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Comparative evaluation of liquid bio-inputs in compost-fertilized quinoa under inter-Andean valley conditions: beneficial microorganisms enhance yield and profitability

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The study was conducted at the Canaán Agrarian Experimental Station (INIA, Ayacucho, Peru) during the 2024–2025 growing season to compare the effects of three liquid bio-inputs—beneficial microorganisms (BM), effective microorganisms (EM), and biol—applied at 15 and 30% concentrations, on the yield and profitability of quinoa crops (*Chenopodium quinoa* Willd., cv. INIA 415–Pasankalla) fertilized with compost (6 t·ha^{-1}). Compost-only and unfertlised control treatments were also included. The experiment was arranged in a randomized complete block design with eight treatments and three replicates. The application of bio-inputs in combination with compost significantly increased aboveground dry biomass, with EM15% and BM15% showing the greatest increases (26.42 and 27.01%, respectively) compared with the control treatment. Regarding yield variables, BM30% achieved the highest values for panicle diameter (11.47 cm), panicle length (46.6 cm), grain weight per panicle (26.76 g), grain yield (2.06 t·ha^{-1}), and 1,000-seed weight (2.89 g). The lowest saponin content was recorded under BM30% (0.0001%), whereas BIOL15% and BIOL30% showed the highest values (14.25 and 14.27%, respectively). Economic analysis revealed that BM30% generated the highest net profit (S/11,047.89) and the greatest benefit-to-cost ratio (2.95). These results indicate that, under compost-based fertilization, the application of 30% BM outperformed EM and biol in enhancing both yield and economic profitability of quinoa cv. INIA 415–Pasankalla under inter-Andean valley conditions.

KEYWORDS
beneficial microorganisms, biol, *Chenopodium quinoa*, compost, effective microorganisms, inter-Andean valleys, profitability, yield

1 Introduction

Quinoa (*Chenopodium quinoa* Willd.) is a crop widely recognized for its high protein content, remarkable adaptability to adverse conditions, and tolerance to extreme environments (Apaza et al., 2013). Its exceptional nutritional value has driven a sustained increase in global demand over the past two decades, with Peru and Bolivia remaining the world's leading producers (FAOSTAT, 2025). In the Peruvian inter-Andean valleys, quinoa plays an important cultural and socioeconomic role, serving as both a traditionally consumed staple food and a key source of income for rural households (Aliaga Lordemann et al., 2024). However, growing international demand has driven a significant expansion in the cultivation of white quinoa varieties in Peru, which accounted for up to 43% of the cultivated area by 2014 (Bedoya-Perales et al., 2018; Cabanillas et al., 2021), with production currently distributed across 19 of the country's 24 departments (MIDAGRI, 2024). This production is predominantly carried out by small-scale conventional farming systems (approximately 90%), which continue to dominate the market compared with the organic production sector (Instituto Nacional de Estadística e Informática, 2013).

The predominance of conventional farming management has led to the increasing use of synthetic fertilizers to sustain productivity. However, their intensive application contributes to soil degradation and negatively affects the yield and quality of Andean crops (Condori-Ataupillco et al., 2025). Soil degradation has not only physical but also chemical and biological consequences. In Bolivia, Cárdenas et al. (2015) reported reductions in microbial activity and in total exchangeable N, K^+, and Mg^{2+} over a seven-year period in long-established quinoa production plots. Similarly, Ortuño et al. (2013) noted that changes in agricultural practices, combined with drought, climate change, and population growth, intensify soil erosion processes in the Altiplano, the center of origin of quinoa shared by Peru and Bolivia. In these high Andean regions, soil degradation is primarily associated with erosion driven by intensive agricultural production and excessive fertilizer use. In this context, the use of liquid bio-inputs has emerged as a promising agroecological strategy (Shahzad et al., 2025). These inputs include beneficial microorganisms (BM), effective microorganisms (EM), and liquid organic extracts such as biol, which improve nutrient availability, stimulate root development, and enhance soil microbial activity (Zhao et al., 2024). In Peru, Mateo (2019) evaluated the use of island guano and manure as fertilizers in quinoa cultivation and observed significant improvements in crop growth and yield. Likewise, Álvarez-Aquise et al. (2025) reported that chicken manure significantly increased plant height and grain productivity. Liquid bio-inputs further promote nutrient uptake and stimulate beneficial microbial processes in the rhizosphere, thereby supporting more vigorous and efficient plant growth (Schlechter et al., 2019). Similarly, the combined application of manure, humus, and biol has been shown to substantially improve quinoa yield (Bolo Valladares et al., 2020). Furthermore, the incorporation of organic compost contributes to optimized soil structure, greater water retention capacity, and enhanced plant tolerance to environmental stress (Quiroz, 2025). Several studies have demonstrated that the combined use of bio-inputs and organic soil management practices can significantly improve vegetative growth, root development, aboveground biomass, and grain yield in Andean crops, including quinoa (Taaime et al., 2023).

However, there is still limited evidence comparing the effects of BM, EM, and biol on quinoa production under compost-based fertilization in the inter-Andean valleys, particularly regarding their influence on yield, grain quality, and root system development (Álvarez-Aquise et al., 2025). A comprehensive evaluation of these factors is essential for designing management strategies that optimize productivity while promoting the adoption of climate-resilient agricultural practices (Villegas-Casaverde et al., 2025).

In this context, the aim of this study was to compare the effects of three liquid bio-inputs—beneficial microorganisms (BM), effective microorganisms (EM), and biol—applied at two concentrations (15 and 30%) on the yield and profitability of quinoa crops (*Chenopodium quinoa* Willd., cv. INIA 415–Pasankalla) fertilized with compost ($6\ t{\cdot}ha^{-1}$) under inter-Andean valley conditions.

2 Materials and methods

2.1 Study setup

This study, conducted in the Peruvian highlands, evaluated the effects of three liquid biofertilizers on the organic production of the red quinoa variety INIA 415–Pasankalla. This cultivar was enhanced and released by the National Institute of Agrarian Innovation (INIA) and is recognized for its high yield potential and superior grain quality (INIA, 2006). Two of the biofertilizers, biol and beneficial microorganisms, were produced in accordance with the practical production guidelines established by INIA (Ortiz et al., 2023a; Ortiz and Perez, 2022), while the third was a commercially sourced product (Effective Microorganisms, EM). The study compared different application doses of these biofertilizers, with all treatments receiving a compost dose before sowing (Ortiz et al., 2023a), except for the control treatment.

2.2 Study location

The study was conducted between November 2024 and April 2025 at the Canaán Agrarian Experimental Station (EEA Canaán) of the National Institute of Agrarian Innovation (INIA), located in the district of Andrés Avelino Cáceres Dorregaray, Huamanga Province, Ayacucho Region, Peru. The study area is part of the central-southern Andean agroecological region of the country (SINIA, 2012), characterized by rainfed production systems and pronounced seasonal variation in water availability, with an average annual precipitation of approximately 550 mm. The area is characterized by alluvial soils with high agricultural suitability, typical of the inter-Andean valleys. It is also located within the Quechua natural region, which presents a temperate sub-humid climate with a tendency toward dry conditions (Gobierno Regional de Ayacucho (GORE), 2016).

