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RESEARCH ARTICLE

Optimisation of Plant Mineral Nutrition, Growth Stimulation and Yield Enhancement Through the Use of a Bio Formulation Based on Phosphate Solubilising Bacteria

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Abstract: The aim of this study was to evaluate the agronomic and fodder efficiency of various fertilisation treatments in relation to their effects on plant growth, chemical composition, and soil properties. The study evaluated the effectiveness of a bio-formulation based on Phosphate-Solubilising Bacteria (PSB) in combination with mineral fertiliser (N60P90 + N30) in enhancing the productivity of forage crops and improving the agrochemical properties of soil. Under field conditions, Mohar, Sudan grass, and barley were investigated. Morphometric parameters, yield, fodder quality, and the dynamics of soil characteristics were determined. Data were statistically analysed using one-way analysis of variance (ANOVA) followed by the Least Significant Difference (LSD) test at $p<0.05$, and results are presented as mean ± Standard Error (SE). The highest values for plant height, number of stems and spikes, as well as spike length, were recorded under the combined application of mineral fertiliser and PSB. In Sudan grass, height reached 36.4 cm, the number of stems 10, spikes 9, spike length 43.5 cm, which exceeded the control by 32.8% and 7.1 cm, respectively. In barley, under the same treatment, green mass yield reached 16.2 t ha^{-1}, dry matter yield 41.2 t ha^{-1}, representing an increase of 7.8% compared with the control. In Mohar, high crude protein content (19.4%), digestible protein (114.7 g kg^{-1}), metabolizable energy (8.15 MJ kg^{-1}) and feed units (0.82 FU) were recorded. From an agrochemical perspective, the content of available phosphorus increased to 62 mg kg^{-1}, potassium to 140 mg kg^{-1}, and humus to 0.75%. At the same time, total salt content decreased to 1.19%, and sodium concentration was reduced by 2.1 mEq 100 g^{-1}. The practical value of this work lies in substantiating the feasibility of integrating PSB into mineral nutrition systems to enhance productivity and sustainability in forage crop production.

Keywords: Microbiota, Soil Degradation, Mineralisation, Humus, Productivity

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Introduction

The relevance of this research stems from the need to improve the efficiency of plant mineral nutrition under conditions of limited resources and soil degradation, particularly in areas with impaired phosphorus regimes. Modern agriculture faces the problem of low phosphorus availability in soils despite the application of substantial doses of phosphorus fertilisers, due to the fixation of phosphorus into poorly soluble forms. In this context, the biologisation of agriculture, based on the use of Phosphate-Solubilising Bacteria (PSB), is considered one of the most promising approaches to the sustainable intensification of crop production. This study focuses on improving plant mineral nutrition under conditions of resource limitation and soil degradation, particularly in soils with disturbed phosphorus availability. However, the integration of biological factors into nutrient-management systems remains poorly studied for forage crops grown on saline and sierozem soils. The absence of local data on the interaction of bioformulations with traditional fertilisers hampers the broad implementation of such technologies in agricultural practice. This calls for a comprehensive analysis of the effects of PSB on plant growth, crop productivity, and the agrochemical status of soils. Specifically, there is scant evidence about the synergistic use of PSB and mineral fertilisers in saline and light loamy soil conditions for forage crop systems, where nutrient availability and salinity stress concurrently interact.

Phosphorus is globally acknowledged as a non-renewable and geopolitically sensitive resource, characterised by finite reserves and uneven distribution across nations. A substantial percentage of applied phosphorus fertilisers is immobilised in soils through fixation into insoluble compounds, significantly reducing their agronomic efficacy. This results in economic losses and exacerbates environmental problems, including the eutrophication of aquatic ecosystems. In this context, PSB serve as a crucial biological mechanism for enhancing phosphorus utilisation efficiency in agroecosystems by transforming insoluble phosphorus into forms accessible to plants through the synthesis of organic acids, enzymes, and other metabolites. Their application facilitates sustainable nitrogen cycling, diminishes reliance on mineral fertilisers, and aids in the establishment of climate-resilient agricultural systems.

Phosphate-solubilising bacteria are widely acknowledged as a crucial element of sustainable agriculture on a global scale, owing to their capacity to enhance phosphorus utilisation efficiency in various agroecosystems, including cereals, legumes, horticultural crops, and degraded soils. Their application has been documented in both intensive and resource-constrained agricultural systems globally, where they aid in diminishing reliance on mineral phosphorus inputs, augmenting soil biological activity, and bolstering crop resilience against abiotic stressors such as salinity, drought, and nutrient deficiency. Thus, PSB-based technologies are regarded as a crucial component of integrated nutrient management strategies aimed at achieving sustainable crop production and long-term soil fertility.

In the work of [1], the high efficacy of PSB in cereal production under phosphorus-deficient conditions was characterised. The authors demonstrated that the use of these microorganisms resulted in a significant increase in yield and improved phosphorus availability in soils. As noted in the study by [2], optimising mineral nutrition for mustard significantly improved nutrient uptake and stimulated plant growth. The application of appropriate fertiliser rates contributed to the accumulation of available phosphorus and improved physiological parameters of crops.

Of particular interest is the work of [3], in which biostimulants, including PSB, were considered as tools for the restoration of disturbed soil ecosystems. It was found that such formulations enhanced the availability of macronutrients and exerted a stabilising effect on soil fertility. According to [4], the systematic application of PSB improves the agrophysical properties of soils and supports sustainable phosphorus management. The authors emphasised the necessity of integrating biological agents into rational farming systems.

The study by [5] underlined the role of microorganisms in maintaining the biogeochemical cycle of phosphorus. The authors showed that the use of PSB could substantially reduce the need for mineral phosphorus fertilisers. As demonstrated by [6], the long-term application of mineral fertilisers in combination with rhizobial inoculants resulted in the formation of stable bacterial communities capable of enhancing phosphate-solubilisation processes. These communities were proven to increase soil biological activity and improve phosphorus nutrition efficiency.

Equally noteworthy is the analysis by [7], which focused on the use of mycorrhizal biofertilisers with PSB activity. The study highlighted the effectiveness of symbiotic fungi in improving plant phosphorus nutrition on depleted and arid soils. In the research by [8], liquid biofertiliser formulations were examined as an alternative to conventional mineral inputs, including those containing PSB, and were shown to increase phosphorus availability and improve crop growth under stress-prone soils.

According to the findings of [9], the use of bacteria of the genus Kosakonia with PSB properties in arid soils actively incorporated phosphorus into the biological cycle and stimulated the growth of groundnut (Arachis hypogaea L.). The study confirmed that the application of specific bacterial inoculants was effective even under arid climates with limited macronutrient bioavailability.

[10] justified the use of PSB as part of integrated biological management strategies for yield and phytosanitary control. The authors emphasised that such inoculants simultaneously improve plant nutrition and suppress pathogens, acting as both biofertility and bioprotection agents.

As reported by [11], a PSB-based inoculant (HG2011) can mobilise phosphorus in the soil and significantly increase rapeseed yield and phosphorus uptake. The authors proved that the application of this bioinoculant increased the content of available phosphorus in the rhizosphere and promoted crop growth under phosphorus-deficient conditions. According to [12], the PSB strain MWP-1 exerted a comprehensive positive effect on vegetation growth, agrochemical properties, and microbial communities in post-coal-mining reclamation zones. It was established that the biofertiliser stimulated phosphorus turnover and improved the ecological condition of disturbed landscapes.

Nevertheless, despite the increasing evidence about PSB efficacy, the majority of prior research has concentrated on monoculture systems, non-saline soils, or laboratory/greenhouse environments, whereas field-scale data under saline light loamy soils and forage crop rotations are still few. Furthermore, comparative data regarding PSB performance under integrated mineral fertilisation regimes in these settings remain inadequate.

