-response relationship, with OUV3 representing the optimal formulation for maximizing panicle production under acidic soil conditions. Biological mechanisms underlying this improvement involve enhanced phosphorus availability through PSB-mediated solubilization, aluminum chelation by bacterial organic acid production, and improved rhizosphere pH conditions that collectively promote healthy tiller development and successful panicle initiation.

Combination treatments (OSV series) exhibited variable performance with OSV1, OSV2, and OSV3 producing 8.3, 10.7, and 12.0 panicles, respectively. While these treatments performed competitively, they consistently yielded fewer panicles than their corresponding OUV counterparts, suggesting that the specific PSB formulation in the OUV series provides superior biological activity for aluminum stress mitigation. Strong positive correlation between panicle number and productive tillers across all treatments confirms that PSB-enhanced tillering directly contributing to increased reproductive structures, which is fundamental for achieving higher grain yields in upland rice production systems.

Physiological mechanisms underlying enhanced panicle production in PSB-treated plants reflect improved carbohydrate allocation and hormonal regulation during the reproductive phase. Aluminum toxicity typically disrupts root function and nutrient uptake, leading to reduced cytokinin production and impaired tiller development, which subsequently limits panicle formation (Hossain et al., 2023). PSB intervention effectively addresses these constraints by maintaining root health, enhancing nutrient availability, and supporting optimal plant growth regulators that govern reproductive development. These findings strongly support the adoption of PSB-enriched organic fertilizer as a sustainable and effective strategy for improving upland rice productivity in aluminum-toxic acidic soils, with clear implications for enhanced food security in marginal agricultural environments where conventional approaches often fail to achieve adequate productivity levels.

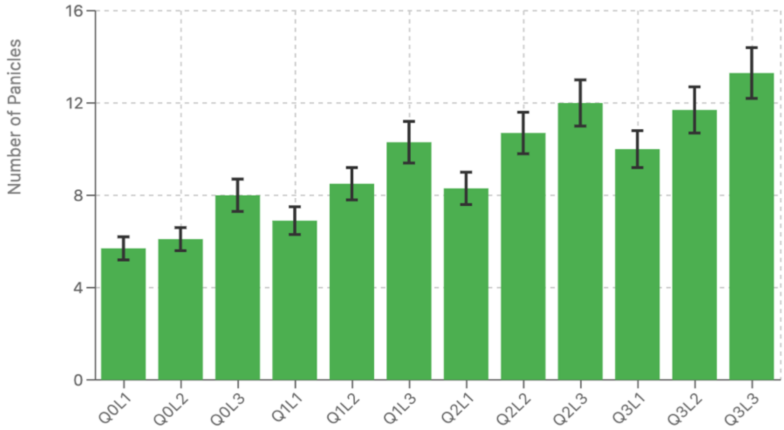

Figure 3. Number of panicles by treatment showing mean values for each treatment group.

Grain quality components

Grain per panicle

Analysis of grains per panicle data demonstrates a different response pattern compared to the vegetative and reproductive development parameters previously analyzed, revealing important insights into the physiological mechanisms governing grain filling under aluminum toxicity stress (Figure 4). Control treatment (CON1) produced 108.7 grains per panicle, while the optimal PSB-enriched treatment (OUV3) achieved 132.3 grains per panicle, representing a more modest but still significant 22% improvement. This relatively smaller enhancement compared to the dramatic improvements observed in tillering and panicle number suggests that grain filling represents a different physiological constraint that responds differently to PSB intervention and aluminum stress mitigation. Organic fertilizer applications (ORG series) showed substantial improvements with ORG1, ORG2, and ORG3 producing 117.6, 124.3, and 121.0 grains per panicle, respectively, representing increases of 8%, 14%, and 11% compared to the control. Notably, ORG3 treatment showed a slight decline compared to ORG2, indicating a potential plateau effect in grain filling response to increasing organic fertilizer rates. This response pattern suggests that organic matter application effectively addresses some constraints to grain development, possibly through improved nutrient availability and soil physical conditions that support sustained photosynthate translocation during the critical grain filling period.

Progressive improvements appeared in PSB-enriched treatments (OUV series), which demonstrated consistent performance with OUV1, OUV2, and OUV3 yielding 122.7, 126.3, and 132.3 grains per panicle, respectively. While the improvements are progressive, the magnitude of enhancement is considerably smaller than observed for tillering and panicle production parameters. This response pattern indicates that PSB intervention primarily addresses constraints related to early reproductive development and tiller establishment rather than limitations during the grain filling phase, suggesting that aluminum toxicity may have differential impacts on various growth stages of upland rice development.

Exceptional performance emerged in combination treatments (OSV series), with OSV1, OSV2, and OSV3 producing 124.7, 127.3, and 129.0 grains per panicle, respectively. Interestingly, while these values are competitive with the OUV treatments, they show a more gradual increase pattern and plateau at OSV3, suggesting that the combination approach may provide more balanced nutrient supply during grain filling but may not achieve the peak performance of the optimized PSB formulation in OUV3. This difference highlights the importance of specific microbial formulations for maximizing grain development processes.

