Research Article

Phosphate-solubilizing microorganisms and phosphorus rates affecting yield, nutrient uptake and economic viability of corn and rice in the off-season[1]

Dennis Ricardo Cabral Cruz[2], Adriano Stephan Nascente[3], Izabely Vitória Lucas Ferreira[4], Natasha Ohanny da Costa Monteiro[5], Gabriella Alves Duarte[4], Izaque de Sousa Rocha[3]

ABSTRACT

Increasing crop yield using bio-inputs and optimized fertilizer application is a key strategy for agricultural sustainability. This study aimed to evaluate the effects of inoculation with phosphate-solubilizing microorganisms combined with phosphorus rates on the agronomic performance, production costs and sustainability in off-season corn and upland rice cultivation. The experiment was conducted using a 2 x 4 factorial design for both crops. Treatments consisted of two phosphorus levels [50 % (45 kg ha^{-1} of P_2O_5) and 100 % of the recommended rate (90 kg ha^{-1} of P_2O_5)], three isolates of multifunctional rhizobacteria [*Burkholderia* sp. (BRM 32111), *Serratia* sp. (BRM 63523) and *Bacillus* sp. (BRM 63524)] and a control treatment (no rhizobacteria). The inoculation with BRM 63524 increased the biomass and nutrient accumulation for both corn and upland rice, highlighting its potential to enhance nutrition and reduce the reliance on synthetic fertilizers, despite the variation in the rice yield response. The reduced phosphorus application (50 % of the recommended dose) generated higher profits, especially for corn, which showed the highest yields and profitability. For rice, the combination of a lower phosphorus rate with rhizobacteria resulted in greater profits than for the full phosphorus application.

KEYWORDS: *Zea mays*, *Oryza sativa*, *Bacillus*, *Burkholderia*, *Serratia*.

RESUMO

Micro-organismos solubilizadores de fosfato e doses de fósforo afetando a produtividade, acúmulo de nutrientes e viabilidade econômica de milho e arroz em safrinha

O aumento da produtividade de culturas, aliado à aplicação de bioinsumos e otimização do uso de fertilizantes, é uma estratégia importante para a sustentabilidade agrícola. Objetivou-se avaliar os efeitos da inoculação com micro-organismos solubilizadores de fósforo associada a doses de fósforo, no desempenho agronômico, custos de produção e sustentabilidade do cultivo de milho e arroz de terras altas conduzidos na safrinha. Utilizou-se delineamento experimental fatorial 2 x 4 para as duas culturas. Os tratamentos foram compostos por dois níveis de fósforo [50 % (45 kg ha^{-1} de P_2O_5) e 100 % da dose recomendada (90 kg ha^{-1} de P_2O_5)], três isolados de rizobactérias multifuncionais [*Burkholderia* sp. (BRM 32111), *Serratia* sp. (BRM 63523) e *Bacillus* sp. (BRM 63524)] e um tratamento controle (sem rizobactérias). A inoculação com BRM 63524 aumentou a biomassa e o acúmulo de nutrientes no milho e arroz, destacando seu potencial para melhorar a nutrição e reduzir a dependência de fertilizantes, apesar da variação na resposta produtiva do arroz. A aplicação reduzida de fósforo (50 % da dose recomendada) gerou maiores lucros, com destaque para o milho, que apresentou maiores produtividades e lucratividade. Para o arroz, a combinação de menor dose de fósforo com rizobactérias resultou em maiores lucros do que a dose completa de fósforo.

PALAVRAS-CHAVE: *Zea mays*, *Oryza sativa*, *Bacillus*, *Burkholderia*, *Serratia*.

INTRODUCTION

To meet the demands of a growing global population - projected to reach 8.5 billion people by 2030 (UN 2021) - food production must increase. This need, coupled with the demand for sustainable production, intensifies pressure to boost the yield of major crops such as corn, wheat, rice and soybean, which account for the highest global production volumes (FAO 2022a).