The aim of this study was to assess the effectiveness of PSB in combination with mineral fertilisers for increasing the yield of forage crops and improving the agrochemical properties of soils. The objectives were to identify the effects of PSB and fertilisers on the growth and yield of forage crops, to evaluate feed value, and to determine changes in soil parameters.

This study offers empirical information about the synergistic use of PSB and mineral fertilisers in saline light loamy soils, offering novel data on crop-specific responses and alterations in soil fertility within integrated nutrient management systems.

Materials and Methods

The research was conducted from May to September 2024 at the research and production site of the Ibray Zhakhaev Kazakh Research Institute of Rice Cultivation, located in the settlement of Karauyltobe, Kyzylorda region (Republic of Kazakhstan). The experimental site is located in the irrigated agricultural zone of the Kyzylorda region, which is characterised by semi-arid climatic conditions. The research was performed on saline-alkali soils, characteristic of the irrigated agricultural areas in this region. The soils are light-loamy alluvial sierozems with neutral to slightly alkaline reaction (pH 7.1-7.4), moderate organic matter content (humus 0.74%), and slight salinity (total salt content 1.42%).

The field trial was established in accordance with the Recommendations for Spring Field Work in the Kyzylorda Region [13]. The experimental design followed the principles of a randomised complete block design with three replications and a plot size of 10 m². Four agronomic treatments were implemented: control (no treatment), application of mineral fertiliser at N60P90 followed by nitrogen top-dressing (N30), application of a PSB-based inoculant, and combined application of PSB inoculant with mineral fertiliser. The PSB inoculant was applied as an aqueous suspension prior to sowing, while mineral fertilisers were incorporated during pre-sowing cultivation. Sowing was performed manually, adhering to the recommended plant density standards. Each treatment was replicated three times ($n = 3$), and all measured parameters were calculated as mean values of these replicates.

The objects of study were three forage crops: barley (*Hordeum vulgare* L.), Sudan grass (*Sorghum sudanense* L.), and Mohar (*Setaria italica* L.). These crops were selected for their high fodder value, adaptability to agro-climatic conditions, and differences in morpho-physiological characteristics. In addition, they were chosen to represent contrasting functional groups of forage crops (C3 and C4 species), differing in photosynthetic pathways, nutrient use efficiency, and responsiveness to phosphorus availability and microbial inoculation, which allows for a more comprehensive assessment of PSB inoculation effects under field conditions. To analyse plant growth dynamics, the following morphometric parameters were recorded: plant height (cm), number of stems (pcs), number of ears (pcs), and ear length (cm). Measurements were taken at the tillering, stem elongation, and heading stages. Plant height was measured with a Stayer Profi 3420-50 (Germany) metal ruler with millimetre graduations, while ear length was measured with a Mitutoyo 500-196-30 (Japan) digital calliper with ±0.01 mm

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accuracy. For each plot, five representative plants (n = 5 per plot) were sampled, and final values represent mean ± Standard Error (SE).

Forage crop yield was determined based on the mass of above-ground biomass harvested from a 1 m² area within each plot. Harvesting was performed manually at the technological maturity stage, and biomass was weighed using an Ohaus Defender 3000 (USA) electronic balance with ±1 g accuracy. Dry matter content was determined gravimetrically by drying samples in a Binder FD 53 (Germany) oven at 105°C to constant weight. Green mass and dry matter yields were expressed as tons per hectare (t ha^{-1}), considering standard moisture content according to the State Standard of the Republic of Kazakhstan [14]. Absolute and relative yield increases were calculated in comparison with the control treatment. Yield data were also based on three replicated plots per treatment (n = 3), and results are presented as mean ± SE.

The nutritional value of the fodder was determined using a laboratory method based on dried and milled plant samples collected from each plot. The crude protein content was determined using the Kjeldahl method, crude fat by solvent extraction, crude fibre according to the Van Soest method, and ash content by incineration. All proximate composition parameters were expressed on a Dry Matter (DM) basis unless otherwise indicated. The Nitrogen-Free Extractives (NFE) were calculated using the following equation according to standard proximate analysis procedures:

$$NFE\ (\%) = 100 - (moisture + crude\ protein + crude\ fat + crude\ fiber + ash) \quad (1)$$

Where moisture (%) represents water content, crude protein (%) represents total protein content, crude fat (%) represents ether extract content, crude fibre (%) represents indigestible structural carbohydrates, and ash (%) represents total mineral residue.

The starch and sugar contents, as well as carotene concentration, were determined photometrically using a Shimadzu UV-1800 spectrophotometer (Japan). Calcium and phosphorus concentrations were measured by atomic absorption spectrophotometry using a PerkinElmer AAnalyst 400 instrument. The concentrations of starch, sugars, carotene, calcium, and phosphorus were also expressed on a dry matter basis. Fodder nutritive value and metabolizable energy content were calculated on a dry matter basis, expressed in feed units (FUs) and MJ/kg, respectively. All laboratory determinations were performed in triplicate (n=3).

Agrochemical and salinity parameters of the soil were assessed twice before the onset of the growing season and after harvest. Samples were collected from a depth of 0-20 cm using the composite sampling method (five points per plot). Total humus content was determined by the Tyurin method, available nitrogen by the Kjeldahl method, and available phosphorus and potassium according to the Chirikov method followed by photometric analysis. Total mineralisation of the soil solution and concentrations of the major ions (HCO_3^-, SO_4^{2-}, Cl^-, Na^+, Ca^{2+}, Mg^{2+}, K^+) were measured using ion-exchange chromatography and titration. Soil solution pH was measured with a portable Hanna HI98103 pH meter (Italy), and electrical conductivity was measured using a Mettler Toledo FiveEasy instrument (Switzerland). Soil analyses were performed in three replicates (n = 3).

All data underwent statistical analysis using Statistica 13 software (StatSoft, USA). A one-way analysis of variance (ANOVA) was applied to assess the effect of fertilisation treatments on all measured parameters. ANOVA was utilised to identify significant differences among treatments, with a significance level established at $p<0.05$. A post hoc comparison of means was conducted utilising the Least Significant Difference (LSD) test at a 5% probability threshold. The computed LSD values were utilised to evaluate the reliability of differences among treatment means, with differences being statistically significant when they surpassed the relevant LSD value.

The experimental components (fertilisation treatments) were regarded as independent variables, whilst all agronomic, nutritional, and soil parameters were classified as dependent response variables. The statistical workflow directly connected raw experimental measurements to the final study findings by transforming observed variability into statistically validated treatment effects. Specifically, ANOVA assessed the statistical significance of differences among treatments, whereas the LSD test facilitated pairwise comparisons and rating of treatment efficacy.

Statistical outcomes yielded mean differences between treatments, percentage increases compared to the control, and the identification of the most effective fertilisation approach. The outputs were later utilised in the Results section to establish treatment superiority and to illustrate the synergistic effects of PSB and mineral fertiliser. The statistical analysis was both confirmatory and inferential, providing a foundation for interpreting agronomic efficiency, soil enhancement, and forage quality responses across treatments. All results are expressed as mean values ± Standard Error (SE).