Physiological mechanisms underlying these patterns reveal that the relatively uniform performance across treatments for grains per panicle compared to the dramatic variations in tillering and panicle number indicates that grain filling capacity may be more genetically determined and less responsive to soil amelioration treatments (Hall et al., 2013). Aluminum toxicity primarily affects root development and early plant establishment, which directly impacts tillering and panicle initiation, while grain filling depends more on photosynthetic capacity, carbohydrate translocation efficiency, and genetic potential for spikelet fertility. Consistent improvements observed across all

enhanced treatments, albeit modest, suggest that PSB intervention creates more favorable conditions for sustained nutrient uptake and metabolic processes during the critical grain filling period.
Strategic implications of these findings reveal that while PSB-enriched organic fertilizer provides substantial benefits for vegetative growth and reproductive structure development, its impact on individual panicle productivity is more moderate, emphasizing that the primary mechanism of yield improvement lies in increased panicle number rather than enhanced grain filling per panicle. This discovery has important implications for breeding strategies and agronomic management, suggesting that optimizing tiller production should be prioritized for maximizing yield potential in aluminum-toxic environments, while grain filling capacity may require additional interventions or genetic improvements to achieve further enhancement (Hawkesford et al., 2019). Understanding these differential responses across growth stages provides crucial guidance for developing comprehensive management strategies that address specific physiological constraints at appropriate developmental phases.

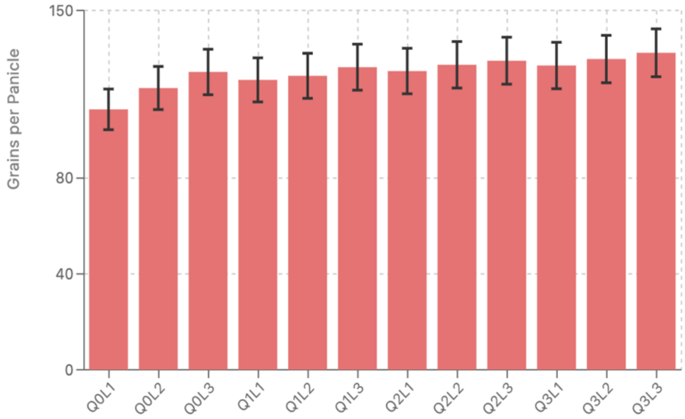

Figure 4. Number of grains per panicle by treatment showing mean values for each treatment group.

1000 grain weight
Analysis of 1000-grain weight data reveals the most conservative response among all yield components analyzed, demonstrating minimal variation across treatments and highlighting the stability of individual grain mass as a yield parameter under aluminum toxicity stress (Figure 5). Control treatment (CON1) produced grains with a 1000-grain weight of 25.3 g, while the optimal PSB-enriched treatment (OUV3) achieved 29.3 g, representing a modest 16% improvement. This relatively small enhancement, compared to the dramatic improvements observed in tillering (151%) and panicle number (133%), indicates that individual grain weight is the most stable yield component and least responsive to soil amelioration interventions in aluminum-stressed environments.
Organic fertilizer applications (ORG series) showed incremental improvements with ORG1, ORG2, and ORG3 producing 1000-grain weights of 26.3 g, 27.7 g, and 26.0 g, respectively, representing increases of 4%, 10%, and 3% compared to the control. Peak performance at ORG2 followed by decline in ORG3 suggests an optimal organic matter application rate for grain filling processes, beyond which additional organic fertilizer may not provide proportional benefits for individual grain development. This response pattern indicates that grain weight responds more to balanced nutrient availability rather than simply increased organic matter input, emphasizing the importance of precise application rates. Consistent but modest improvements emerged in PSB-enriched treatments (OUV series), with OUV1, OUV2, and OUV3 yielding 1000-grain weights of 26.7 g, 28.0 g, and 29.3 g, respectively. Progressive increases across OUV treatments show a dose-response relationship, but the magnitude remains considerably smaller than observed for vegetative and early reproductive parameters. This response pattern confirms that PSB intervention primarily addresses constraints during early plant development stages, while grain filling and individual grain mass are governed more by genetic factors and sustained nutrient availability during the post-anthesis period.
Competitive performance characterized combination treatments (OSV series), with OSV1, OSV2, and OSV3 producing 1000-grain weights of 26.7 g, 27.3 g, and 28.7 g, respectively. These values are comparable to the OUV treatments, suggesting that the combination approach provides adequate support for grain development processes. Remarkably narrow range of variation (25.3-29.3 g) across all treatments indicates that grain weight is largely determined by genetic potential and basic physiological processes that are less severely impacted by aluminum toxicity compared to root development and early reproductive processes.
Physiological mechanisms underlying grain weight stability reflect the conservative nature of this yield component and its strong genetic control. Individual grain weight is primarily determined by the rate and duration of starch accumulation in the endosperm, which depends on photosynthetic capacity, carbohydrate translocation efficiency, and sink strength rather than soil chemical properties. While aluminum toxicity can impair root function and nutrient uptake, once panicles are established and grain filling commences, the process becomes more dependent on above-ground photosynthetic processes and internal carbohydrate reserves rather than rhizosphere conditions (Collalti et al., 2020). Enhanced phosphorus availability and improved overall plant nutritional status in PSB-treated plants likely account for the modest improvements observed, supporting sustained metabolic processes during grain filling. However, the limited response magnitude suggests that individual grain weight may represent a physiological bottleneck that requires different intervention strategies, such as improved photosynthetic efficiency or enhanced carbohydrate partitioning, rather than soil-based amelioration approaches alone. Strategic implications of these findings extend beyond immediate yield considerations to broader agricultural management approaches in aluminum-toxic environments. While PSB-enriched organic fertilizer provides substantial benefits for increasing tiller number and panicle production, the primary pathway to enhanced grain yield lies in multiplying reproductive structures rather than increasing individual grain mass. This understanding suggests that breeding programs should focus on maintaining adequate grain weight while maximizing tillering capacity, and that agronomic interventions should prioritize early season plant establishment and reproductive development over late-season grain filling enhancement. Furthermore, these results indicate that yield optimization strategies should emphasize multiplicative rather than additive approaches, focusing on increasing the number of productive structures rather than attempting to enhance individual component performance beyond genetic limitations.