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[2] Universidade Estadual de Goiás, Unidade Universitária Posse, Posse, GO, Brazil.
E-mail/ORCID: denisribral@gmail.com/0000-0002-5209-7751.
[3] Empresa Brasileira de Pesquisa Agropecuária (Embrapa Arroz e Feijão), Santo Antônio de Goiás, GO, Brazil.
E-mail/ORCID: adriano.nascente@embrapa.br/0000-0002-6014-3797; izaque.rocha@embrapa.br/0009-0000-4452-9764.
[4] Universidade Federal de Goiás, Escola de Agronomia, Goiânia, GO, Brazil.
E-mail/ORCID: izabelyvitoria1995@gmail.com/0000-0002-6027-5474; galvesduarte1@gmail.com/0009-0004-5386-1549.
[5] Universidade de Brasília, Faculdade de Agronomia e Medicina Veterinária, Brasília, DF, Brazil.
E-mail/ORCID: natasha.ohanny@gmail.com/0000-0003-0453-9727.

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The continuous demand for food has led conventional agriculture to rely heavily on chemical inputs. Thus, beyond population growth, several pressing issues require solutions, including the reduction of excessive pesticide use and the high dependency on synthetic fertilizers (Monteiro et al. 2024).

In Brazil, the second cropping season is typically sown from January onwards and has become a key agricultural strategy for increasing yield and sustainability in the Brazilian agribusiness (Jesus et al. 2023). Originally limited to corn, it now includes other crops of interest, such as rice, offering alternatives for crop diversification and year-round land-use optimization (Silva et al. 2022a). This production model seeks to maximize yields without expanding agricultural land - a critical factor for both environmental and economic sustainability in Brazil, a globally significant grain producer (Monteiro et al. 2024).

The application of plant growth-promoting rhizobacteria has shown promising results in enhancing crop yield. According to Silva et al. (2022b), these microorganisms can solubilize nutrients and stimulate plant growth, increasing the resistance to both biotic and abiotic stresses. Studies have demonstrated that plant growth-promoting rhizobacteria inoculation can improve nutrient use efficiency and crop yields in corn (Cruz et al. 2023) and rice (Nascente et al. 2017), particularly in soils with limitations that hinder plant development.

Phosphorus (P) is an essential nutrient, but its availability is often restricted due to chemical and physical fixation in the soil, forming complexes unavailable to plants (Sasabuchi et al. 2023). To overcome this limitation, high doses of phosphate fertilizers are commonly applied, increasing both production costs and environmental risks, such as eutrophication. In this context, phosphorus-solubilizing rhizobacteria represent a promising alternative, as they can mobilize fixed soil phosphorus and make it available to plants (Parra et al. 2022).

Research has shown that such rhizobacteria enhance phosphorus availability and crop growth (Gupta et al. 2022, Cruz et al. 2024b, Sanadhya et al. 2025). Cruz et al. (2025a) demonstrated that soybean yields can be maintained or even improved using only 50 % of the recommended phosphorus dose, when inoculated with the strains BRM 32111 (*Burkholderia* sp.), BRM 63523 (*Serratia* sp.) and BRM 63524 (*Bacillus* sp.). Similar results were reported by Oliveira-Paiva et al. (2024) for corn, with field trials showing that rhizobacterial inoculation enabled a 50 % reduction in phosphate fertilization while maintaining or increasing grain yields by up to 15.9 %, if compared to treatments with 100 % of phosphorus without inoculants. Fitriatin et al. (2022) further demonstrated that the inoculation with *Burkholderia* sp. and *Penicillium* sp. increased the soil acid phosphatase activity, phosphorus availability, plant phosphorus content and crop yield, even with only 75 % of the recommended phosphate fertilization. By integrating optimized phosphorus doses with rhizobacterial inoculation, nutrient uptake in corn and rice can be maximized, thereby enhancing crop yield and sustainability.