Results and Discussion

In *Setaria italica* during the tillering-stem elongation stage, the plant height in the control group (no treatment) was 18.1±SE cm (n = 3), with five stems. At the heading stage, the number of panicles was four, with a mean panicle length of 13.8±SE cm (n = 3). The application of mineral fertiliser ($N_{60}P_{90}$+N_{30}) increased plant height to 20.3±SE cm, the number of stems increased to seven, the number of panicles to seven, and panicle length to 14.8±SE cm. In the group treated with the PSB inoculant without fertiliser application, plant height was lower than in the control (16.1±SE cm); however, the number of stems increased to seven, and the number of panicles increased to seven, while panicle length reached 14.5±SE cm. The highest values for all parameters were recorded in the group receiving both mineral fertiliser and the PSB inoculant: plant height reached 22.8±SE cm, the number of stems increased to eight, the number of panicles increased to eight, and panicle length to 23.4±SE cm. These exceeded the control by 4.7 cm in height (25.9%), by three stems, by four panicles, and by 9.6 cm in panicle length (69.6%). Statistical analysis confirmed significant differences among treatments (one-way ANOVA, $p<0.05$). Figure 1 provides a visual comparison of plant height responses across all three forage crops under different fertilisation treatments, clearly illustrating the observed synergistic effects of mineral fertiliser and PSB inoculation.

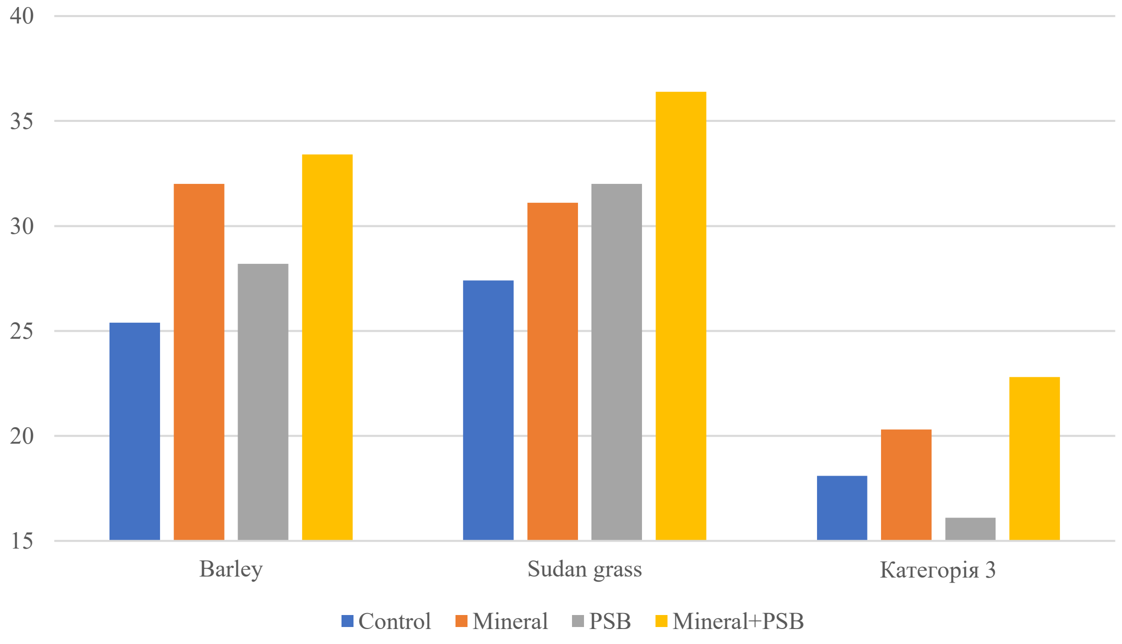

Fig. 1: Comparative plant growth responses of forage crops under different fertilisation treatments

Figure 1 demonstrates that the combined application of mineral fertiliser and PSB consistently resulted in the highest plant height across all studied crops, confirming a consistent and stable synergistic interaction between mineral and biological nutrition under field conditions.

In *Sorghum sudanense* at the tillering-stem elongation stage, plant height in the control was 27.4±SE cm (n = 3), with four stems. At the heading stage, there were also four panicles, with an average panicle length of 36.4±SE cm (n = 3). Mineral fertiliser application ($N_{60}P_{90}$+N_{30}) increased height to 31.1±SE cm; the number of stems increased to six, panicles to five, and panicle length to 39.4±SE cm. The PSB inoculant group showed similar results: height of 32.0±SE cm, the number of stems increased to six, panicles of six, and panicle length 36.9±SE cm. The combined application of mineral fertiliser and the PSB inoculant produced the highest values: height 36.4±SE cm (32.8% higher than the control), the number of stems increased to ten, the number of panicles increased to nine, and panicle length of 43.5±SE cm.

In *Hordeum vulgare* during the tillering-stem elongation stage, the control variant (no treatment) had a height of 25.4±SE cm (n = 3) and four stems (no.). At the heading stage, the number of spikes was also four, with a spike length of 6.7±SE cm. Mineral fertiliser application ($N_{60}P_{90}$+N_{30}) resulted in a height increase to 32.0±SE cm; the number of stems increased to six, the number of spikes increased to six, and the spike length increased to 7.3±SE cm. In the PSB inoculant-treated group, plant height reached 28.2± SE cm, the number of stems increased to seven, the number of spikes increased to six, but spike length decreased slightly to 6.2± SE cm. The best results were recorded in the group treated with mineral fertiliser in combination with the PSB inoculant: height 33.4±SE cm, the number of stems increased to eight, the number of spikes increased to eight, and spike length of 7.7± SE cm (Table 1).

Table 1: Growth dynamics of forage crops

Crops	Study groups	Plant height, cm	Stems (no.)	Reproductive organs (no.)	Spike length, cm
Mohar (*Setaria italica*)	Control (untreated)	18.1	5	4	13.8
	Mineral fertiliser ($N_{60}P_{90}$+N_{30})	20.3	7	7	14.8
	Treated with PSB	16.1	7	7	14.5
	Mineral fertiliser + PSB	22.8	8	8	23.4
Sudan grass	Control (untreated)	27.4	4	4	36.4
	Mineral fertiliser ($N_{60}P_{90}$+N_{30})	31.1	6	5	39.4
	Treated with PSB	32	6	6	36.9
	Mineral fertiliser + PSB	36.4	10	9	43.5
Barley (*Hordeum vulgare*)	Control (untreated)	25.4	4	4	6.7
	Mineral fertiliser ($N_{60}P_{90}$+N_{30})	32	6	6	7.3
	Treated with PSB	28.2	7	6	6.2
	Mineral fertiliser + PSB	33.4	8	8	7.7

Note: n = 3; values are presented as mean±SE; statistical differences among treatments were determined using one-way ANOVA with significance set at $p<0.05$. Different letters within columns indicate significant differences between means ($p<0.05$). Increase over control is presented as absolute values with percentage change relative to control in parentheses

Thus, in all crops, the most substantial growth during both vegetative development and the heading stage was observed in the group treated with mineral fertiliser and PSB, indicating a clear synergistic interaction between mineral and biological inputs. Alongside enhancements in morphology and yield, a comparable synergistic trend was evident in biochemical quality measures, such as protein synthesis. Specifically, PSB combined with mineral fertilisation was more successful in promoting protein accumulation than mineral fertiliser alone, which mainly enhanced biomass production rather than protein enrichment. This suggests that mineral nutrition primarily facilitates structural growth, while PSB increases phosphorus availability and boosts nitrogen incorporation into protein molecules.

This conclusion is directly supported by the simultaneous increase in both structural (plant height, stems, panicles) and productive (biomass yield, dry matter) parameters across all species, demonstrating that morphological improvements translated into measurable yield gains. The PSB-based biopreparation, despite the absence of mineral fertilisation, exerted a generally positive influence on the formation of secondary shoots (stems) and productive panicles/spikes in barley and Sudan grass, although in Setaria italica its effect on plant height was less pronounced compared with the control and fertilised variants, while yield components remained improved.