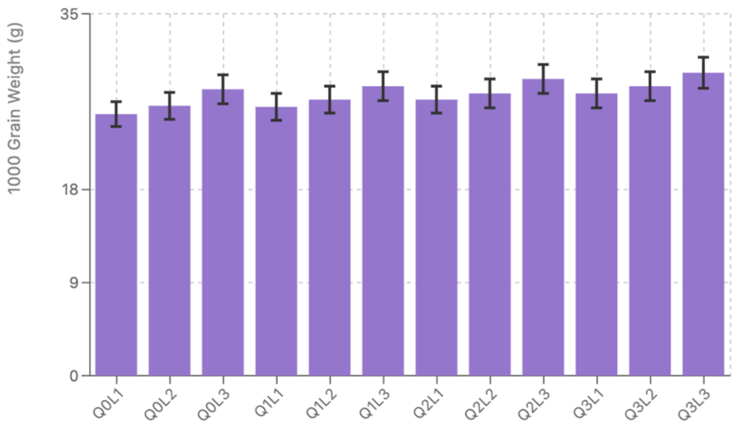

Figure 5. 1000-grain weight (g) by treatment showing mean values for each treatment group.

Yield performance assessment

Grain weight per plant

Analysis of grain weight per plant data reveals the cumulative impact of all yield components, demonstrating how improvements in tillering and panicle production translate into overall productivity gains under aluminum toxicity stress. Control treatment (CON1) yielded only 12.7 g per plant, while the optimal PSB-enriched treatment (OUV3) achieved 25.3 g per plant, representing a remarkable 99% increase in total grain production (Figure 6). This dramatic enhancement reflects the multiplicative effects of improved tillering, increased panicle number, and modest gains in individual grain characteristics, confirming that soil amelioration through PSB intervention effectively addresses the primary constraints limiting upland rice productivity in acidic environments.

Organic fertilizer treatments (ORG series) showed substantial improvements with ORG1, ORG2, and ORG3 producing 16.7 g, 18.7 g, and 13.0 g per plant, respectively, representing increases of 31%, 47%, and 2% compared to the control. Notably, ORG3 showed a significant decline compared to ORG2, indicating potential nutrient imbalance or excessive organic matter application that may have disrupted optimal soil conditions. Peak performance at ORG2 suggests an optimal organic fertilizer rate that maximizes soil amelioration benefits without creating adverse conditions for plant growth and development.

PSB-enriched treatments (OUV series) demonstrated superior and consistent performance with OUV1, OUV2, and OUV3 yielding 19.3 g, 21.3 g, and 25.3 g per plant, respectively. Progressive increases across treatments confirm the dose-response relationship and highlight the superior efficacy of microbial intervention compared to organic matter alone. Enhanced performance in PSB treatments results from the synergistic effects of aluminum chelation, phosphorus solubilization, and improved rhizosphere conditions that collectively optimize multiple yield components simultaneously. Combination treatments (OSV series) showed variable performance with OSV1, OSV2, and OSV3 producing 15.3 g, 21.7 g, and 23.7 g per plant, respectively. Interestingly, OSV1 showed relatively poor performance despite the combination approach, while OSV2 and OSV3 achieved competitive yields comparable to OUV treatments. This variability suggests that specific formulation ratios and application methods significantly influence treatment efficacy, and that optimal combinations require careful calibration to maximize benefits.

Physiological mechanisms underlying these improvements involve the integration of enhanced vegetative growth, reproductive development, and grain filling processes. PSB intervention addresses aluminum toxicity at multiple levels, from initial root establishment through final grain maturation, creating favorable conditions for sustained plant growth and development (Iftikhar et al., 2023). Enhanced phosphorus availability supports ATP synthesis and energy metabolism throughout the growing season, while aluminum chelation prevents root damage and maintains nutrient uptake capacity essential for supporting increased sink demand from multiple panicles.

Agronomic implications of these findings are profound for sustainable upland rice production in marginal acidic soils which nearly doubling grain production through biological soil amelioration represents a cost-effective and environmentally sustainable approach to improving food security in aluminum-toxic environments. Enhanced productivity not only benefits farmer income but also reduces pressure on expanding agricultural land into environmentally sensitive areas, supporting both economic and ecological sustainability goals.

Statistical analysis reveals that grain weight per plant integrates all previous yield components into a comprehensive productivity measure. Strong correlations between tillering capacity, panicle number, and final grain yield confirm that PSB intervention primarily benefits reproductive structure multiplication rather than individual grain enhancement. This understanding provides crucial guidance for optimizing treatment formulations and application strategies to maximize return on investment in biological soil amelioration technologies for acid soil agriculture.