In addition to yield, the economic viability of crop systems is a key consideration. Cost-benefit analysis is essential to assess the profitability of agricultural practices (Bezerra et al. 2020). According to Cruz et al. (2024b), adopting technologies that enhance yield - such as rhizobacterial inoculation and optimized nutrient management - can significantly increase the farmers' income. Therefore, it is crucial to evaluate not only agronomic outcomes, but also the financial implications of cultivation practices.

Despite the demonstrated benefits of diversifying cropping systems and using phosphate-solubilizing microorganisms in agriculture, few studies have assessed both strategies in combination and their economic feasibility. Thus, this study aimed to evaluate the effects of inoculation with phosphorus-solubilizing microbial strains in combination with phosphorus fertilization levels on the agronomic performance, production costs and sustainability of corn and upland rice cultivated during the off-season.

MATERIAL AND METHODS

The experiment was conducted under no-tillage conditions at the Embrapa Arroz e Feijão, in Santo Antônio de Goiás, Goiás state, Brazil (16º28′00″S, 49º17′00″W and 823 m of altitude), during the 2023 and 2024 second crop seasons. The region has an AW Tropical climate, according to the Köppen classification, with average temperature of 23.3 ºC and annual rainfall of 1,428 mm. The climatic data were monitored throughout the experimental period, and pivot irrigation was applied when necessary to meet the crop water requirements (Figure 1). Prior to the experiment, soil fertility was analyzed at the 0-0.20 m layer. The soil was classified as Acric Red Latosol with a clayey texture (Teixeira et al. 2017), equivalent to Acric Rhodic Ferralsol (clayey) (FAO 2022b), and presented the following characteristics: pH (H_2O) = 5.8; organic matter = 33.8 g kg^{-1}; P-Mehlich = 12.9 mg dm^{-3}; K = 2 mmol$_c$ dm^{-3}; Ca^{2+} = 14.2 mmol$_c$ dm^{-3}; Mg^{2+} = 6.1 mmol$_c$ dm^{-3}; Al^{3+} = 1 mmol$_c$ dm^{-3}; H + Al = 27 mmol$_c$ dm^{-3}; SB = 22.3 mmol$_c$ dm^{-3}; Cu^{2+} = 1.4 mg dm^{-3}; Zn^{2+} = 4.3 mg dm^{-3}; Fe^{3+} = 21 mg dm^{-3}; Mn^{2+} = 13.7 mg dm^{-3}.

The experiment was carried out in a single experimental area where corn and upland rice were grown simultaneously, but evaluated independently. A randomized block design was used in a 2 × 4 factorial scheme, with four replicates for each crop. Treatments consisted of two phosphorus application rates [50 % (45 kg ha^{-1} of P_2O_5) and 100 % (90 kg ha^{-1} of P_2O_5) of the recommended dose], three isolates of multifunctional rhizobacteria [*Burkholderia* sp. (BRM 32111), *Serratia* sp. (BRM 63523) and *Bacillus* sp. (BRM 63524)] and a control (no microorganisms). Plots measured 10 × 4.5 m, with a useful area defined as the central 2.7 m, excluding 0.90 m from each lateral edge. Data analysis was performed separately for each crop, with no direct comparisons between corn and rice.

The AG 8088 corn cultivar and the BRS A 501 CL upland rice cultivar were sown in February of each year, following the summer soybean harvest. Harvests took place in May, covering both crop seasons (2023 and 2024). Crop establishment and management followed species-specific technical recommendations. Basal fertilization, excluding phosphorus, was determined based on soil analysis and crop requirements.

The rhizobacterial isolates used in the experiment were obtained from the Embrapa Arroz e Feijão Collection of Multifunctional Microorganisms and were identified as phosphorus-solubilizing bacteria based on their biochemical characteristics (Table 1). Bacterial suspensions were prepared in nutrient broth from cultures grown for 24 hours on solid nutrient agar at 28 ºC. The concentration was adjusted to A_{540} = 0.5 (10^8 CFU) (Fillipi et al. 2011). Suspensions were applied directly into the sowing furrow using a furrow sprayer (Micron®) at the dose of 300 mL ha^{-1}, with a total spray volume of 20 L ha^{-1}.