In barley (*Hordeum vulgare* L.), the control group (no treatment) yielded 14.6 t ha^{-1} of green mass and 38.2 t ha^{-1} of dry matter (n=3 for all treatments and all measured parameters). This served as the baseline for calculating yield increments in other treatments. In the mineral fertiliser group ($N_{60}P_{90}$+N_{30}), green mass yield increased to 16.7 t ha^{-1}, giving an increment of 2.1 t ha^{-1} (14.4%). Dry matter yield increased to 39.5 t ha^{-1}, an increment of 1.3 t ha^{-1} (3.4%). PSB application alone resulted in a green mass yield of 16.1 t ha^{-1} (1.5 t ha^{-1} or 10.3% above control) and a dry matter yield of 40.6 t ha^{-1} (2.4 t ha^{-1} or 6.3% above control). The highest yields were obtained with mineral fertiliser plus PSB: green mass – 16.2 t ha^{-1}, dry matter – 41.2 t ha^{-1}, corresponding to increases of 1.6 t ha^{-1} (10.9%) and 3.0 t ha^{-1} (7.8%) over the control, respectively.

In Sudan grass (*Sorghum sudanense* L.), the baseline yield in the control was 182.4 t ha^{-1} of green mass and 42.0 t ha^{-1} of dry matter. Green mass refers to fresh above-ground biomass, whereas dry matter represents the oven-dried fraction of the same biomass; values are reported on a dry matter basis for comparability. With mineral fertiliser ($N_{60}P_{90}$+N_{30}), green mass yield increased to 196.6 t ha^{-1} (14.2 t ha^{-1} or 7.9% above control), and dry matter yield reached 48.0 t ha^{-1} (6.0 t ha^{-1} or 14.2% increase). PSB treatment resulted in a green mass yield of 197.9 t ha^{-1} (15.5 t ha^{-1} or 8.5% increase) and dry matter

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yield of 49.0 t ha^{-1} (7.0 t ha^{-1} or 16.6% increase). The combination of mineral fertiliser and PSB provided the highest results: green mass 198.1 t ha^{-1} (15.7 t ha^{-1} or 8.6% increase) and dry matter 49.7 t ha^{-1} (7.7 t ha^{-1} or 18.3% increase). Sudan grass exhibited the strongest response to both biological and mineral nutrition, particularly in dry matter yield, suggesting enhanced photosynthetic activity and biomass accumulation. This crop-specific response highlights the novelty of the study, as it demonstrates that PSB efficiency is not uniform across species but depends on physiological and metabolic characteristics of the crop, which has been rarely quantified in previous PSB studies.

The observed differences in plant height across treatments are presented in Figure 2, which provides a comparative visual representation of crop growth responses under different fertilisation regimes. This figure facilitates clearer interpretation of the synergistic effect between mineral fertiliser and PSB.

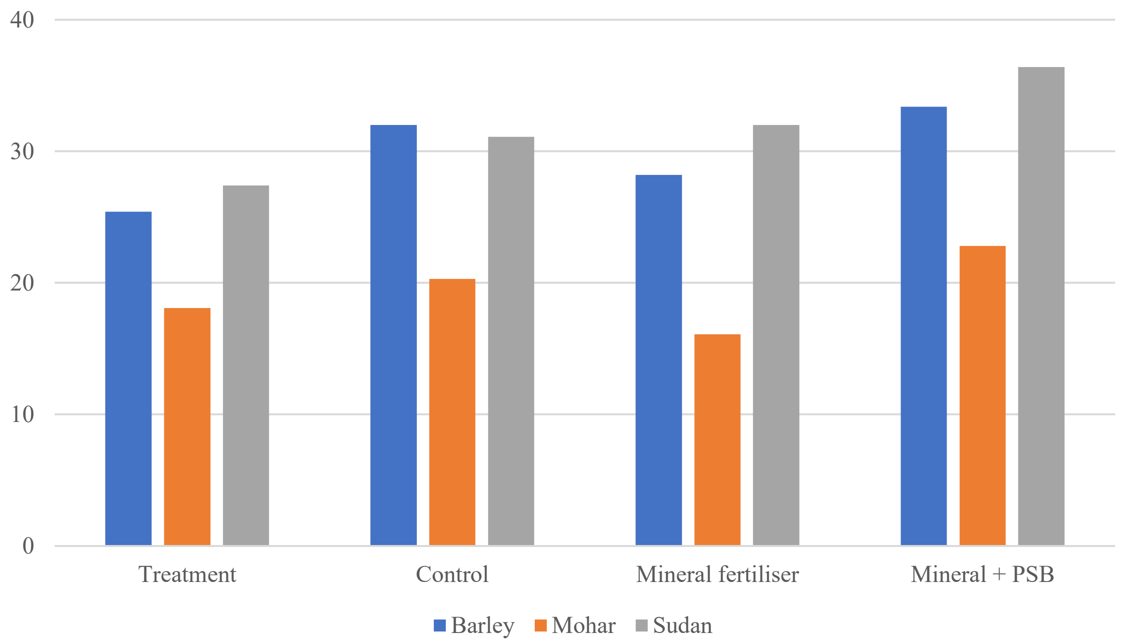

Fig. 2: Plant height of forage crops under different fertilisation treatments

Figure 2 demonstrates that the combined application of mineral fertiliser and PSB inoculant consistently produced the greatest plant height across all examined crops, indicating a pronounced synergistic effect between mineral and biological nutrition. In contrast, the PSB inoculant alone showed crop-dependent variability in its effect, depending on the crop species.

In Mohar (*Setaria italica* L.), the control yield was 130.0 t ha^{-1} of green mass and 54.8 t ha^{-1} of dry matter. Mineral fertiliser application ($N_{60}P_{90}$+N_{30}) increased green mass yield to 134.0 t ha^{-1} (4.0 t ha^{-1} or 3.1% increase) and dry matter to 55.4 t ha^{-1} (0.6 t ha^{-1} or 1.1% increase). Application of the PSB inoculant alone gave yields of 136.0 t ha^{-1} of green mass (6.0 t ha^{-1} or 4.6% increase) and 55.9 t ha^{-1} dry matter (1.1 t ha^{-1} or 2% increase). The maximum yields, as in the other crops, were recorded with mineral fertiliser plus PSB inoculant: green mass – 136.5 t ha^{-1} (6.5 t ha^{-1} or 5% increase) and dry matter 56.2 t ha^{-1} (1.4 t ha^{-1} or 2.6% increase). It should be noted that yield increments in *S. italica* were the lowest compared to Sudan grass and barley, which may be attributable to the species' biological characteristics and lower responsiveness to PSB (Table 2).

Thus, the data obtained unequivocally indicate the effectiveness of both mineral and biological nutrition; however, the highest results are achieved through their combined application. Unlike previous studies that typically evaluated either microbial inoculants or mineral fertilisation separately, this experiment demonstrates their integrated and synergistic effects within a unified fertilisation system under field conditions. In all crops, an increase was recorded in both green mass yield and dry matter accumulation. The use of a PSB-based bioformulation resulted in significant yield increments even in the absence of mineral fertilisation, particularly in Sudan grass and barley, making it a promising component for the biologisation of

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agriculture. Nevertheless, when applied in conjunction with fertilisers, a synergistic effect was observed, ensuring a consistent yield increase, especially during critical growth phases.

The yield response of S. italica under different fertilisation treatments is illustrated in Figure 3, showing changes in both green mass and dry matter production.