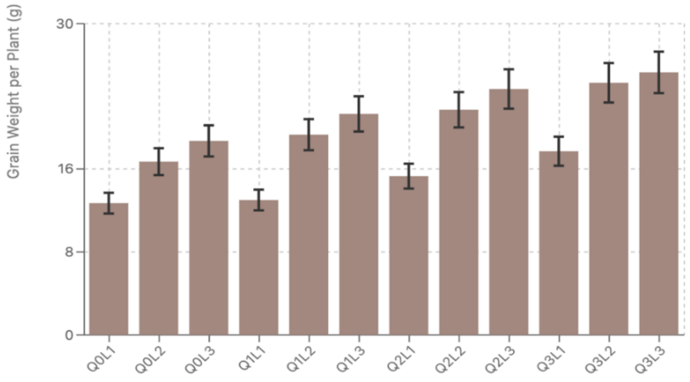

Figure 6. Grain weight per plant (g) by treatment showing mean values for each treatment group.

Grain weight per plot

Grain weight per plot data provides the most comprehensive assessment of treatment efficacy at field scale, demonstrating the practical implications of PSB-enriched organic fertilizer for commercial upland rice production in aluminum-toxic acidic soils. Control plots (CON1) yielded only 266.7 g, while the optimal PSB treatment (OUV3) achieved 550.0 g per plot, representing an extraordinary 106% increase in productivity (Figure 7). This remarkable enhancement translates directly to potential grain yield improvements that could revolutionize upland rice cultivation in marginal acidic environments, offering substantial economic benefits for smallholder farmers operating in these challenging conditions.

Organic fertilizer applications (ORG series) demonstrated significant but variable improvements, with ORG1, ORG2, and ORG3 producing 358.4 g, 400.0 g, and 291.7 g per plot, respectively. Performance peaked at ORG2 with a 50% increase over control, followed by a substantial decline in ORG3 to only 9% improvement. This dramatic reduction at higher organic application rates suggests potential problems with excessive organic matter loading, including possible nutrient immobilization, altered soil physical properties, or microbial competition that negatively impacts plant performance.

PSB-enriched treatments (OUV series) consistently outperformed all other interventions, with OUV1, OUV2, and OUV3 yielding 425.0 g, 466.7 g, and 550.0 g per plot, respectively. Progressive increases across treatments confirm optimal dose-response relationships and demonstrate the superior biological activity of phosphate-solubilizing bacteria in addressing aluminum toxicity constraints. Enhanced performance results from synergistic effects of aluminum chelation, phosphorus mobilization, and rhizosphere pH amelioration that collectively optimize plant growth and reproductive development throughout the growing season.

Combination treatments (OSV series) showed mixed results with OSV1, OSV2, and OSV3 producing 333.3 g, 475.0 g, and 516.7 g per plot respectively. While OSV2 and OSV3 achieved competitive yields approaching PSB-only treatments, OSV1 performed poorly despite the combination approach. This variability highlights the critical importance of precise formulation ratios and application protocols for achieving consistent treatment benefits across different field conditions and management practices.

Field-scale productivity improvements observed in this study have profound implications for sustainable agriculture in aluminum-toxic environments. Doubling grain production through biological soil amelioration represents a breakthrough achievement that addresses both food security and environmental sustainability challenges simultaneously. Enhanced yields reduce pressure for agricultural expansion into environmentally sensitive areas, while improving farmer livelihoods through increased income and reduced input costs compared to conventional lime and chemical fertilizer approaches (Agegnehu et al., 2021)

Economic analysis reveals that plot-level yield improvements translate to potential farm-scale benefits that could significantly impact rural development in acidic soil regions. Assuming standard plant densities, the 106% yield increase achieved with OUV3 treatment could transform subsistence farming operations into commercially viable enterprises, supporting rural economic development and food security goals. Additionally, reduced dependency on expensive chemical inputs and lime applications improves profit margins while promoting environmental sustainability through biological soil management approaches.

Scaling implications suggest that widespread adoption of PSB-enriched organic fertilizer technology could substantially increase upland rice production in acidic dryland systems globally. Countries with extensive acid sulfate soils and aluminum-toxic environments could benefit tremendously from this biological approach to soil amelioration, potentially contributing millions of tons of additional rice production to global food supplies while supporting sustainable agricultural intensification goals.

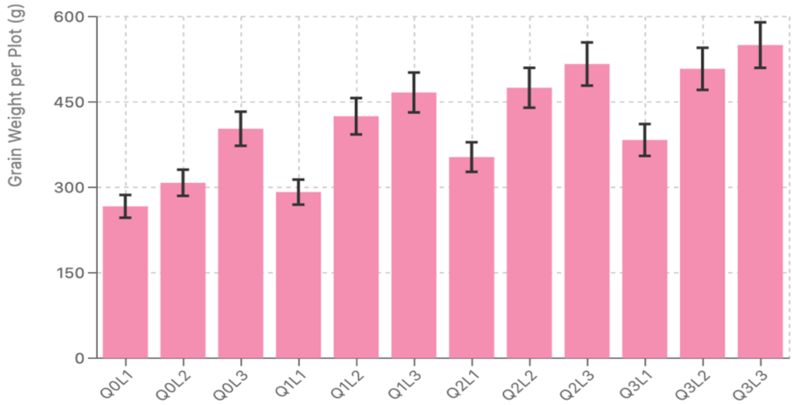

Figure 7. Grain weight per plot (g) by treatment showing mean values for each treatment group.