The experimental plot was located at an altitude of 2,750 m.a.s.l., at coordinates 13°09′55″S and 74°12′21.71″W (Figure 1). During the experimental period, the mean air temperature was 18.14 °C, with maximum and minimum values of 27.13 °C and 9.15 °C, respectively, reflecting the typical thermal range of high-Andean environments. Cumulative precipitation

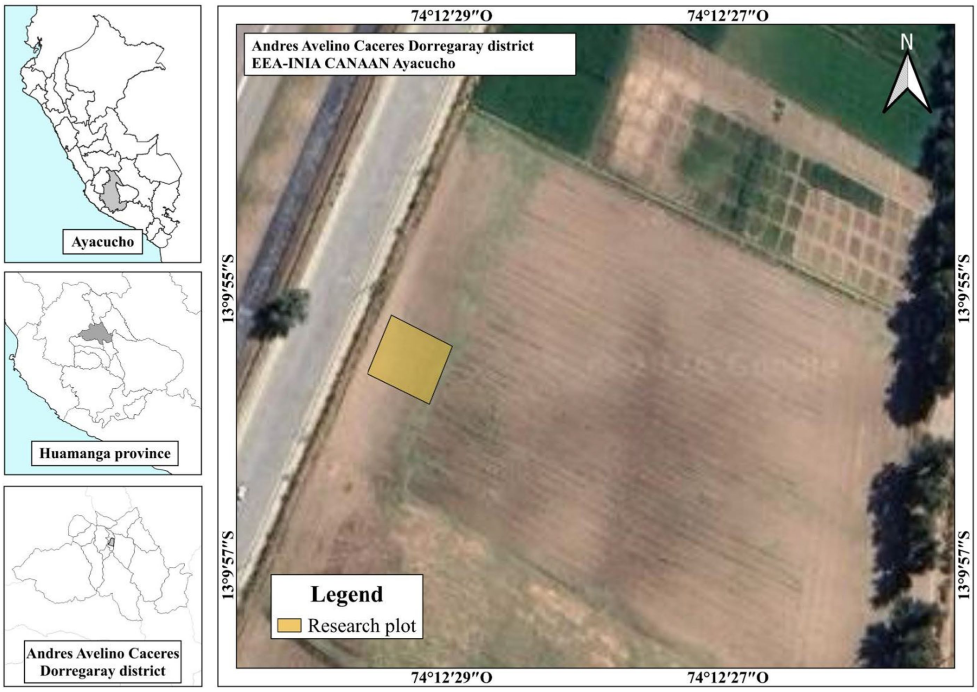

FIGURE 1
Location map of the study area at the Canaán Agrarian Experimental Station (INIA), Huamanga, Ayacucho, Peru.

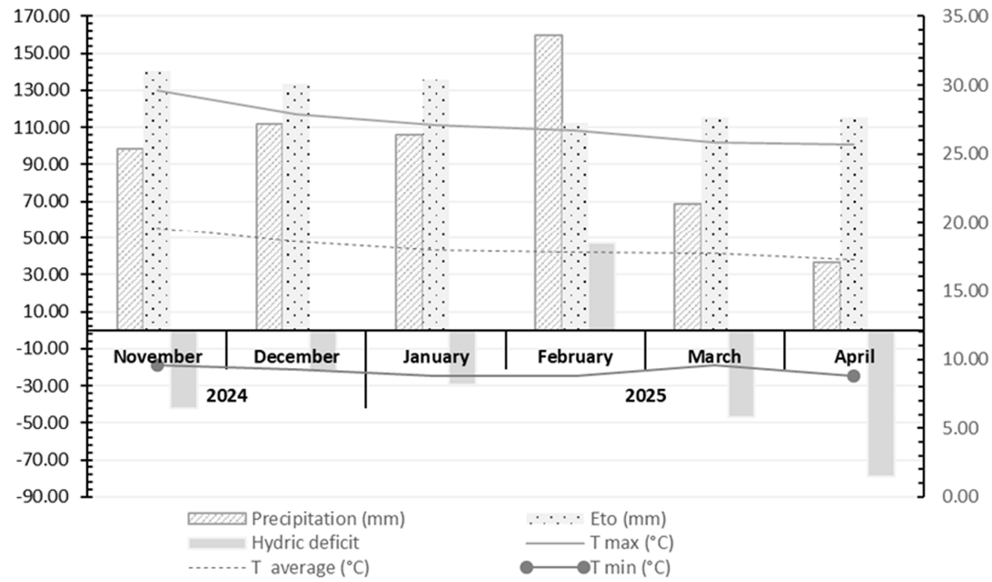

FIGURE 2
Meteorological parameters of the experimental plot: maximum (Tmax), minimum (Tmin), and average temperature, precipitation (mm), evapotranspiration (ETo), and monthly hydric deficit.

reached 581.40 mm (Figure 2), consistent with the seasonal rainfall pattern and sufficient to support crop development under rainfed conditions. Meteorological data were recorded using a Vantage Pro2 Plus automatic weather station, located within the experimental area (13°10′4.14″S, 74°12′24.60″W), which enabled continuous monitoring of key climatic variables, including air temperature, precipitation, relative humidity, and reference evapotranspiration (ETo).

2.3 Production and physicochemical characterization of liquid bio-inputs

Biol was produced through controlled fermentation processes using locally available inputs, including whey, alfalfa, molasses, and cattle manure, supplemented with yeast, phosphate rock, agricultural lime, and other additives (Ortiz et al., 2023a). The final product was obtained after 2 months of fermentation. Beneficial microorganisms (BM) were produced under anaerobic conditions using chicken liver, lettuce, salt, and molasses, with a 1-month fermentation period (Ortiz and Perez, 2022). The production of both biofertilizers (biol and BM) was carried out under controlled conditions of moisture, temperature, and fermentation time. The third biofertilizer, Effective Microorganisms (EM), was a commercially sourced product (EMBIOECSA EM.1) containing *Saccharomyces cerevisiae* (2.4×10^5 CFU·mL^{-1}) and *Lactobacillus casei* (1.3×10^5 CFU·mL^{-1}), with a pH < 3.5 (EMBIOECSA, 2021).

The biol and BM were physicochemically characterized at the Valle Grande Agricultural Chemistry Laboratory, located in Cañete, Peru. The pH and electrical conductivity (EC) were determined using the electrometric methods established by International Organization for Standardization (ISO) (1994). Density, total solids, organic matter, dissolved ash and impurities, and organic carbon were determined using the gravimetric method (International Organization for Standardization (ISO), 1993). Total nitrogen (N) was quantified using the Kjeldahl method, in accordance with International Organization for Standardization (ISO) (1995), while total phosphorus (P_2O_5) was determined by the colorimetric method (AOAC International, 1998). Potassium (K_2O), calcium (CaO), magnesium (MgO), sodium (Na), copper (Cu), zinc (Zn), manganese (Mn), iron (Fe), and boron (B) were quantified by flame atomic absorption spectrometry (FAAS) following the methodology of the United States Environmental Protection Agency (2007). Total sulfur (S) was determined using the turbidimetric method (International Organization for Standardization (ISO 9280), 1990), whereas total chlorine (Cl) was determined using the argentometric method (International Organization for Standardization (ISO), 1989). The physicochemical characteristics of the evaluated bio-inputs are presented in Table 1.

TABLE 1 Physicochemical characteristics of biol and beneficial microorganisms (BM).

Parameter	Simbol	Unit	Values biol	Values BM
pH	pH	–	4.86	3.54
Electrical conductivity	EC	dS·m^{-1}	10.45	4.79
Density	–	%	1.02	1.04
Total solids	–	%	2.45	3.97
Organic matter	OM	%	1.28	1.63
Organic carbon	–	%	0.74	0.95
Dissolved ash	–	%	1.12	1.79
Impurities	–	%	0.06	0.55
Total nitrogen	N_T	%	0.60	0.03
Total phosphorus	P	%	0.07	0.01
Total potassium	K	%	0.30	0.30
Total calcium	Ca	%	0.22	0.05
Total magnesium	Mg	%	0.05	0.04
Total sulfur	S	%	0.07	0.04
Total sodium	Na	%	0.01	0.34
Total chlorine	Cl	%	0.12	0.21
Total copper	Cu	ppm	0.77	0.2
Total zinc	Zn	ppm	0.62	0.37
Total manganese	Mn	ppm	7.37	1.3
Total iron	Fe	ppm	22.47	6.16
Total boron	B	ppm	2.06	2.90

2.4 Experimental design

The experiment was established using a randomized complete block design (RCBD), consisting of eight treatments and three replicates, for a total of 24 experimental units (Table 2). The study variables were evaluated according to days after sowing (DAS). It is important to note that all treatments, except the control treatment (T8), received a basal application of compost (6 t·ha^{-1}) before sowing.