Table 2: Yield of forage crops (mean values)

Crops	Study groups	Green mass yield (t ha⁻¹)	Dry matter yield (t ha⁻¹)	Increase over control (green mass, t ha⁻¹)	Increase over control (dry matter, t ha⁻¹)
Barley	Control (untreated)	14.6	38.2	-	-
	Mineral fertiliser ($N_{60}P_{90}+N_{30}$)	16.7	39.5	2.1 (14.4%)	1.3 (3.4%)
	Treated with PSB	16.1	40.6	1.5 (10.3%)	2.4 (6.3%)
	Mineral fertiliser + PSB	16.2	41.2	1.6 (10.9%)	3.0 (7.8%)
Sudan grass	Control (untreated)	182.4	42	-	-
	Mineral fertiliser ($N_{60}P_{90}+N_{30}$)	196.6	48	14.2 (7.9%)	6.0 (14.2%)
	Treated with PSB	197.9	49	15.5 (8.5%)	7.0 (16.6%)
	Mineral fertiliser + PSB	198.1	49.7	15.7 (8.6%)	7.7 (18.3%)
Mohar	Control (untreated)	130	54.8	-	-
	Mineral fertiliser ($N_{60}P_{90}+N_{30}$)	134	55.4	4.0 (3.1%)	0.6 (1.1%)
	Treated with PSB	136	55.9	6.0 (4.6%)	1.1 (2.0%)
	Mineral fertiliser + PSB	136.5	56.2	6.5 (5.0%)	1.4 (2.6%)

Note: n = 3; values are presented as mean±SE. Statistical differences among treatments were assessed using one-way ANOVA ($p<0.05$). Different letters within columns indicate statistically significant differences between means ($p<0.05$). "Increase over control" is expressed as absolute difference (t ha⁻¹) and relative change (%) compared with the control

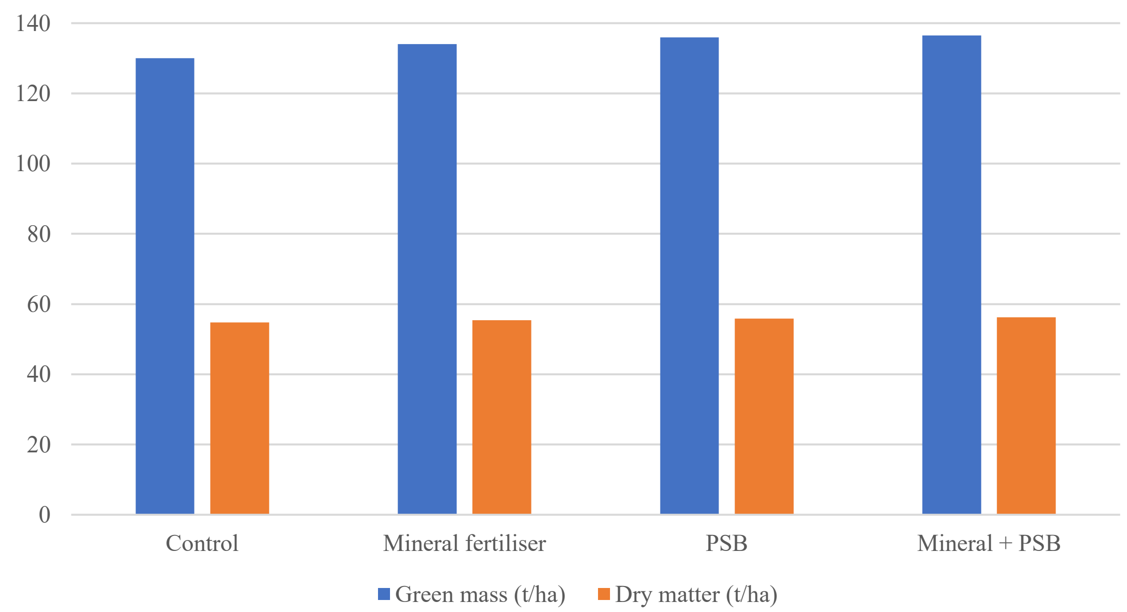

Fig. 3: Yield of Setaria italica under different fertilisation treatments (green mass and dry matter)

Figure 3 illustrates that all fertilisation treatments enhanced both green mass and dry matter yield in comparison to the control. The most pronounced effect was noted with the simultaneous use of mineral fertiliser and PSB inoculant, validating a synergistic relationship between mineral and biological nutrition. The PSB inoculant alone also led to yield enhancement, although the magnitude of the reaction varied according to the crop variety.

Particular attention was drawn to the crude protein content, which in mohar reached 19.4% the highest value among all samples studied. By comparison, Sudan grass contained 10.25% and barley 8.10%. Such protein levels in mohar are attributable to its high biological potential under optimal phosphorus nutrition. The PSB inoculant applied during cultivation may have enhanced the transformation of insoluble phosphorus forms into plant-available forms, which in turn intensified amino acid synthesis and protein accumulation. The elevated protein content in mohar makes it particularly valuable for inclusion in diets for productive livestock requiring high levels of nitrogenous nutrition. Importantly, these biochemical improvements directly correspond to the fertilisation treatments, confirming that changes in soil phosphorus availability (driven by PSB activity) are reflected in feed quality indicators, thereby linking soil processes to final agronomic output.

In comparison to conventional mineral fertilisation alone, treatments containing the PSB inoculant exhibited a consistently superior efficacy in enhancing protein accumulation, especially when applied in conjunction, as mineral nutrition supplied the requisite nitrogen foundation while PSB inoculant facilitated phosphorus mobilisation and uptake efficiency, leading to more effective nitrogen assimilation into plant proteins. Conversely, mineral fertiliser alone enhanced biomass production but exhibited a diminished impact on protein enrichment, suggesting that nutrient amount did not entirely convert into enhanced protein synthesis without the biological activation of the phosphorus cycle.

The digestible protein indicator confirmed the high quality of Mohar protein: 114.7 g/kg dry matter almost 1.8 times higher than in Sudan grass (65.4 g/kg) and more than fivefold greater than in barley (21.1 g/kg). Thus, mohar not only contained a substantial amount of protein but also exhibited high protein digestibility, which is critically important when formulating diets for young stock and high-yielding cattle.

Compared to mineral fertiliser treatments, the application of PSB inoculant, particularly in conjunction with NPK, resulted in a more effective transformation of total protein into digestible protein fractions, indicating enhanced nitrogen utilisation efficiency and superior protein quality development under conditions of biological phosphorus mobilisation. This signifies that PSB enhances not only the quantitative aspects of protein content but also its qualitative enhancement regarding digestion.

The metabolisable energy content of mohar was 8.15 MJ/kg, compared with 7.02 MJ/kg for barley and 6.95 MJ/kg for Sudan grass. The elevated energy value of mohar was also reflected in the Feed Unit for Cattle (FUC) index – 0.82, exceeding that of barley (0.71) and Sudan grass (0.70). This indicates that mohar provides a higher energy output in feeding, which is particularly important under intensive livestock production conditions.

Fat content analysis showed that mohar contained 3.7%, exceeding barley (3.1%) and being markedly higher than in Sudan grass (1.65%). Fat is a concentrated energy source, and its elevated level complemented the energy value of mohar. As for fibre, its content was within the physiological norm for all crops: barley 34.9%, Sudan grass 32.95%, mohar – 33.85%. Such fibre levels ensure an adequate intake of structural carbohydrates that support normal rumen function in ruminants.

The Nitrogen Free Extract (NFE) content, which characterises carbohydrate levels, ranged from 26.15% in mohar to 37.45% in barley. Sudan grass had a value of 35.9%. Thus, barley exhibited the highest carbohydrate saturation, including starch content – 5.2% compared with 2.4% in mohar. No starch was detected in Sudan grass; however, it contained a higher amount of simple sugars 1.85%, compared with 0.12% in barley and 0.05% in mohar. The presence of sugars and a moderate fibre content makes Sudan grass suitable for ensiling.

The mineral composition was expressed as ash content and the levels of macronutrients phosphorus and calcium. Ash content was 6.45% in Sudan grass, 5.25% in mohar, and 2.65% in barley. Phosphorus content was highest in mohar – 0.39%, compared with 0.20% in Sudan grass and 0.15% in barley. Calcium was detected only in Sudan grass (1.15%) and mohar (1.30%), being absent in barley. This confirms that mohar is not only a source of protein and energy but also a complete mineral feed.