Integrated parameter analysis

Pearson correlation matrix of rice plant parameters

Correlation analysis reveals critical relationships among rice plant parameters, providing insights into the physiological mechanisms underlying treatment responses and identifying key drivers of productivity improvement in aluminum-toxic environments (Figure 8). Strong positive correlations dominate the matrix, with most parameters showing correlation coefficients above 0.8, indicating highly coordinated responses to PSB-enriched organic fertilizer treatments across different aspects of plant growth and development.

Productive tillers demonstrate exceptionally strong correlations with final yield parameters, showing correlation coefficients of 0.970 with panicle number, 0.848 with grain weight per plant, and 0.863 with grain weight per plot. These robust relationships confirm that tillering capacity represents the primary determinant of overall productivity in upland rice under aluminum stress conditions. Enhanced tillering directly translates to increased panicle production, which subsequently drives higher total grain production despite modest improvements in individual grain characteristics.

Panicle number exhibits similarly strong correlations with yield components, particularly with grain weight per plant ($r = 0.925$) and grain weight per plot ($r = 0.959$). Remarkably high correlation between panicles and productive tillers ($r = 0.970$) confirms the direct relationship between vegetative development and reproductive structure formation. These findings validate that PSB intervention primarily benefits rice productivity through multiplicative effects on reproductive structure development rather than enhancement of individual grain filling processes.

Individual grain quality parameters show more moderate correlations with overall productivity measures. Grains per panicle correlates moderately with grain weight per plant (r = 0.823) and grain weight per plot (r = 0.838), while 1000-grain weight shows weaker relationships with final yield (r = 0.926 for grain weight per plant, r = 0.923 for grain weight per plot). These patterns indicate that while grain filling parameters contribute to overall yield, their influence is secondary to the dominant effects of reproductive structure multiplication. Plant height correlations reveal interesting physiological relationships, showing strong associations with productive tillers (r = 0.900), panicles (r = 0.943), and final yield parameters (r = 0.853 for grain weight per plant, r = 0.955 for grain weight per plot). Enhanced plant height in PSB-treated plants likely reflects improved nutritional status and reduced aluminum stress, supporting vigorous vegetative growth that provides the foundation for increased tillering and reproductive development.

Interrelationships among grain quality parameters demonstrate moderate to strong correlations, with grains per panicle and 1000-grain weight showing a correlation of 0.886. This relationship suggests some degree of compensation between grain number and individual grain size within panicles, indicating that genetic and physiological constraints govern the balance between these components. Enhanced grain filling in PSB-treated plants appears to optimize both grain number and weight simultaneously rather than favoring one component over another (Jain et al., 2022).

Yield component correlations provide crucial insights for breeding and agronomic strategies. Extremely high correlations between grain weight per plant and grain weight per plot (r = 0.995) confirm the scalability of individual plant responses to field-level productivity, validating the reliability of individual plant assessments for predicting treatment efficacy. These relationships support the use of individual plant measurements for rapid screening of soil amelioration treatments and variety selection under aluminum stress conditions.

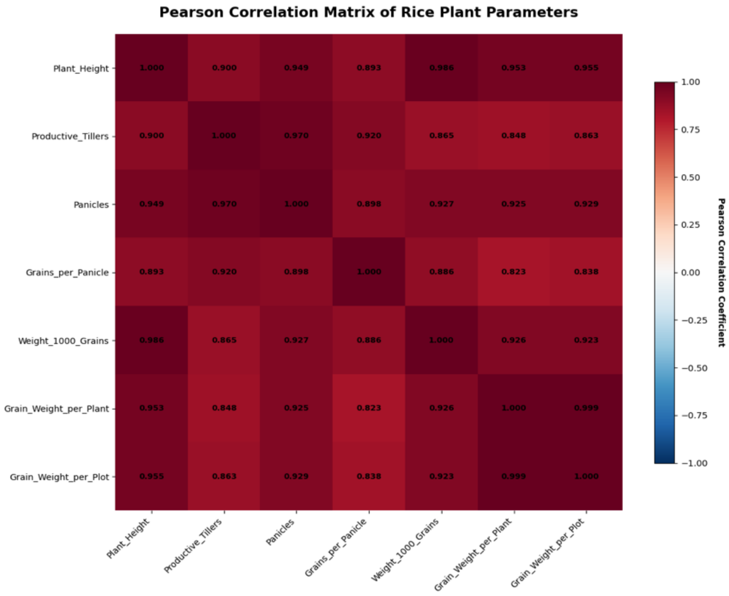

Figure 8. Pearson correlation matrix of rice plant parameters showing correlation coefficients between measured variables.

Statistical relationships revealed in this correlation matrix have profound implications for understanding how PSB intervention addresses aluminum toxicity constraints. Strong correlations among vegetative, reproductive, and yield parameters indicate that biological soil amelioration creates coordinated improvements across multiple physiological processes simultaneously. Rather than addressing isolated constraints, PSB-enriched organic fertilizer appears to optimize the entire plant development continuum from establishment through grain maturation, explaining the remarkable productivity improvements observed in field trials.

Materials and Methods

Experimental site and soil characterization

The field experiment was conducted at the acidic dryland research station in South Sumatra, Indonesia (3°45'S, 104°15'E) during the dry season from May to September 2023. The experimental site is characterized by a tropical monsoon climate with an average annual rainfall of 2,500 mm and mean temperature of 27°C. The soil type is classified as Ultisol according to USDA Soil Taxonomy, typical of acidic dryland conditions in Southeast Asia.