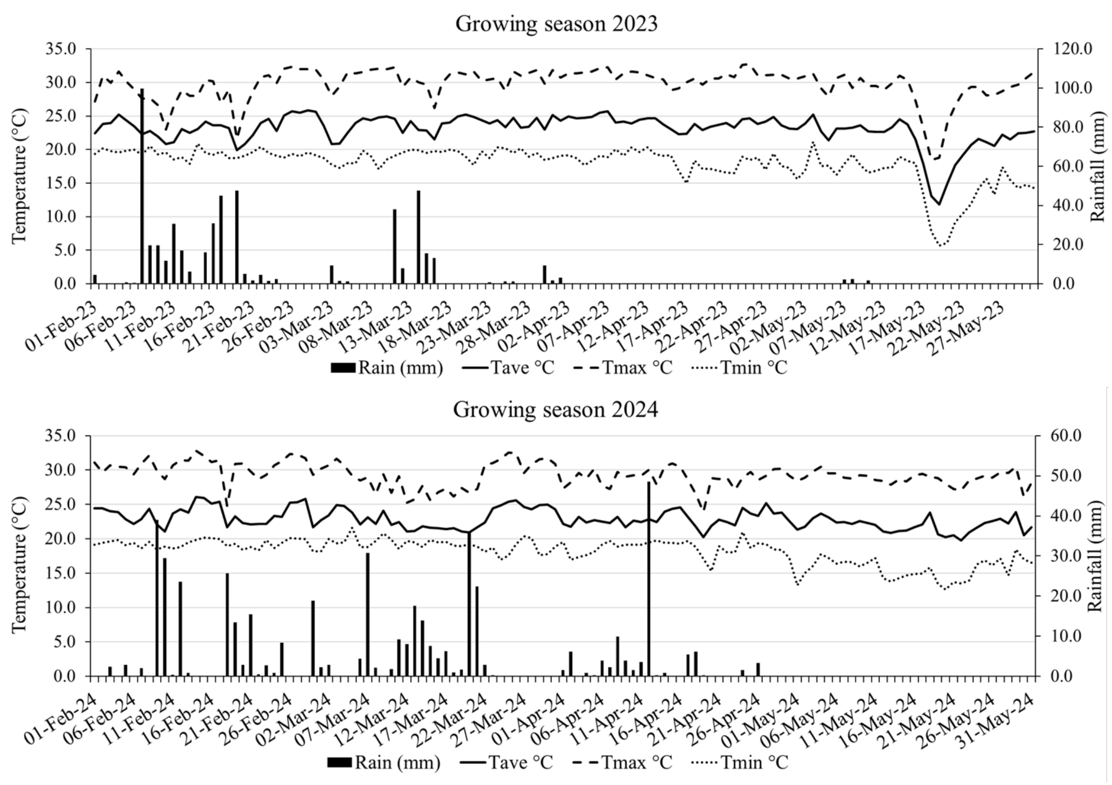

Figure 1. Temperature and rainfall during the growing of corn and upland rice in the 2023 and 2024 off-season in Santo Antônio de Goiás, Goiás state, Brazil. Tmax: maximum temperature; Tmin: minimum temperature; Tave: average temperature.

Table 1. Collection code, biochemical traits and taxonomic classification of the three isolates used in this study originated from the Pará state, Brazil.

Code	Colony color	Biochemical characterization*					Taxonomy**
		Indole-3-acetic acid	Cellulase	Phosphatase	Siderophore	Biofilm	
BRM 32111	Yellow	-	+	+	+	+	*Burkholderia* sp.
BRM 63523	Red	-	+	+	+	+	*Serratia* sp.
BRM 63524	Yellow	+	+	+	+	-	*Bacillus* sp.

* Cruz et al. (2025b); ** Nascente et al. (2017).