The carotene content, an important precursor of vitamin A, was highest in barley 36.9 mg/kg. In mohar and Sudan grass, values were also high 32.1 mg/kg and 29.85 mg/kg, respectively ensuring antioxidant and immunomodulatory functions of the feed (Table 3).

Thus, as a result of agronomic measures involving mineral nutrition and PSB, high nutritional value was achieved in all three crops. The most notable improvements were recorded in mohar, allowing it to be recommended for the production of high-quality protein-energy feeds. Sudan grass demonstrated a balanced composition with a high sugar concentration, whereas barley exhibited stable carbohydrate-vitamin characteristics.

Table 3: Nutritional value of forage grasses (mean values)

Parameters	Crops		
	Barley	Sudangrass	Mohar
Initial moisture, %	9.1	8.02	9.05
Hygroscopic moisture, %	3.05	3.25	3
Dry matter, %	88	89.6	87.95
Protein, %	8.1	10.25	19.4
Fat, %	3.1	1.65	3.7
Fibre, %	34.9	32.95	33.85
Nitrogen-free extract, %	37.45	35.9	26.15
Sugar, %	0.12	1.85	0.05
Starch, %	5.2	ND	2.4
Ash, %	2.65	6.45	5.25
Ca, %	ND	1.15	1.3
P, %	0.15	0.2	0.39
Carotene, mg/kg	36.9	29.85	32.1
Feed unit, FU/kg dry matter	0.52	0.49	0.54
Digestible protein, g/kg	21.1	65.4	114.7
Metabolisable energy, MJ/kg	7.02	6.95	8.15
ECM	0.71	0.7	0.82

Note: n = 3; all values are presented as mean ± SE; statistical differences among crops were assessed using one-way ANOVA with significance set at $p<0.05$. Where applicable, different letters indicate significant differences between means ($p<0.05$)

Initially, prior to the experiment, the soil was characterised by a medium level of nutrient provision. Humus content was 0.74%, available nitrogen 47.6 mg/kg, phosphorus 22 mg/kg, potassium – 100 mg/kg. Based on the sum of readily soluble salts (1.423%), the soil was classified as slightly saline, with predominance of such ions as sulphates (3.31 meq 100 g^{-1}), bicarbonates (0.867), chlorides (0.117), sodium (8.5), calcium (8.13), magnesium (4.97), and potassium (0.06). These data served as a baseline for further comparisons of changes under different nutrition treatments.

By the end of the growing season in autumn, in the group where only mineral fertiliser ($N_{60}P_{90}$+N_{30}) was applied, humus content decreased to 0.55%, likely due to accelerated decomposition of soil organic matter in the absence of biological activity capable of compensating for organic matter losses. Available nitrogen decreased to 42 mg/kg, possibly due to active plant uptake and losses through leaching and denitrification. Available phosphorus remained unchanged at 22 mg/kg, while potassium increased to 130 mg/kg. In this treatment, a slight decrease in total salts to 1.31% was observed, as well as moderate reductions in bicarbonates to 0.76 meq/100 g, sulphates to 3.10 meq/100 g, chlorides to 0.105 meq/100 g, sodium to 7.20 meq/100 g, magnesium to 4.70 meq/100 g, and an increase in potassium to 0.07 meq/100 g. Despite the improvement in potassium status, the reduction in humus and nitrogen makes this treatment less sustainable in the long term.

In the group with only the PSB-based bioformulation, the agrochemical profile was characterised by a more balanced and environmentally sustainable pattern. Humus content increased to 0.75%, exceeding the initial value, indicating activation of microbiological processes contributing to organic matter accumulation. Available nitrogen increased to 56 mg/kg, attributable both to enhanced mineralisation of organic compounds and possible biological nitrogen contribution from associated microbial activity. Available phosphorus rose to 24 mg/kg, and potassium to 140 mg/kg. The salt composition improved significantly: total salts decreased to 1.19%, sodium to 6.4, bicarbonates to 0.71, sulphates to 2.95, chlorides to 0.096. Such changes indicate improved soil buffering capacity, reduced sodium toxicity, and better cation-anion balance. Magnesium and calcium remained at consistently high levels – 4.6 and 8.5 respectively ensuring good exchange capacity. The increase in potassium to 0.08 mEq suggests improved macroelement availability due to the production of organic acids and enzymes by bacteria.

The most pronounced and comprehensive improvements were recorded in the group with combined application of mineral fertiliser and PSB-based bioformulation. Here, humus content was 0.71%, indicating no degradation of the soil organic horizon, unlike the mineral-only treatment. Most strikingly, available phosphorus increased to 62 mg/kg almost three times the baseline value. This confirms the high phosphate-mobilising activity of the bioformulation under conditions where a mineral phosphorus source is supplied. Available nitrogen in this treatment decreased to 36.4 mg/kg, likely due to maximal plant uptake under conditions of intensive growth. Available potassium was 110 mg/kg. Total salts decreased to 1.21%, sodium to 6.9, bicarbonates to 0.735, sulphates to 3.05, chlorides to 0.101, magnesium to 4.65, calcium to 8.2, with potassium remaining elevated at 0.08 mEq. This ionic profile indicates that microbiological activity, in combination with a mineral background, contributes not only to improved element availability but also to stabilisation of the soil salinity regime (Table 4). Despite monitoring pH and electrical conductivity during the experiment, no significant variations across treatments were observed; hence, these indicators were excluded from the table.

Table 4: Agrochemical and saline soil parameters before and after the experiment

Parameters	Before experiment (spring)	Mineral fertiliser (autumn)	PSB treatment (autumn)	Mineral fertiliser + PSB (autumn)
Humus, %	0.74	0.55	0.75	0.71
Available nitrogen, mg/kg (N)	47.6	42.0	56.0	36.4
Available phosphorus, mg/kg (P_2O_5)	22.0	22.0	24.0	62.0
Available potassium, mg/kg (K_2O)	100.0	130.0	140.0	110.0
Total salts, %	1.423	1.31	1.19	1.21
Bicarbonates (meq/100 g HCO_3^-)	0.867	0.76	0.71	0.735
Sulphates (meq/100 g SO_4^{2-})	3.31	3.1	2.95	3.05
Chlorides (meq/100 g Cl^-)	0.117	0.105	0.096	0.101
Sodium (meq/100 g Na^+)	8.5	7.2	6.4	6.9
Calcium (meq/100 g Ca^{2+})	8.13	8.0	8.5	8.2
Magnesium (meq/100 g Mg^{2+})	4.97	4.7	4.6	4.65
Potassium (meq/100 g K^+)	0.06	0.07	0.08	0.08

Note: n = 3; all values are presented as mean ± SE; statistical differences among treatments were assessed using one-way ANOVA with significance set at $p<0.05$. Different letters within rows (where applicable) indicate significant differences between means ($p<0.05$). pH and electrical conductivity were measured during the experiment but are not presented as they showed no statistically or practically significant variation among treatments

The field experiment was performed in a single-season open-field setting; hence, meteorological variables such as temperature and precipitation may have affected crop growth and yield development. During the growing season, the mean air temperature and total precipitation were close to the long-term regional averages, with no extreme drought or excessive rainfall events recorded. Throughout the growing season, climatic conditions were predominantly conducive to forage crop development; nevertheless, transient fluctuations in precipitation and temperature may have influenced nutrient absorption and biomass growth. These environmental parameters must be taken into account while analysing the acquired data and generalising them to other agro-climatic zones.