Prior to the experiment, composite soil samples were collected from 0-20 cm depth across the experimental site using a systematic sampling approach. Soil samples were air-dried, ground, and passed through a 2-mm sieve for laboratory analysis. Soil physical and chemical properties were determined using standard methods: pH (H_2O) by potentiometric method (1:2.5 soil:water ratio), organic carbon by Walkley-Black method, total nitrogen by Kjeldahl method, available phosphorus by Bray-1 method, cation exchange capacity (CEC) by ammonium acetate method, and exchangeable aluminum by KCl extraction method. Soil texture was determined using the hydrometer method.

Phosphate-Solubilizing Bacteria (PSB) Isolation and Characterization

Phosphate-solubilizing bacteria were isolated from the rhizosphere of healthy rice plants growing in acidic soils using selective media. The isolation was performed using Pikovskaya's agar medium containing tricalcium phosphate as the sole phosphorus source. Bacterial colonies exhibiting clear zones around them were selected as potential PSB isolates. Selected isolates were purified by repeated streaking and maintained on nutrient agar slants at 4°C.

PSB isolates were characterized for their phosphate-solubilizing ability using quantitative assay in Pikovskaya's broth medium. Isolates were tested for pH tolerance, aluminum tolerance, and plant growth-promoting activities including indole acetic acid (IAA) production, nitrogen fixation ability, and siderophore production. The most efficient isolate showing highest phosphate solubilization (>150 mg L^{-1}) and aluminum tolerance (up to 100 μM $AlCl_3$) was selected for the field experiment.

Preparation of PSB-enriched organic fertilizer

Organic fertilizer was prepared using chicken manure and rice bran at a ratio of 10:1 (w/w) as the basal material. Composting was carried out in a controlled environment for 21 days with regular turning every 5 days to maintain aerobic conditions and ensure uniform decomposition. Compost temperature was monitored daily and maintained between 55-65°C during the active phase.

After composting, the selected PSB isolate was cultured in nutrient broth for 48 hours at 28°C with continuous shaking at 150 rpm. Bacterial culture was applied to the mature compost at a concentration of 10^8 CFU g^{-1} dry weight using a zigzag application method to ensure uniform distribution. PSB-enriched organic fertilizer was stored in sealed plastic bags and cured for 7 days before field application. Nutrient composition of the PSB-enriched organic fertilizer was analyzed using standard methods: total nitrogen by Kjeldahl method, total phosphorus by wet digestion method, total potassium by flame photometry, and organic carbon by dry combustion method. Viable bacterial count was determined using serial dilution and plating technique on nutrient agar medium.

Experimental design and treatments

The field experiment was conducted using a split plot design arranged in a randomized complete block design (RCBD) with three replications. The experiment consisted of two factors: the main plot factor representing types of fertilizer applications, and the subplot factor representing application rates. The main plot factor included five levels: control without fertilizer (CON1), organic fertilizer (ORG), PSB-enriched organic fertilizer (OUV), combination of PSB-enriched organic fertilizer with chemical fertilizer system 1 (OSV), and combination of PSB-enriched organic fertilizer with chemical fertilizer system 2 (OOV). The subplot factor consisted of three application rate levels: 200 kg ha^{-1} (Level 1), 400 kg ha^{-1} (Level 2), and 600 kg ha^{-1} (Level 3). The control treatment (CON1) was applied uniformly without subplot divisions across all replications.

The experimental layout consisted of main plots measuring 4.5 × 1.0 m, with each main plot subdivided into three subplots of 1.5 × 1.0 m each. Spacing between adjacent main plots was maintained at 1.0 m, while spacing between replications was set at 1.5 m. This arrangement resulted in a total of eleven treatment combinations: CON1 (control), ORG1, ORG2, and ORG3 (organic fertilizer at 200, 400, and 600 kg ha^{-1} respectively), OUV1, OUV2, and OUV3 (PSB-enriched organic fertilizer at 200, 400, and 600 kg ha^{-1} respectively), OSV1, OSV2, and OSV3 (combination system 1 at 200, 400, and 600 kg ha^{-1} respectively), and OOV1, OOV2, and OOV3 (combination system 2 at 200, 400, and 600 kg ha^{-1} respectively).

Treatment applications were implemented according to the factorial structure, where organic fertilizer was applied at rates of 200, 400, and 600 kg ha^{-1} for ORG1, ORG2, and ORG3 treatments, respectively. PSB-enriched organic fertilizer was applied at similar rates for the OUV treatments. The combination treatments (OSV and OOV) involved integrated applications of PSB-enriched organic fertilizer with chemical fertilizers at optimized ratios, following the same three-level rate structure. This split plot design provided greater efficiency in managing main plot treatments that required specific application methods while allowing precise measurement of dose-response relationships in the subplots.

Crop management

Upland rice variety 'Situbagendit', known for its tolerance to acidic soil conditions, was used in this study. Seeds were pre-soaked in distilled water for 48 hours with water changes every 6 hours to ensure uniform germination. Soaked seeds were sown directly by dibbling method at 2 cm depth with plant spacing of 20 × 20 cm, resulting in 25 plants per plot.

PSB-enriched organic fertilizer was applied one day before sowing by broadcasting method according to treatment levels. Chemical fertilizers were applied as per treatment requirements. Urea (46% N) was applied in split doses: half at sowing and remaining half at 30 days after sowing (DAS) at a rate of 150 kg ha^{-1}. Potassium chloride (KCl) was applied at 75 kg ha^{-1} at sowing.