The crops were mechanically harvested at the physiological maturity within the useful plot area. Grain yield from each plot was collected in cloth bags and weighed. Yields were expressed in kilograms per hectare and corrected to 13 % of moisture. Additionally, ten plants randomly selected from the useful area of each plot were harvested to determine the 100-grain weight for corn and 1,000-grain weight for upland rice, both adjusted to 13 % of moisture (Nascente et al. 2017).

To evaluate the dry matter accumulation, 1 m² samples of corn and rice plants were collected at 70 days after sowing (DAS) (Nascente et al. 2013). After the dry matter determination, subsamples were taken to assess the concentrations of N, P, K, Ca, Mg, Fe, Cu, Zn and Mn in the plant straw (Claessen 1997). The nutrient accumulation per hectare was calculated by multiplying the nutrient concentrations by the corresponding plant dry matter values.

The economic analysis was conducted using the partial budgeting method described by Noronha (1987), which considers the additional costs and revenues of treatments relative to a baseline. Differential profit (DP) was used as the economic indicator and calculated using the following equation: $DP = DR - DC$, with the differential revenue (DR) calculated for each treatment based on yield and the historical average deflated prices of corn and rice over the past five years in Goiás (Agrolink 2024) - the only source with a 10-year historical series. The DR was obtained by multiplying the mean yield of each treatment combination (crop × microorganism × phosphorus dose) by the deflated prices of 60 kg bags of corn (US$ 11.01) and rice (US$19.35), and the differential cost (DC) included the cost of treatment-specific inputs, as well as operational, administrative, maintenance, depreciation and remuneration expenses. Variables in the cost analysis included seed prices for each crop, the two phosphorus doses (50 or 100 %) and the presence or absence of microorganism inoculation, with bacterial suspension costs based on the recommended dose of 300 mL ha^{-1}.

All values were converted to US dollars at the exchange rate on August 30, 2024 (US$ 1.00 = R$ 5.67). The data were subjected to analysis of variance, and when the F-test indicated significance, means were compared using the LSD test at $p < 0.05$. Statistical analyses were performed using the Sisvar software version 5.6.

RESULTS AND DISCUSSION

The BRM 63524 application was the only treatment to show a statistically significant improvement, when compared to the control, resulting in a 3.9 % increase in the 100-grain weight of corn (Table 2). This effect may be attributed to enhanced nutrient availability or beneficial interactions with the root system, leading to greater biomass accumulation. The *Bacillus* genus is widely studied for its ability to produce phytohormones and enzymes that stimulate plant growth, as well as for facilitating the uptake of essential nutrients important for grain filling

Table 2. One hundred-grain weight (M100) of corn and one thousand-grain weight (M1000) of upland rice as influenced by the application of the isolates BRM 32111, BRM 63523, BRM 63524 and a control (no microorganisms), and by phosphorus dose (50 and 100 %), averaged over the 2023 and 2024 seasons.

Treatments	M100 (g)	M1000 (g)
Microorganism		
BRM 32111 (*Burkholderia* sp.)	20.93 ab*	17.45 b
BRM 63523 (*Serratia* sp.)	20.51 b	18.71 a
BRM 63524 (*Bacillus* sp.)	21.15 a	18.34 a
Control	20.35 b	17.65 b
Phosphorus doses		
Half	20.75^{ns}	18.34^{ns}
Full	20.72	17.73

* Means followed by the same letter do not differ by the LSD test ($p < 0.05$); ^{ns} non-significant according to the Anova.

(Ferreira et al. 2021). The BRM 63523 and BRM 63524 isolates also showed statistically superior performance, when compared to the control, for the 1,000-grain weight of upland rice (Table 2), with increases of 6.0 and 3.9 %, respectively. Fernandes et al. (2020) found that the highest 1,000-grain weights in upland rice were achieved with *Bacillus*-inoculated plants, significantly outperforming uninoculated controls. Similarly, Nascente et al. (2020) reported an increase of 1,000-grain weight in upland rice following *Serratia* inoculation, in relation to the control.