The trial was established over a total area of 504 m^2 (28 m × 18 m). Each experimental plot covered 14.0 m^2 (5.0 m × 2.8 m) and consisted of four furrows spaced 0.70 m apart, with 0.35 m buffer strips between plots. Quinoa was sown at a seeding rate of 10 kg·ha^{-1}, followed by thinning to achieve a final density of 25 plants per linear meter. Service alleys of 1.5 m and 0.80 m were maintained to ensure experimental independence among plots (Figure 3).

2.5 Plot management

Prior to land preparation (by tilling and leveling), soil samples were collected at a depth of 30 cm for physicochemical analysis at the Soil, Water, and Foliar Laboratory of the Canaán Agrarian Experimental Station (EEA Canaán). The results indicated a pH of 7.5, classified as moderately alkaline (NOM-021-RECNAT-2000, 2002), and an electrical conductivity of 7.3 mS·m^{-1}, corresponding to non-saline soil conditions (International Organization for Standardization (ISO), 1994). Soil organic matter (OM) content was 1.60%, classified as medium, and the soil had a clay loam texture. Available phosphorus (P) was 22.0 ppm, determined by the Olsen method, indicating a high level (NOM-021-RECNAT-2000, 2002), whereas total nitrogen (N) was 0.08%, classified as low (International Organization for Standardization (ISO), 1995). Available potassium (K) reached 512.80 ppm, considered very high (Bazán, 2017). Exchangeable cation concentrations of Ca^{2+}, Mg^{2+}, K^+, and Na^+ were 30.24, 0.46, 0.65, and 0.26 cmol(+)·kg^{-1}, respectively, corresponding to very high, low, high, and low levels according to NOM-021-RECNAT-2000 (2002). The effective cation exchange capacity (ECEC) was 31.62 cmol(+)·kg^{-1}, classified as very high.

To compensate for deficiencies in soil organic matter, compost (6 t·ha^{-1}) was incorporated into all treatments prior to sowing, with the exception of the control treatment. The compost was produced from organic residues, including guinea pig manure and oat and maize crop residues, with periodic watering and pile turning every 15 days over a three-month composting period (Ortiz et al., 2023b). The physicochemical properties of the compost were analysed at the Soil, Water, and Foliar Laboratory (LABSAF) of the Canaán Agrarian Experimental Station, yielding the following values: pH 7.9, electrical conductivity (EC) 18 dS·m^{-1}, organic matter (OM) 47.6%, total N 1.9%, available P 2.6%, available K 3.9%, and a C/N ratio of 13.8.

TABLE 2 Experimental treatments.

Treatment	Code	Description
T1	BM15%	Beneficial microorganisms (BM) 15%
T2	EM15%	Effective microorganisms (EM) 15%
T3	BIOL15%	Biol 15%
T4	BM30%	Beneficial microorganisms (BM) 30%
T5	EM30%	Effective microorganisms (EM) 30%
T6	BIOL30%	Biol 30%
T7	COMPOST	Only compost (6 t·ha^{-1})
T8	CONTROL	Unfertilized control

Quinoa seeds were sown using the continuous-flow sowing method. The crop was cultivated under rainfed conditions, relying exclusively on seasonal precipitation throughout its phenological cycle. The three biofertilizers were diluted to concentrations of 15 and 30% and applied using a Jacto PJH-20 backpack sprayer equipped with an adjustable conical nozzle. Applications were performed both foliarly and directly to the soil on three occasions: 30, 60, and 90 days after sowing (DAS).

During the growing season, standard crop management practices were performed, including manual weeding at 22 and 74 DAS, as well as thinning and earthing-up at 41 DAS. During crop development, the presence of insect pests such as *Diabrotica* sp., *Epicauta* spp., and *Eurysacca quinoae* was recorded, along with diseases including root collar rot (*Fusarium* sp.) and downy mildew (*Peronospora* variabilis). These were controlled through the application of plant protection products (Fitoklin, 0.75 g·L^{-1}; Cyperklin, 0.5 mL·L^{-1}) (Insumos Agricolas Emserge E. I. R. L., Ayacucho, Peru.). Harvesting was performed manually at 131 DAS for each experimental plot, followed by drying, threshing, and air-drying of the harvested grain.

2.6 Assessment of biometric traits, yield components, grain quality attributes, and economic analysis

Assessments were conducted at each phenological stage of the crop (vegetative growth, tillering onset, flowering, physiological maturity, and harvest maturity) in accordance with the technical specifications of the variety (INIA, 2006). During each evaluation, five plants were randomly sampled from each experimental unit at 30, 60, 90, and 120 DAS (Ulloa and Valle, 2021). Root length (cm), measured from the root collar to the apex of the primary root, and plant height (cm), measured from the root collar to the apex of the panicle, were determined using a 5 m measuring tape and a 30 cm metal ruler. Fresh weight of the aboveground and root biomass was determined using a precision balance (Explorer™ Pro Precision, Ohaus, USA; measurement accuracy: 0.001 g). Dry weight was determined after oven-drying the samples at 65 °C for 48 h.

At harvest, plants were manually cut, dried, and threshed in the drying facility of the Canaán Agrarian Experimental Station. The following yield-related variables were recorded: panicle diameter (cm), panicle length (cm), grain weight per panicle (g), and 1,000-seed weight (g), using the previously described precision balance. Grain yield (t·ha^{-1}) was estimated based on the net plot area (4.2 m^2; 3.0 m × 1.40 m) and extrapolated to one hectare. To minimize border effects and improve estimation accuracy, a 1 m strip at each end of the furrows was excluded from the harvest area. This procedure reduced experimental variability associated with interplant competition and increased the precision of yield estimates (Gomez and Gomez, 1984; Montgomery, 2013).

Protein content (%) was determined from total nitrogen concentration using the Kjeldahl method at the Soil, Water, and Foliar Laboratory (LABSAF) of the Canaán Agrarian Experimental Station. Saponin content was assessed using the afrosimetric (foam) method (Mora-Ocación et al., 2022), which is based on the ability of saponins to form stable foam when an aqueous suspension of quinoa flour is vigorously shaken. For this analysis, a suspension containing 1 g of flour in 10 mL of distilled water was prepared and shaken vigorously for 30 s. Foam height (cm) was measured after 5 min of standing. Based on foam height, samples were classified into three categories: sweet (foam height <1 cm), intermediate (foam height between 1 and 3 cm), and bitter (foam height >3 cm). All determinations were performed in triplicate. Finally, an economic analysis was conducted to determine treatment profitability using Equations (1–3), together with Equation (4) proposed by Galecio-Julca et al. (2023). This indicator represents a key parameter for comparing the economic efficiency of the evaluated treatments.

$$PC = Pi \times A \tag{1}$$

$$TI = Pp \times Y \tag{2}$$

$$B = TR - PC \tag{3}$$

$$B / C = TI / PC \tag{4}$$

Where: PC, production cost; Pi, price of the activity or input; A, activity; TR, total revenue; Pp, product price; Y, yield; B, economic benefit; and C, cost.