Crop management practices included manual weeding at 15 and 35 DAS, gap-filling at 7 DAS to replace dead plants, and irrigation by sprinkler system twice daily (morning and evening) to maintain adequate soil moisture. Plant protection measures were applied as needed based on field observations.

Data collection and measurements

Plant height was measured from ground level to the tip of the longest leaf at maximum tillering stage using a measuring scale. Productive tillers were counted at maturity, considering only tillers bearing panicles with filled grains. Panicle number was recorded by counting all productive panicles per plant at harvest. Grains per panicle were determined by counting filled grains from five randomly selected panicles per plant and calculating the average. Thousand-grain weight was measured by counting 1000 randomly selected grains and weighing them after sun-drying to 14% moisture content. Grain weight per plant was determined by weighing total grain yield from individual plants after sun-drying and cleaning. Plot-level grain weight was measured by harvesting all plants from each plot, threshing, cleaning, and weighing the grains after sun-drying to standard moisture content. All measurements were recorded from five randomly selected plants per plot for individual plant parameters, while plot-level measurements included the entire harvest area.

Statistical analysis

All data were subjected to analysis of variance (ANOVA) using statistical software (SPSS version 26.0). Significance of treatment effects was determined using F-test at $\alpha = 0.05$. Correlation analysis was performed to determine relationships between measured parameters using Pearson correlation coefficient.

Data were tested for normality using Shapiro-Wilk test and homogeneity of variance using Levene's test before statistical analysis. Data transformation was performed when necessary to meet the assumptions of ANOVA. Coefficient of variation (CV) was calculated to assess experimental precision. Results are presented as mean values with standard error of the mean.

Conclusions

PSB-enriched organic fertilizer effectively mitigates aluminum toxicity in acidic dryland systems, achieving remarkable productivity improvements of 106% in grain yield per plot compared to control treatments. Enhanced performance results from multiple synergistic mechanisms including aluminum chelation through bacterial organic acids, phosphorus solubilization, and improved rhizosphere conditions. Productive tillering represents the primary driver of yield enhancement, with the optimal treatment (OUV3) producing 151% more tillers and 133% more panicles than control.

This biological approach provides superior sustainability benefits compared to conventional chemical amendments, reducing input costs while improving soil health and microbial diversity. Results demonstrate that PSB-enriched organic fertilizer offers an economically viable and environmentally sustainable solution for upland rice cultivation in marginal acidic soils, particularly benefiting resource-limited farming systems where expensive lime applications are prohibitive. The technology shows significant potential for widespread adoption in aluminum-toxic environments to enhance food security while maintaining ecological integrity.

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References

Adnan M, Fahad S, Saleem MH, Lal R (2025) Sustainable phosphorus management in calcareous soils: problems and prospects. Journal of Plant Nutrition. 1-22. doi:10.1080/01904167.2025.2477269

Agegnehu G, Amede T, Erkossa T, Yirga C, Henry C, Tyler R, Sileshi GW (2021) Extent and management of acid soils for sustainable crop production system in the tropical agroecosystems: a review. Acta Agriculturae Scandinavica, Section B—Soil & Plant Science. 71(9):852-869. doi:10.1080/09064710.2021.1954239

Arif MS, Shahzad SM, Yasmeen T, Riaz M, Ashraf M, Ashraf MA, Kausar R (2017) Improving plant phosphorus (P) acquisition by phosphate-solubilizing bacteria. In: Essential plant nutrients: uptake, use efficiency, and management. Springer International Publishing, Cham, pp 513-556. doi:10.1007/978-3-319-58841-4_21

Bamdad H, Papari S, Lazarovits G, Berruti F (2022) Soil amendments for sustainable agriculture: Microbial organic fertilizers. Soil Use and Management. 38(1):94-120. doi:10.1111/sum.12762

Chauhan DK, Yadav V, Vaculík M, Gassmann W, Pike S, Arif N, Tripathi DK (2021) Aluminum toxicity and aluminum stress-induced physiological tolerance responses in higher plants. Critical Reviews in Biotechnology. 41(5):715-730. doi:10.1080/07388551.2021.1874282

Collalti A, Tjoelker MG, Hoch G, Mäkelä A, Guidolotti G, Heskel M, Prentice IC (2020) Plant respiration: controlled by photosynthesis or biomass? Global Change Biology. 26(3):1739-1753. doi:10.1111/gcb.14857

Ghosh M, Devi A (2019) Assessment of crop growth, soil properties and crop yield in an upland acidic soil with inorganic fertilizer blended with organic amendments in summer rice cropping seasons. International Journal of Recycling of Organic Waste in Agriculture. 8(Suppl 1):1-9.