The alterations in soil nutrient levels were directly manifested in plant growth and production outcomes. The decrease in accessible nitrogen in the mineral fertiliser treatment correlated with less stable development of generative structures across all crops, despite some instances of increased biomass, suggesting that nitrogen losses were not entirely offset by plant uptake efficiency and that reduced nitrogen availability limited protein synthesis and consequently constrained the development of reproductive organs and the formation of productive shoots. Conversely, the PSB treatment augmented nitrogen availability and stabilised humus content, correlating with increased tillering and a greater quantity of productive shoots among all species, which can be explained by improved nitrogen retention in soil organic matter and enhanced nitrogen mineralisation stimulated by microbial activity, resulting in better vegetative development and shoot proliferation.

The stabilisation of salinity parameters, particularly the decreases in sodium and chloride ions in the PSB-containing treatments, likely alleviated ionic stress in the rhizosphere, hence enhancing nutrient uptake efficiency. This reduction in soil salinity improved root physiological functioning, including membrane permeability and ion selectivity, thereby facilitating more efficient uptake of nitrogen, phosphorus, and potassium. The observed enhancements in morphology and yield can be regarded as a direct physiological response to enhanced soil nutrient availability and a more balanced ion composition, rather than merely attributable to fertiliser input levels. In particular, improved phosphorus availability in PSB-treated soils strengthened root development and energy metabolism, which directly translated into more intensive tillering, stem elongation, and formation of reproductive organs.

Thus, the use of PSB should be regarded as an effective biological tool for enhancing soil fertility, enabling stabilisation of the agroecosystem and ensuring sustainable productivity when mineral nutrition is applied rationally. Compared with earlier studies that focused mainly on either yield response or isolated soil chemical parameters, this study demonstrates an integrated plant-soil response, linking nutrient mobilisation, salinity regulation, and productivity within a single field framework. This approach not only increased available phosphorus content and improved potassium status but also prevented degradation of the humus horizon. Concurrently, ionic composition was balanced and salinity reduced, particularly with respect to sodium and chlorides. These combined effects indicate that PSB function not only as a phosphorus-mobilising agent but also as a regulator of soil chemical stability under field conditions.

The synergistic application of $N_{60}P_{90}$+N_{30} with PSB exhibits a distinct agronomic advantage: it reduces dependence on mineral fertilisation alone while concurrently facilitating the progressive restoration of degraded soil structure and enhancement of soil biological activity.

Thus, the results obtained demonstrated a consistent stimulation of forage crop growth when mineral fertiliser and the phosphate-mobilising bioformulation were applied together. This pattern of response was consistently reflected across all measured parameters, confirming a direct causal relationship between treatment type, soil nutrient availability, and plant productivity. In the case of mohar, this combined approach increased all morphometric parameters, particularly spike length, which rose by almost 1.7-fold compared with the control. Although the bioformulation alone did not promote increased plant height, its influence on the formation of secondary shoots and productive spikes was significant. A similar trend was observed in Sudan grass, where maximum values at the heading stage were recorded under combined application, indicating a pronounced synergistic effect. In barley, comparable results confirmed that biological nutrition actively stimulates tillering, whereas mineral nutrition predominantly affects biomass gain and the productive part of the plant. Green mass and dry matter yield also showed positive dynamics in all crops under bioformulation use. Sudan grass was particularly notable, showing the largest increases in dry matter yield. Overall, the crop-specific responses suggest a consistent functional pattern: PSB primarily enhance plant architectural development (tillering and shoot formation), while mineral fertilisation supports biomass accumulation, and their combination ensures balanced yield formation across C3 and C4 forage species.

Recent integrated geoecological studies conducted within the same transboundary hydro-ecological system of the Yertis River basin, including the works by [15, 16], provide important evidence on chemical environmental stabilisation processes, salinity regulation, and pollution control mechanisms in closely related regional agro ecosystems. These studies are particularly relevant because they describe long-term soil-water-salt interaction dynamics and environmental buffering processes within the same geographical and hydro-ecological context, thereby directly supporting the interpretation of improved salinity balance, reduced ionic stress, and enhanced agrochemical stability observed in the present experiment.

In this regard, the studies by [17, 18] focused on phosphorus nutrition in agricultural crops within the framework of sustainable agriculture. Poonia considered the potential of biofertilisers in agroecosystems but limited the discussion to a general description of benefits without analysing specific quantitative effects on productivity or plant chemical composition. [18] demonstrated that the return of crop residues can activate the phosphorus cycle and improve phosphorus uptake in maize, but did not investigate the involvement of specific phosphate-mobilising strains or include yield or quality indicators in the analysis. Unlike these studies, the present research recorded high efficiency from the combined use of mineral fertiliser and the bioformulation: green mass yield in Sudan grass increased by 15.7 t ha^{-1}, and digestible protein content in foxtail millet reached 114.7 g/kg. This effect was accompanied by improved soil conditions, including increased humus content and reduced salinity, confirming the agroecological effectiveness of the proposed technology.

In addition, the results of [19, 20] addressed the application of microbial inoculants under conditions of limited phosphorus availability. [19] focused on the stimulation of plant growth by plant growth-promoting rhizobacteria; however, they did not assess their effect on forage quality, nor did they analyse interactions with the mineral nutrient background. [20] investigated the effect of biofertilisers on *Andrographis paniculata* (green chiretta) and noted a slight improvement in phosphorus availability in the soil, but yield parameters remained at the control level. In contrast, the present study demonstrated the effectiveness of a combined approach: the application of mineral fertiliser ($N_{60}P_{90}$+N_{30}) in conjunction with PSB led to a substantial increase in plant productivity, raising crude protein content to 19.4% and metabolizable energy to 8.15 MJ kg^{-1}, thus making this technology promising for protein-energy forage production.

Finally, the works of [21, 22] complemented the scientific picture with studies of microbe plant interactions under phosphorus deficiency. [21] recorded a positive effect of Serratia spp. on peanut and maize, but confined their analysis to physiological responses of plants without assessing forage nutritive value or soil parameters. [22] substantiated the role of mycorrhizae and associated bacteria in enhancing crop growth, with key conclusions focusing on tolerance mechanisms rather than productivity or chemical composition. Unlike these studies, the present work encompassed the full range of indicators: biomass, chemical composition, macroelement content, protein quality, and the dynamics of humus and salts in the soil. This broader analytical scope allows the present study to move beyond single-factor assessments and provide a systems-level evaluation of PSB performance under field conditions.

Additionally, the study by [23] emphasised the potential of biological phosphorus sources in sustainable agriculture. The authors considered biofertilisers as a microbiological strategy for improving plant growth and soil health, with emphasis on the principles of bacterial interaction with the rhizosphere; however, they did not provide a quantitative assessment of technological efficiency on specific crops. In contrast, the present study recorded not only an increase in biomass and nutritional value (e.g., 114.7 g digestible protein in foxtail millet) but also improvements in the soil profile for key parameters such as humus, available phosphorus, and reduced salinity, thereby confirming the practical applicability of the model.

The works of [24], 25] examined the prospects and limitations of liquid biofertilisers and engineering solutions for microbiota delivery into the soil. Richa noted the potential effectiveness of liquid bioformulations, but the focus was primarily on production-related technological challenges and the need for strain stability, rather than agronomic effects. [25] investigated the porosity of hydrochar as a vector for bacterial delivery, discussing the innovative properties of the carriers; however, these developments were largely confined to theoretical and laboratory contexts. Unlike the aforementioned studies, the present work demonstrated a realised field effect: an increase in green biomass yield to 19.81 t ha^{-1}, crude protein content to 19.4%, and an overall improvement in the ionic composition of the soil after the growing season, making the results readily applicable in farm-scale conditions.