The interaction between microorganisms and phosphorus doses showed that corn grain yield was higher with BRM 32111 and BRM 63524 under 50 % of phosphorus application, as well as with BRM 63523 and the control under 100 % of phosphorus (Table 3). This increase in yield may be attributed to the beneficial effects of phosphorus-solubilizing microorganisms and enhanced availability of non-labile phosphorus reserves in the soil (Timofeeva et al. 2022). BRM 32111 and BRM 63524, when combined with 50 % of the recommended phosphorus dose, yielded increases of 18.7 and 20.8 %, respectively, when compared to the 50 % phosphorus control. Previous studies have shown that *Burkholderia* and *Bacillus* isolates can improve nutrient uptake - especially phosphorus - promoting greater growth and yield, even under reduced fertilizer application (Kalayu 2019, Oliveira-Paiva et al. 2022, Cruz et al. 2024b). The strong performance of the control treatment at 100 % of phosphorus suggests that full phosphorus fertilization is effective, but its combination with microorganisms can further enhance results and contribute to a more sustainable production.

The interaction between microorganisms and phosphorus doses also led to higher grain yields in upland rice, when BRM 63523 and BRM 63524 were applied with 50 % of phosphorus (Table 4). These results were comparable to those obtained with BRM 63524 combined with 100 % of phosphorus and with the control treatment under 100 % of phosphorus. BRM 63523 and BRM 63524 with 50 % of phosphorus led to yield increases of 157 and 181 %, respectively, when compared to the 50 % of phosphorus control. This effect may be attributed to the microorganisms' ability to enhance phosphorus availability in the soil and stimulate plant growth through nutrient solubilization and phytohormone production (Gupta et al. 2022). Silva et al. (2023) reported an increase of up to 18 % in upland rice grain yield following coinoculation with *Bacillus* and *Azospirillum*. Nascente et al. (2020) showed that, in the absence of phosphorus, *Serratia*-treated rice produced 23 % more grains than the control and showed no statistical difference from phosphorus-fertilized plants, suggesting that microbial-solubilized phosphorus was sufficient to sustain yield. These microorganisms can mineralize non-labile phosphorus, making it available to plants (Martins 2015), and solubilize insoluble phosphate compounds by secreting organic acids and enzymes, thereby compensating for reduced phosphorus application (Cruz et al. 2024a).

The application of the BRM 63524 isolate to corn resulted in an average dry matter accumulation 14.3 % higher than in uninoculated plants, reflecting a greater efficiency in converting resources into biomass (Table 5). This effect may be linked to phytohormone production, phosphorus solubilization and improved nutrient uptake associated with the

Table 3. Corn grain yield as influenced by application of BRM 32111, BRM 63523, BRM 63524 and a control (no microorganisms), and by phosphorus dose (50 and 100 %), averaged over the 2023 and 2024 seasons.

Microorganism	Corn yield (kg ha^{-1})	
	Phosphorus doses	
	50 %	100 %
BRM 32111 (*Burkholderia* sp.)	10,624 aA*	8,823 aB
BRM 63523 (*Serratia* sp.)	9,454 abA	9,027 aA
BRM 63524 (*Bacillus* sp.)	1,0817 aA	8,352 aB
Control	8,942 bA	9,362 aA

* Means followed by the same letter - lowercase in the columns, uppercase in the rows - do not differ by the LSD test ($p < 0.05$).

Table 4. Upland rice grain yield as influenced by application of BRM 32111, BRM 63523, BRM 63524 and a control (no microorganisms), and by phosphorus dose (50 and 100 %), averaged over the 2023 and 2024 seasons.