Hall AJ, Richards RA (2013) Prognosis for genetic improvement of yield potential and water-limited yield of major grain crops. Field Crops Research. 143:18-33. doi:10.1016/j.fcr.2012.05.014

Hawkesford MJ, Griffiths S (2019) Exploiting genetic variation in nitrogen use efficiency for cereal crop improvement. Current Opinion in Plant Biology. 49:35-42. doi:10.1016/j.pbi.2019.05.003

Hossain A, Maitra S, Sarker S, Al Mahmud A, Ahmad Z, Emon RM, Brestic M (2023) Aluminium stress in plants: consequences and mitigation mechanisms. In: Beneficial chemical elements of plants: recent developments and future prospects. Wiley, pp 123-168. doi:10.1002/9781119691419.ch6

Iftikhar A, Aijaz N, Farooq R, Aslam S, Zeeshan A, Munir M, Shiraz A (2023) Beneficial role of phosphate solubilizing bacteria (PSB) in enhancing soil fertility through a variety of actions on plants growth and ecological perspective: An updated review. Journal of Xi'an Shiyou University, Natural Science Edition. 19(9):520-547. doi:10.1007/s11104-024-06617-7

Jain R, Bana RS, Kumar P, Singh B, Sharma VK, Vanlalruati, Godara S (2022) Nutrient management in potted Syngoniums using water soluble fertilizers and biofertilizers: effects on growth and soil fertility. Canadian Journal of Plant Science. 102(6):1090-1100. doi:10.1139/cjps-2022-0017.

Kishore N, Pindi PK, Ram Reddy S (2015) Phosphate-solubilizing microorganisms: a critical review. In: Plant Biology and Biotechnology: Volume I: Plant Diversity, Organization, Function and Improvement. Springer, pp 307-333. doi:10.1007/978-81-322-2286-6_12

Kuai J, Li X, Ji J, Li Z, Xie Y, Wang B, Zhou G (2022) Response of leaf carbon metabolism and dry matter accumulation to density and row spacing in two rapeseed (Brassica napus L.) genotypes with differing plant architectures. The Crop Journal. 10(3):680-691. doi:10.1016/j.cj.2021.10.006

Kumar M, Shankar A, Chaudhary S, Prasad V (2023) Phosphate solubilizing microorganisms: multifarious applications. In: Plant microbiome for plant productivity and sustainable agriculture. Springer Nature Singapore, Singapore, pp 245-262. doi:10.1007/978-981-19-5029-2_10

Liu J, Shu A, Song W, Shi W, Li M, Zhang W, Gao Z (2021) Long-term organic fertilizer substitution increases rice yield by improving soil properties and regulating soil bacteria. Geoderma. 404:115287. doi:10.1016/j.geoderma.2021.115287

Ma D, He Z, Zhao W, Li R, Sun W, Wang W, Ju W (2024) Long-term effects of conventional cultivation on soil cation exchange capacity and base saturation in an arid desert region. Science of The Total Environment. 949:175075. doi:10.1016/j.scitotenv.2024.175075

Ma Q, Chen H, Yang Y, Zhou B (2025) Unlocking phosphorus resources: phosphate-solubilizing microorganisms as a green strategy for activating phosphorus in acidic red soils and promoting crop growth. Frontiers in Microbiology. 16:1630650. doi:10.3389/fmicb.2025.1630650

Moinet GY, Hijbeek R, van Vuuren DP, Giller KE (2023) Carbon for soils, not soils for carbon. Global Change Biology. 29(9):2384-2398. doi:10.1111/gcb.16570

Munyaneza V, Zhang W, Haider S, Xu F, Wang C, Ding G (2024) Strategies for alleviating aluminum toxicity in soils and plants. Plant and Soil. 504(1):167-190. doi:10.1007/s11104-024-06617-7

Prabhu N, Borkar S, Garg S (2019) Phosphate solubilization by microorganisms: overview, mechanisms, applications and advances. In: Advances in biological science research. Academic Press, pp 161-176. doi:10.1016/B978-0-12-817497-5.00011-2

Sade H, Meriga B, Surapu V, Gadi J, Sunita MSL, Suravajhala P, Kavi Kishor PB (2016) Toxicity and tolerance of aluminum in plants: tailoring plants to suit to acid soils. Biometals. 29(2):187-210. doi:10.1007/s10534-016-9910-z

Sharma UC, Datta M, Sharma V (2025) Chemistry, microbiology, and behaviour of acid soils. In: Soil Acidity: Management Options for Higher Crop Productivity. Springer Nature Switzerland, Cham, pp 121-322. doi:10.1007/978-3-031-76357-1_3

Verma BC, Pramanik P, Bhaduri D (2019) Organic fertilizers for sustainable soil and environmental management. In: Nutrient dynamics for sustainable crop production. Springer Singapore, Singapore, pp 289-313. doi:10.1007/978-981-13-8660-2_10

Xu Y, Li H, Li Y, Zheng X, Zhang C, Gao Y, Tan L (2022) Systematically assess the advancing and limiting factors of using the multi-soil-layering system for treating rural sewage in China: From the economic, social, and environmental perspectives. Journal of Environmental Management. 312:114912.

Yuan R, Mao Y, Zhang D, Wang S, Zhang H, Wu M, Zhang Z (2024) The Formation of Rice Tillers and Factors Influencing It. Agronomy. 14(12):2904. doi:10.3390/agronomy14122904

Zhang Y, Ye C, Su Y, Peng W, Lu R, Liu Y, Zhu S (2022) Soil Acidification caused by excessive application of nitrogen fertilizer aggravates soil-borne diseases: Evidence from literature review and field trials. Agriculture, Ecosystems & Environment. 340:108176. doi:10.1016/j.agee.2022.108176

Zhu XF, Shen RF (2024) Towards sustainable use of acidic soils: Deciphering aluminum-resistant mechanisms in plants. Fundamental Research. 4(6):1533-1541. doi:10.1016/j.fmre.2023.03.004.