Furthermore, [26, 27] examined the effects of biofertilisers on peanut productivity and phosphorus regimes in sloping soils. [26] summarised data on the influence of microbiological inoculants on peanut productivity and aflatoxin reduction, but without forage-quality analysis, which limits applicability in feed systems. [27] assessed phosphatase activity and phosphorus-related genes under maize cultivation, demonstrating an increase in available phosphorus under integrated agronomic practices; however, the study did not include plant productivity or nutritive value data. Unlike these authors, the present research covered the entire production chain from plant morphometry and yield to chemical composition, including energy and protein metrics, as well as the agrochemical status of the soil thus allowing the proposed technology to be considered complete and ready for practical implementation.

In addition to these studies, [28, 29] focused on technologies for the production and biotransformation of biofertiliser components. [28] considered various methods of encapsulating and delivering microorganisms to the rhizosphere, relevant for product stability, but did not accompany this with an assessment of the effect of such bioforms on crop productivity or soil conditions. In the study by [29], the emphasis was placed on processing agro-industrial waste by microbiological means to improve soil health and yield, without evaluating macroelement composition or plant physiological traits. In contrast, the present study not only assessed the efficacy of the biopreparation but also provided a detailed analysis of forage nutritive value (including digestible protein, fat, metabolizable energy) and the dynamics of humus content, available phosphorus, and soil salt balance, making it more comprehensive and applied than laboratory-scale developments.

Meanwhile, the studies by [30, 31] examined the effects of bioinoculants on horticultural and model cereal crops. [30] substantiated the contribution of biopreparations to improving fruit quality and plant growth activity, but without direct comparison to mineral nutrition or analysis of soil salinity profiles. In the dissertation by Baudson, the effect of PSB on developmental plasticity of Brachypodium distachyon was analysed, describing morphological plant responses, but without quantitative data on yield, nutritive value, or agrochemical changes. In contrast, the present work encompassed the full cycle of a field experiment from biomass and ear length to humus level, content of available nitrogen forms, and salinity degree thereby enabling the direct application of the results in forage production and restorative agriculture.

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Similarly, the studies of [32, 33] addressed microbial diversity and strategies to enhance soil fertility in coastal agriculture and degraded lands. [32] emphasised the importance of maintaining the soil microbiome as a factor in agroecosystem resilience; however, their analysis remained at the level of an ecosystem review, without reference to specific crops or yield measurements. Sekhon and Keshani highlighted the need to improve the composition of microbial inoculants and to monitor their activity, but the practical aspects of their use in real agro-landscapes were only partially addressed. In contrast, in the present study, the proposed fertilisation system (mineral component and PSB) demonstrated pronounced improvements across all target indicators from morphometry and productivity to enhanced mineral nutrition rendering it highly effective in applied and commercial agrotechnologies. The previous analysis showed that most studies were limited to theoretical approaches, laboratory conditions, or isolated aspects of biofertilizer impact. Unlike these, the present study encompassed the full cycle from plant growth and yield to forage value and the agrochemical status of the soil making it more comprehensive and practice-oriented.

The originality of this study resides in the comprehensive assessment of PSB under combined mineral-biological fertilisation, concurrently connecting plant morphogenesis, yield development, feed quality, and soil salinity fluctuations within a unified experimental framework.

Conclusion

In the course of this study, a comprehensive agro-ecological and economic assessment was conducted on the efficacy of a PSB-based biopreparation in fertilisation systems for forage crops under various application schemes. The test crops were barley (*Hordeum vulgare*), Sudan grass (*Sorghum sudanense*), and Mohar (*Setaria italica*), cultivated on light loamy soils with signs of slight salinity, representing vulnerable agroecosystems where nutrient limitation and salt stress simultaneously constrain productivity and soil functionality.

The experiment included four main fertilisation schemes: control (no treatment), mineral fertiliser only ($N_{60}P_{90}$+N_{30}), biopreparation only (PSB-based bioformulation), and their combined application. Based on the data obtained, the greatest efficiency was observed under the combined application of mineral fertiliser and PSB based bioformulation. This treatment consistently outperformed all other variants across all studied crops. In all crops, this treatment provided the highest values for both vegetative growth (plant height, number of stems and ears) and generative development (ear length, above-ground biomass, dry matter yield), demonstrating that biological-mineral integration enhances both productivity and resource-use efficiency at the system level rather than only at the plant level.

In Sudan grass, maximum height reached 36.4 cm, the number of stems reached 10, the number of ears reached 9, and ear length reached 43.5 cm. In barley, plant height reached 33.4 cm, with a green mass yield of 1.62 t ha^{-1}, which was 0.16 t ha^{-1} (10.9%) above the control. In mohar, maximum ear length reached 23.4 cm, representing an increase of 69.6% compared with the control. These results confirm a stable and crop-consistent positive response to integrated PSB and mineral nutrition.

The PSB-based bioformulation applied without mineral background had a positive effect on the number of tillers, productive stems, and protein content, especially in Sudan grass and barley. This indicates that PSB can effectively enhance phosphorus availability even under reduced mineral input conditions. In mohar, protein content was 19.4%, digestible protein 114.7 g kg^{-1}, and metabolizable energy 8.15 MJ kg^{-1}, indicating high forage value and suitability for inclusion in the diets of productive livestock. Agrochemical analyses showed that PSB application contributed to improving soil humus status (up to 0.75%), increasing available phosphorus content (up to 62 mg kg^{-1}) and potassium (up to 140 mg kg^{-1}), while simultaneously reducing total soluble salts (to 1.19%).

A decrease was also observed in the concentrations of sodium ions, chlorides, bicarbonates, and sulphates, indicating stabilisation of the ionic balance and improvement of the buffering capacity of the soil solution. Overall, PSB application improved both soil fertility indicators and salinity-related parameters. Thus, the study confirmed the feasibility of using PSB-based bioformulations as a biological component of fertilisation systems. Their integration with mineral fertilisation demonstrates a clear synergistic effect, leading to simultaneous improvements in crop productivity, forage quality, and soil chemical stability.

This study's innovation is in showing that the integration of mineral fertiliser (N60P90+N30) and PSB diminishes reliance on chemical fertilisers while aiding in the partial restoration of degraded soil structures by enhancing nutrient cycling, phosphorus mobilisation, and stabilising soil salinity and humus equilibrium in field conditions, thereby positioning PSB as a key component in the transition toward low-input, environmentally sustainable agricultural systems.

The findings underscore the significant agro-ecological role of PSB as a sustainable approach to enhance soil fertility, improve nutrient cycling efficiency, and diminish reliance on mineral phosphorus inputs, thus promoting long-term soil health and stability of agroecosystems, with particular importance for maintaining soil productivity under conditions of salinity stress and progressive soil degradation, where conventional fertilisation alone is insufficient to ensure long-term sustainability.

The study offers strong single-season field evidence; however, its limitations arise from the lack of multi-year observations and analysis of seasonal climatic variability, which could affect the stability and reproducibility of the observed effects under varying agro-meteorological conditions. Future research should focus on long-term, multi-season field experiments, coupled with continuous agro-meteorological monitoring, to quantify annual variability and enhance the predictive reliability of PSB-based fertilisation techniques. Moreover, broadening the experimental design to encompass a wider variety of soil types, salinity gradients, and climatic zones would facilitate the validation of the technology across diverse agroecological settings and enhance its applicability to various agricultural systems. Subsequent research may incorporate soil microbiome characterisation and nutrient cycling kinetics to elucidate the biological mechanisms underlying PSB efficiency and to improve application rates for various crop species and environmental conditions.

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Author’s Contributions

Zhanar Zhumadilova: Conceptualization, data curation, formal analysis, funding acquisition.
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Gulsim Baimbetova: Resources, write original draft, project administration.
Aidos Zhalbyrov: Investigation, write original draft, write review and edited.
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Ethics

The study was conducted without human participation. Ethical approval is not required.

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