2.7 Statistical analysis

Experimental data were analysed in the R statistical environment (version 4.5) using the RStudio interface. Data analysis was performed using generalized linear models (GLMs) and generalized linear mixed models (GLMMs) (Bolker et al., 2009). For each evaluated variable, multiple candidate models were fitted and selected based on the Akaike Information Criterion corrected (AICc) for small sample sizes (Burnham and Anderson, 2002). The selected models were validated using simulation-based diagnostic tests, assessing the assumption of residual uniformity, the absence of overdispersion or underdispersion, the absence of outliers, and homogeneity of variance, using the *DHARMa* package (Hartig, 2024). Subsequently, estimated marginal means were calculated and pairwise treatment comparisons were

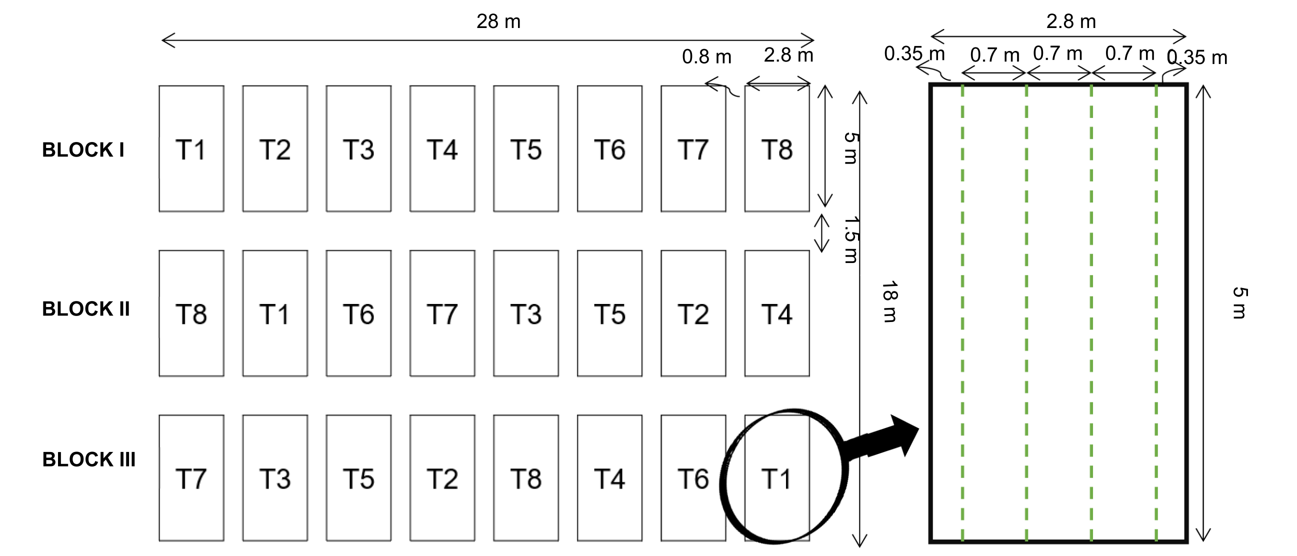

FIGURE 3
Distribution of treatments according to the established experimental design.

performed using the *emmeans* package (Lenth and Piaskowski, 2022), adopting a significance level of $p < 0.05$ and applying the false discovery rate (FDR) correction method (Benjamini and Hochberg, 1995). Finally, to explore multivariate association patterns among treatments and measured variables, a principal component analysis (PCA) was performed (Jolliffe, 2002) using the *factoextra* package, and a PCA biplot was generated with the *fviz_pca_biplot* function.

3 Results

3.1 Biometric traits of quinoa plants

Analysis using GLMMs showed that plant age had a significant effect ($p < 0.01$) on all biometric traits evaluated (Table 3). Likewise, treatment effects were significant and consistent for most variables, with the exception of aboveground dry weight ($p = 0.60$). Likewise, treatment effects depended on plant age for root fresh weight (RFW) ($p < 0.01$), aboveground fresh weight (AFW) ($p < 0.01$), and aboveground dry weight (ADW) ($p < 0.01$), but were independent of plant age for root lenght (RL) ($p = 0.47$), plant height (PH) ($p = 0.70$), and root dry weight (RDW) ($p = 0.33$). The blocking structure accounted for a significant proportion of experimental variability across all biometric traits ($p < 0.01$). In addition, the random-effects component revealed greater heterogeneity among replicates for root length, with an estimated standard deviation of 0.5.

As no significant treatment × time interaction was detected for RL, PH, and RDW, *post hoc* comparisons were interpreted based on the main effects. In this context, treatments receiving biological inputs (biol, BM, and EM) showed higher estimated marginal means than the control treatments (COMPOST, compost control (only the plant + compost); CONTROL, plant control (only the plant without compost or biofertilizers)), suggesting an overall positive effect on the biometric development of quinoa plants. Regarding plant age, all evaluated variables exhibited a consistent and cumulative response over time. However, root length stabilized at 120 days after sowing, showing no further increase compared with the previous evaluation period.

Time-dependent post hoc analysis showed that, across the evaluated periods, BIOL30 produced the most consistent and greatest response in root fresh weight, with values of 0.18, 2.12, and 11.74 g at 30, 60, and 90 DAS, respectively (Table 4). For aboveground fresh weight, BIOL30 and BM15 exhibited the highest values and maintained a sustained response over time. For BIOL30, values reached 5.28, 69.10, and 105.91 g, while BM15 recorded 4.73, 66.13, and 99.36 g at 30, 60, and 90 DAS, respectively (Table 5). Regarding aboveground dry weight, the greatest and most consistent responses over time were observed for EM15 and BM15, with values of 0.50, 7.54, and 26.42 g for EM15, and 0.45, 7.67, and 27.01 g for BM15 at 30, 60, and 90 DAS, respectively (Table 6).

3.2 Quinoa yield components

For the yield components, GLM analysis revealed significant treatment effects on all evaluated variables (panicle diameter (PD), panicle lenght (PL), grain weight per panicle (GWP), and grain yield; $p < 0.01$), as shown in Table 7, confirming that the application of the different biological inputs consistently influenced quinoa yield performance. In addition, the blocking structure accounted for a significant proportion of experimental variability for PD ($p = 0.02$) and grain yield ($p < 0.01$).

Post hoc comparisons consistently showed that the unfertilized control and the treatment receiving compost alone produced the lowest responses across all yield components. For PD, the highest value was recorded for BM30 (11.47 cm), which was statistically similar to BIOL30, although numerically superior (Figure 4A). Likewise, PL reached its highest value under BM30 (46.6 cm), with no significant differences compared with BIOL15, BIOL30, EM15, and BM15, although BM30 showed the highest numerical value (Figure 4B). For GWP, the highest value was also observed under BM30 (26.76 g), with no significant differences relative to BM15, despite its numerically greater response (Figure 4C). Finally, the highest grain yield values were recorded for BM30 (2.06 $t \cdot ha^{-1}$), BIOL30 (2.02 $t \cdot ha^{-1}$), EM30

TABLE 3 Longitudinal analysis of biometric growth variables using generalized linear mixed models (GLMMs).

	RL (cm)	PH (g)	RFW (g)	RDW (g)	AFW (g)	ADW (g)
Fixed factors (*p*-value)						
Block (B)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Days (D)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Treatment (T)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
D*T	0.47	0.70	0.03	0.33	<0.01	<0.01
Random factors (σ)						
Experimental unit (Plot)	0.00	0.02	0.08	0.00	0.00	0.00
Marginal means treatments						
CONTROL	16.28b	59.14c	1.06c	1.02c	21.84d	3.29d
COMPOST	18.06a	62.52bc	1.28bc	1.08c	21.3d	3.51cd
BIOL15	18.1a	64.2b	1.5ab	1.30bc	26.76c	3.84bc
BIOL30	17.65ab	65.99ab	1.65ab	1.70a	33.81a	4.41ab
EM15	17.93ab	64.43b	1.59ab	1.39ab	28.9bc	4.63a
EM30	17.45ab	64.65b	1.58ab	1.56ab	29.57bc	4.43a
BM15	19.2a	63.08bc	1.73a	1.77a	31.45ab	4.54a
BM30	16.28b	70.46a	1.6ab	1.46ab	28.12c	4.37ab
Plant age (days)						
30	6.59c	16.20d	0.16c	–	4.58c	0.47c
60	13.80b	75.34c	2.07b	0.54b	51.35b	6.71b
90	31.03a	116.85b	9.77a	3.57a	87.50a	21.68a
120	31.02a	119.42a	–	–	–	–

RL, root length; PH, plant height; RFW, root fresh weight; RDW, root dry weight; AFW, aboveground fresh weight; ADW, aboveground dry weight. Different letters indicate significant differences at the 0.05 significance level according to the false discovery rate (FDR) correction method.

TABLE 4 Root fresh weight under biological-input treatments across the evaluation periods.

DAS	CONTROL	COMPOST	BIOL15	BIOL30	EM15	EM30	BM15	BM30
30	0.13 (b)	0.15 (ab)	0.16 (ab)	0.18 (a)	0.17 (a)	0.15 (ab)	0.18 (a)	0.18 (a)
60	1.36 (a)	1.66 (a)	2.39 (a)	2.12 (a)	2.07 (a)	2.36 (a)	2.58 (a)	2.35 (a)
90	6.98 (d)	8.49 (cd)	8.76 (c)	11.74 (a)	11.25 (ab)	10.87 (ab)	11.35 (ab)	9.85 (bc)

Values represent estimated marginal means; different letters within columns for the same row indicate significant differences among treatments at each evaluation time according to the false discovery rate (FDR) correction.

TABLE 5 Aboveground fresh weight under biological-input treatments across the evaluation periods.

DAS	CONTROL	COMPOST	BIOL15	BIOL30	EM15	EM30	BM15	BM30
30	4.41 (a)	3.35 (b)	4.81 (a)	5.28 (a)	5.23 (a)	4.59 (a)	4.73 (a)	4.54 (a)
60	36.29 (e)	39.79 (de)	50.74 (bc)	69.1 (a)	44.45 (cd)	54.68 (b)	66.13 (a)	59.41 (ab)
90	65.07 (c)	72.62 (bc)	78.45 (b)	105.91 (a)	103.76 (a)	103.04 (a)	99.36 (a)	82.36 (b)

Values represent estimated marginal means; different letters within columns for the same row indicate significant differences among treatments at each evaluation time according to the false discovery rate (FDR) correction.

TABLE 6 Aboveground dry weight under biological-input treatments across the evaluation periods.

DAS	CONTROL	COMPOST	BIOL15	BIOL30	EM15	EM30	BM15	BM30
30	0.44 (a)	0.44 (a)	0.48 (a)	0.52 (a)	0.5 (a)	0.51 (a)	0.45 (a)	0.45 (a)
60	5.05 (b)	5.79 (ab)	6.27 (ab)	7.78 (a)	7.54 (a)	6.62 (ab)	7.67 (a)	7.49 (a)
90	16.11 (d)	16.79 (d)	18.83 (cd)	20.99 (bc)	26.42 (a)	25.97 (a)	27.01 (a)	24.67 (ab)

Values represent estimated marginal means; different letters within columns for the same row indicate significant differences among treatments at each evaluation time according to the false discovery rate (FDR) correction.

TABLE 7 Analysis of quinoa yield components using generalized linear models (GLMs).

	PD (cm)	PL (cm)	GWP (g)	Grain yield (kg·ha⁻¹)
Fixed factors (*p*-value)				
Block	0.02	0.41	0.10	<0.01
Treatment	<0.01	<0.01	<0.01	<0.01

PD, panicle diameter; PL, panicle length; GWP, grain weight per panicle.

(1.97 t·ha^{-1}), and BM15 (1.94 t·ha^{-1}), which together constituted the group with the best yield performance (Figure 4D).

3.3 Grain quality components of quinoa

Analysis using GLMs revealed significant treatment effects on 1,000-seed weight (W1000), germination percentage, and protein content ($p < 0.01$), indicating that the application of the different biological inputs consistently influenced these quinoa grain quality components (Table 8). However, no significant differences among treatments were detected for saponin content ($p = 0.08$), although a marginal trend toward variation was observed. In addition, the blocking structure accounted for a significant proportion of the experimental variability associated with W1000 ($p = 0.02$).

Post hoc comparisons showed that, overall, the unfertilized control produced the lowest values for most grain quality components, except for saponin content, for which a marginal trend toward higher values was observed. For 1,000-seed weight (W1000), the best responses were recorded for BM15 and BM30 (2.89 g), with no statistically significant differences relative to EM30, BIOL30, and BIOL15, although BM treatments showed numerically higher values (Figure 5A). For germination percentage, the highest values were obtained with BIOL30 (93.7%) and BM15 (93.5%), with no significant differences compared with BIOL15, BM30, EM15, and EM30, although they exhibited slightly higher numerical values (Figure 5B). Regarding protein content, the highest values were recorded in treatments receiving BIOL, BM, EM, and compost (Figure 5C). In contrast, saponin content did not differ significantly among treatments, although the unfertilized control showed a marginal tendency toward higher concentrations (Figure 5D).

3.4 Associations of the evaluated components with quinoa grain yield

Figure 6 shows significant positive associations between grain yield and the biometric, productive, and quality variables evaluated, with Spearman's correlation coefficients ranging from 0.54 to 0.76 ($p < 0.01$). The strongest relationships were observed for root dry weight (RDW) ($R = 0.76$; Figure 6H), grain weight per panicle (GWP) ($R = 0.75$; Figure 6C), panicle length (PL) ($R = 0.74$; Figure 6B), aboveground dry weight (ADW) ($R = 0.73$; Figure 6I), and panicle diameter (PD) ($R = 0.72$; Figure 6A). Likewise, significant positive associations were recorded for germination percentage and root length (RL) ($R = 0.68$ in both cases), as well as for plant height (PH) ($R = 0.67$; Figure 6F). To a lesser extent, although still statistically significant, positive associations were also observed for 1,000-seed weight (W1000) ($R = 0.60$; Figure 6D) and protein content ($R = 0.54$; Figure 6J). The LOESS-smoothed curves exhibited upward and predominantly monotonic trends, consistent with both the magnitude and direction of the estimated correlations.

All reported correlations were statistically significant ($p < 0.01$). Other evaluated variables, such as protein and saponin content, showed no significant correlation with grain yield (data not shown).

3.5 Principal component analysis (PCA)

The principal component analysis (PCA) revealed that the first two dimensions explained 67.38% of the total variance, with the first principal component (PC1) accounting for 57.67% and clearly dominating the second principal component (PC2) (9.71%). This supports an adequate overall representation of the multivariate structure among treatments and the evaluated variables. In the first factorial plane, most variables were well represented, with $\cos^2$ values ranging from 0.52 to 0.85, whereas saponin content showed poor representational quality ($\cos^2 = 0.17$), suggesting that its variability was mainly associated with higher-order dimensions. Regarding axis construction, PC1 was mainly defined by grain yield, (PL), panicle diameter (PD), root length (RL), and aboveground fresh weight (AFW), whereas PC2 was more strongly influenced by aboveground fresh weight (AFW), grain weight per panicle (GWP), root dry weight (RDW), panicle diameter (PD), root fresh weight (RFW), and plant height (PH) (Figure 7).

Among the evaluated variables, a positive association was observed among AFW, RFW, RDW, ADW, and grain yield, suggesting a close relationship between biomass accumulation and crop productivity response. Likewise, PD, PL, GWP, RL, and PH exhibited closely aligned vector orientations, indicating a positive association with plant structural traits and yield-related components.

When jointly considering treatment distribution and variable orientation, PC1 clearly discriminated the biological-input treatments from the control treatments, positioning CONTROL and COMPOST at the negative end of the axis, opposite to most biometric and yield-related variables. In contrast, the BIOL, EM, and BM treatments tended to cluster toward the positive end of the axis, indicating an association with enhanced plant growth and yield values. Notably, BM30 was associated with relatively higher values of panicle diameter (PD), panicle length (PL), grain weight per panicle (GPW), root length (RL), and plant height (PH). Meanwhile, BM15, EM15, EM30, and BIOL30 were more strongly associated with higher values of aboveground fresh weight (AFW), root fresh weight (RFW), root dry weight (RDW), aboveground dry weight (ADW), grain yield, and germination percentage (GER).

The low representation of saponin content in the PCA ($\cos^2 = 0.17$) suggests that its variability was poorly explained by the principal dimensions, consistent with the absence of statistically significant differences among treatments ($p = 0.08$) and supporting its interpretation as a complementary qualitative variable.

3.6 Soil physicochemical composition after quinoa harvest

The results of the post-harvest soil physicochemical analysis indicate that the application of biological inputs positively affected soil organic matter content. The BM30 and EM30 treatments reached the highest values (2.3 and 2.1%, respectively), clearly exceeding that of the unfertilized control (1.0%). A similar trend was observed for total nitrogen (N), with BM30 and EM30 maintaining the highest concentrations (0.12 and 0.11%, respectively) among the treatments. These

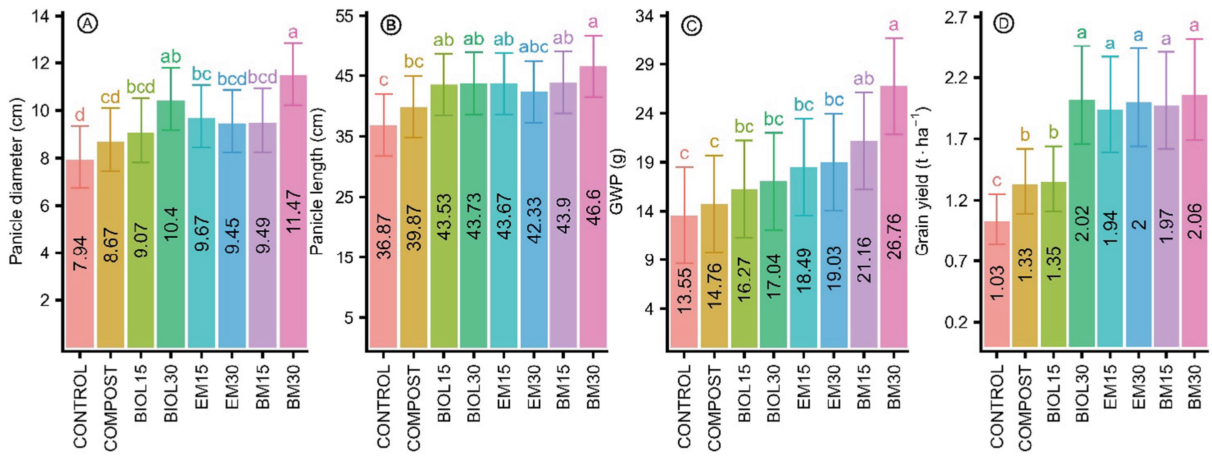

FIGURE 4
Yield components of quinoa under different biological-input treatments. **(A)** Panicle diameter; **(B)** panicle length; **(C)** grain weight per panicle; and **(D)** grain yield. Values within each bar represent the estimated marginal means of the model, and error bars indicate the 95% confidence intervals. Different letters indicate significant differences among treatments according to the false discovery rate (FDR) correction.

TABLE 8 Analysis of quinoa grain quality components using generalized linear models (GLMs).

	W1000 (g)	Germination (%)	Protein (%)	Saponin (%)
Fixed factors (*p*-value)				
Block	0.02	0.48	0.39	0.42
Treatment	<0.01	<0.01	<0.01	0.08

W1000: 1000-seed weight.

results suggest that the 30% application rate were more effective than the 15% rate, indicating a dose-dependent effect.

Available phosphorus (P) content increased under BM30 and BM15, reaching values of 39.7 and 39.5 mg·kg^{-1}, respectively, and exceeding those recorded for the other treatments. In contrast, exchangeable potassium (K) showed its highest concentrations under BM15 (1,222 mg·kg^{-1}) and BIOL15 (1,202 mg·kg^{-1}). Overall, these results indicate that higher application rates (30%) were more effective in enhancing soil OM and N, whereas moderate application rates (15%) were more favorable for optimizing P and K levels (Figure 8).

3.7 Economic analysis results

The economic analysis (Table 9) revealed marked differences in profitability among the evaluated treatments. T4 (BM30) achieved the highest grain yield (2,088.27 kg·ha^{-1}) and generated the greatest total revenue (S/16,706.16), resulting in the highest net profit (S/11,047.89) and the best benefit–cost (B/C) ratio (2.95). This result indicates a high level of economic efficiency associated with the application of beneficial microorganisms at higher concentrations, likely related to improved nutrient availability and enhanced crop development. Similarly, BIOL30 and BM15 showed high profitability, with B/C ratios of 2.91 and 2.90, respectively, demonstrating that both biol and beneficial microorganisms, even at moderate application rates, substantially improved crop productivity and economic returns. In contrast, BIOL15 showed the lowest profitability (B/C = 2.03), accompanied by lower total revenue (S/10,874.98) and net profit (S/5,529.50), suggesting that this application rate was insufficient to produce a substantial effect on grain yield. Likewise, T7 (compost-only treatment) showed relatively low profitability (B/C = 2.15), indicating that the exclusive application of compost, without the incorporation of biological inputs, limited both productive performance and economic return.

It is noteworthy that T8, despite receiving no fertilizer application, achieved a relatively high benefit–cost ratio (B/C = 2.71), surpassing that of some treatments receiving biological inputs. This result is primarily explained by its low production costs (S/3,026.67), which increased its relative economic efficiency. However, its grain yield (1,025.45 kg·ha^{-1}) and total revenue were considerably lower than those of the enhanced treatments, limiting its practical suitability for production systems aimed at maximizing productivity.

4 Discussion

The Pasankalla red quinoa variety responded favorably to the application of the three liquid biological inputs and their respective doses. BIOL, BM, and EM all exerted significant effects on the biometric traits of quinoa. Previous studies have reported that biological inputs promote increases in plant biomass by regulating physiological growth processes and improving nutritional balance (Rodríguez-Medina et al., 2024; Ortiz-Calcina et al., 2023). In this regard, BIOL30 and BM15 stood out by producing the highest aboveground and root biomass values, reflecting greater agronomic efficiency. The variation observed among treatments in relation to application rate and biological-input composition is consistent with the findings of Ramos-Tarifa et al. (2025), who evaluated bioinoculants in Andean crops. This response may be explained by the greater microbial diversity generated through the combined inputs used in the production of BIOL and BM, which likely enhanced plant development. In this context, Singh et al. (2023) reported that the synergistic action of microbial consortia is generally more effective than individual microbial applications, as it promotes greater plasticity in plant height and other structural traits (Li et al., 2024).

In terms of grain yield, the liquid biological-input treatments BM30, BIOL30, and EM30 achieved the highest values (>2 t·ha^{-1}), demonstrating improved efficiency of the soil–plant system. This

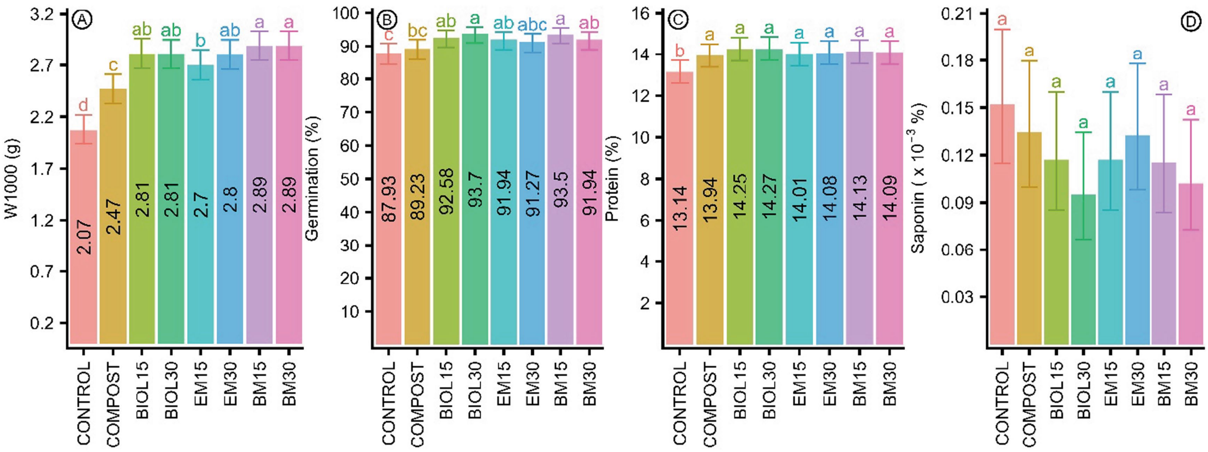

FIGURE 5
Grain quality components of quinoa under different biological-input treatments. **(A)** 1,000-seed weight; **(B)** germination percentage; **(C)** protein content (%); and **(D)** saponin content (%). Values within each bar represent the estimated marginal means of the model, and error bars indicate the 95% confidence intervals. Different letters indicate significant differences among treatments according to the false discovery rate (FDR) correction.

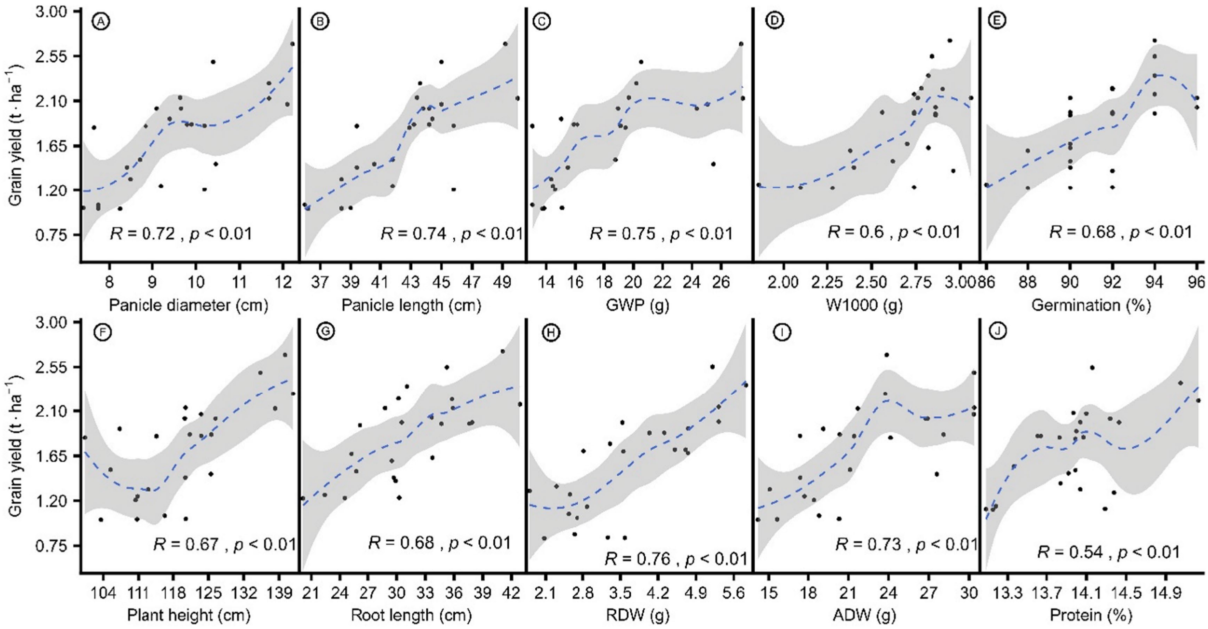

FIGURE 6
Relationships between biometric, productive, and grain quality variables and quinoa grain yield. The figure shows the relationship between grain yield and: **(A)** panicle diameter (PD); **(B)** panicle length (PL); **(C)** grain weight per panicle (GWP); **(D)** 1,000-seed weight (W1000); **(E)** germination percentage; **(F)** plant height (PH); **(G)** root length (RL); **(H)** root dry weight (RDW); **(I)** aboveground dry weight (ADW); and **(J)** protein content (%). The dashed line represents the LOESS-smoothed fit, while the shaded band indicates the 95% confidence interval. R values correspond to Spearman's correlation coefficients and are presented together with their corresponding levels of statistical significance.

effect is likely associated with enhanced nutrient availability and the regulation of crop physiological processes (Altieri, 2018). Consistent with this, panicle size and grain weight were positively influenced by the action of plant growth-promoting microorganisms, which enhance nutrient uptake and stimulate the production of phytohormones (Vessey, 2003; Bhattacharyya and Jha, 2012). Likewise, the positive response observed at higher application rates is consistent with the findings of Mäder et al. (2002). In contrast, the lower values recorded for the unfertilized control and the compost-only treatment reflect limitations in immediate nutrient availability, likely due to the slow mineralization dynamics of organic amendments (Lal, 2020). Although these results are promising within a synthetic fertilizer-free management context, further studies are required to directly compare these biological inputs with conventional chemical fertilization in order to establish their potential as agronomically viable alternatives, an aspect that was not evaluated in the present study.

Regarding grain quality components, 1,000-seed weight showed no significant differences among treatments, consistent with the findings of Álvarez-Aquise et al. (2025), who evaluated different biostimulant doses combined with varying levels of composted poultry manure. The highest germination percentages were recorded for BIOL30 (93.7%) and BM15 (93.5%), in agreement with the results

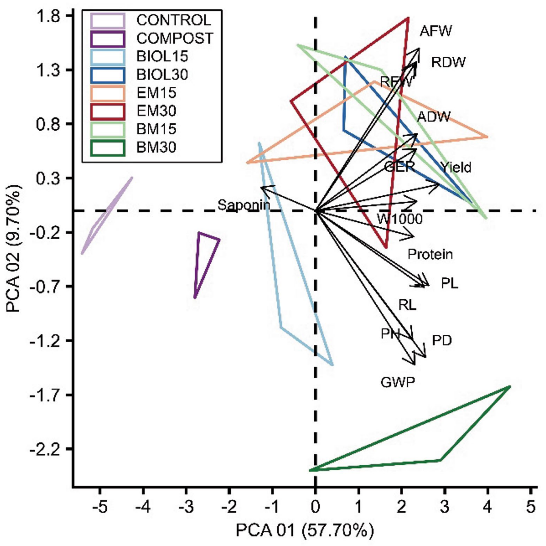

FIGURE 7
Principal component analysis (PCA) biplot of productive, biometric, and grain quality variables of quinoa at the final evaluation. PD, panicle diameter; PL, panicle length; GWP, grain weight per panicle; GER, germination percentage; W1000, 1,000-seed weight; RL, root length; PH, plant height; RFW, root fresh weight; RDW, root dry weight; AFW, aboveground fresh weight; and ADW, aboveground dry weight.

reported by Torre et al. (2020). Protein content increased significantly with the application of BIOL, reaching 14.27%, although this value remains lower than the value reported in the technical specification for the Pasankalla variety (17.41%) (INIA, 2006). Regarding saponin content, assessed using the afrosimetric foam method, all treatments were classified as sweet grains (<0.12%), according to the criteria established by the FAO (2011). These findings are consistent with the values reported in the technical data sheet for the INIA-415 'Pasankalla' variety (INIA, 2006). However, the BIOL30 treatment showed a slight reduction in saponin concentration. In this regard, Lim et al. (2020) reported that saponin content in quinoa grains is relatively stable and does not increase during crop development.

The principal component analysis (PCA) robustly captured the quinoa crop's response pattern, highlighting a strong association between the BM30 treatment and variables related to panicle development, grain traits, plant height, and root length. In contrast, grain yield, germination percentage, and several other biometric variables were more strongly associated with BM15, BIOL30, and EM15 and EM30. Grain yields exceeding 1.9 $t \cdot ha^{-1}$ benefited from the application of liquid foliar biological inputs, reaching values comparable to the average yields reported for the Junín region (1.9–2.2 $t \cdot ha^{-1}$) (MINAGRI, 2017; Sanchez, 2024). These results are particularly promising considering the complete absence of synthetic fertilizer application. Similarly, Muthukrishanan et al. (2024) reported a 25% reduction in chemical fertilizer requirements when biological foliar applications were integrated into rice production systems. Likewise, Javaid (2007) found that the combined application of effective microorganisms and green manure amendments increased pea productivity by 145%.

The post-harvest physicochemical characterization of the soil showed superior values under the BM30 treatment, particularly for organic matter, available phosphorus, and total nitrogen. These findings are consistent with Ali et al. (2024), who reported improved post-harvest soil conditions in wheat following the application of biofertilizers, compared with conventional chemical fertilization. Likewise, Wang et al. (2024) reported significant increases in soil total nitrogen availability under organic fertilization, ranging from 4.40 to 12.09%. In contrast, soil potassium (K) concentrations showed a different response pattern, with the highest values recorded under BM15 (1,222 $mg \cdot kg^{-1}$) and BIOL15 (1,202 $mg \cdot kg^{-1}$), whereas this increase was not observed at the 30% application rate. This response is consistent with the interpretation of Brady and Weil (2016), who noted that potassium availability is primarily influenced by soil physicochemical dynamics rather than by direct microbial activity.

The economic analysis showed that BM30 achieved the highest grain yield (2,088.27 $kg \cdot ha^{-1}$), generated the highest total revenue, and recorded the highest benefit–cost ratio (B/C = 2.95). This value is lower than that reported by Galecio-Julca et al. (2023), who obtained a B/C ratio of 5.68 using EM combined with compost. However, it exceeds the values reported by Torre et al. (2020) for the combined application of organic matter and microorganisms (B/C = 1.82) and by Rojas et al. (2025) using certified quinoa seed (B/C = 1.31). These differences may be attributed to variations in quinoa market prices, local production costs, and the baseline yield conditions of each study; therefore, direct comparisons should be interpreted with caution.

4.1 Study limitations

The results of this study are based on a single growing season and one experimental location (Canaán, Ayacucho); therefore, their extrapolation to other agroecological conditions should be made with caution. No microbiological characterization of the BM and BIOL bio-inputs was performed (e.g., microbial genera composition and colony-forming units per milliliter [$CFU \cdot mL^{-1}$]), which limits a mechanistic understanding of their effects on crop performance. In addition, saponin content was assessed using a qualitative afrosimetric foam method; therefore, the numerical values reported in the tables and figures should be interpreted cautiously until validated through quantitative analytical methods. The application of plant protection products (Fitoklin and Cyperklin) for pest and disease control may have influenced the activity of the applied microorganisms, an aspect that was not evaluated in the present study. Finally, the experimental design did not include a chemical fertilization treatment. Consequently, it is not possible to conclude that the evaluated biological inputs constitute a direct alternative to synthetic fertilization, but rather that they are effective within a compost-based organic management system.

5 Conclusion

The results of this study demonstrate that, under compost-based fertilization, the application of the liquid biological inputs BM, EM, and BIOL significantly increased the yield and profitability of the INIA 415 'Pasankalla' quinoa crop compared with both the compost-only treatment and the unfertilized control. Among the evaluated bio-inputs, BM30 showed the best agronomic performance, achieving the highest values for panicle diameter, panicle length, grain weight per panicle, grain yield, and 1,000-seed weight. Likewise, the economic analysis indicated that BM30 generated the highest net profit, outperforming EM and BIOL at both application rates. Regarding grain quality, all treatments were classified as sweet quinoa

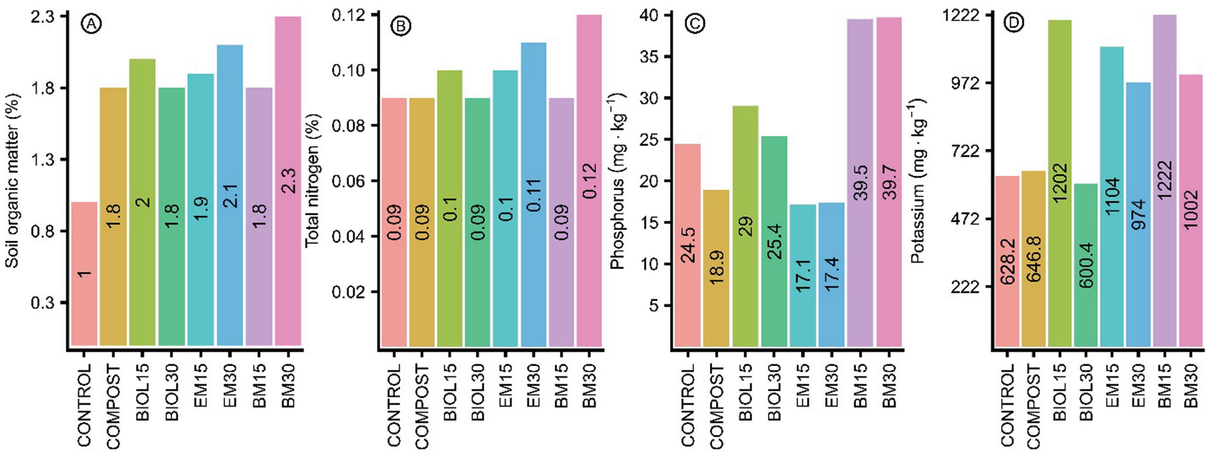

FIGURE 8
Soil physicochemical composition after quinoa harvest under different biofertilizer treatments (15 and 30% application rates). **(A)** Organic matter (%); **(B)** total nitrogen (%); **(C)** available phosphorus (mg·kg^{-1}); and **(D)** exchangeable potassium (mg·kg^{-1}).

TABLE 9 Economic cost–benefit analysis of quinoa production under different biological-input treatments.

Treatment	Grain yield (kg·ha^{-1})	Total production costs	Total revenue	Net profit	Benefit/Cost ratio
T1	1,975.06	5,457.39	15,800.51	10,343.12	2.90
T2	1,955.74	5,805.00	15,645.90	9,840.90	2.70
T3	1,359.37	5,345.48	10,874.98	5,529.50	2.03
T4	2,088.27	5,658.27	16,706.16	11,047.89	2.95
T5	2,002.21	6,348.53	16,017.65	9,669.12	2.52
T6	2,020.87	5,556.69	16,166.98	10,610.29	2.91
T7	1,331.11	4,948.77	10,648.89	5,700.12	2.15
T8	1,025.45	3,026.67	8,203.62	5,176.95	2.71

The quinoa market price was set at S/8.00 per kg, based on values reported for Peru by AgroPerú Informa (2025).

based on their saponin content. Principal component analysis revealed positive associations between biometric traits and grain yield, indicating that yield improvement was primarily related to greater biomass accumulation and enhanced panicle development. Furthermore, the BM30 and EM30 treatments increased soil organic matter and total nitrogen contents after harvest compared with the control, demonstrating the potential of liquid biological inputs to improve selected soil fertility properties within a single growing season.

Overall, the results suggest that microbial bio-inputs have considerable potential to contribute to the development of more productive, profitable, and environmentally sustainable quinoa production systems in the inter-Andean valleys.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MY-Q: Methodology, Conceptualization, Investigation, Writing – original draft. CP: Writing – original draft, Conceptualization, Methodology, Investigation. TC: Writing – original draft, Methodology, Investigation, Conceptualization. SA: Investigation, Writing – original draft. LR-C: Investigation, Writing – original draft. RB: Writing – review & editing. RS: Validation, Supervision, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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