Microorganism	Rice yield (kg ha^{-1})	
	Phosphorus doses	
	50 %	100 %
BRM 32111 (*Burkholderia* sp.)	2,354 bA*	3,704 abA
BRM 63523 (*Serratia* sp.)	5,062 aA	2,157 bB
BRM 63524 (*Bacillus* sp.)	5,532 aA	4,383 aA
Control	1,967 bB	4,890 aA

* Means followed by the same letter - lowercase in the columns, uppercase in the rows - do not differ by the LSD test ($p < 0.05$).

biochemical characteristics of BRM 63524 (Cruz et al. 2025b). A high dry matter production in off-season crops enhances soil quality, as the generated phytomass, once desiccated and incorporated into the soil, gradually releases nutrients through straw decomposition (Cordeiro Junior et al. 2017). These results highlight the potential of rhizobacteria to intensify agricultural production sustainably, reducing dependence on synthetic fertilizers and improving resource use efficiency.

Regarding macronutrient accumulation in corn dry biomass, the inoculation with BRM 63524 led to the highest increases per hectare in N (46.6 %), P (104.8 %), K (53.4 %) and Mg (35.9 %), when compared to the control treatment, showing statistically superior values in these parameters (Table 5). Previous studies have demonstrated the ability of *Bacillus* species to enhance macronutrient uptake in crops through multiple plant growth-promoting mechanisms (Silva et al. 2022b, Cruz et al. 2023, Cruz et al. 2024b). As for micronutrient accumulation, BRM 63524 resulted in the greatest increases for Cu (46.6 %) and Zn (68.3 %), in relation to the control. The accumulation of other macro and micronutrients in upland rice seedlings was not significantly influenced by microorganism application. Additionally, phosphorus application rates did not directly affect nutrient accumulation.

Upland rice plants treated with BRM 63524 showed the highest dry matter production per hectare; however, this was not statistically different from the control (Table 6). This result suggests that, despite the isolate's potential to stimulate plant growth, factors such as environmental variability, root colonization efficiency or nutrient availability may have influenced the crop's response (Timofeeva et al. 2022). Further studies are needed to better understand the conditions under which inoculation produces significant benefits, particularly across different soil types and management systems.

Table 5. Dry matter (DM) production and accumulation of N, P, K, Ca, Mg, Cu, Fe, Mn and Zn in corn plants grown during the off-season as influenced by the application of BRM 32111, BRM 63523, BRM 63524 and a control (no microorganisms), and by phosphorus dose (50 or 100 %), averaged over the 2023 and 2024 growing seasons.

Treatments	DM	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	kg ha^{-1}						g ha^{-1}			
Microorganism										
BRM 32111 (*Burkholderia* sp.)	10,450 ab*	66.94 b	6.67 b	122 ab	22.99^{ns}	15.09 ab	26.54 b	1,346^{ns}	386^{ns}	182 ab
BRM 63523 (*Serratia* sp.)	10,622 ab	79.79 ab	7.65 ab	125 ab	21.16	13.55 b	28.13 ab	1,414	312	186 ab
BRM 63524 (*Bacillus* sp.)	11,367 a	92.59 a	10.18 a	155 a	26.14	17.30 a	32.53 a	1,647	408	239 a
Control	9,944 b	65.48 b	4.97 b	101 b	20.28	12.73 b	22.19 b	1,140	319	142 b
Phosphorus dose										
Half	8,633^{ns}	72.50^{ns}	7.01^{ns}	122^{ns}	23.54^{ns}	14.58^{ns}	26.72^{ns}	1,519^{ns}	379^{ns}	186^{ns}
Full	8,790	79.87	7.72	130	21.75	14.74	27.97	1,255	333	188

* Means followed by the same letter do not differ by the LSD test ($p < 0.05$); ^{ns} non-significant according to the Anova.

Table 6. Dry matter (DM) production and accumulation of N, P, K, Ca, Mg, Cu, Fe, Mn and Zn in upland rice plants grown during the off-season as influenced by the application of BRM 32111, BRM 63523, BRM 63524 and a control (no microorganisms), and by phosphorus dose (50 or 100 %), averaged over the 2023 and 2024 growing seasons.

Treatments	DM	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
	kg ha^{-1}						g ha^{-1}			
Microorganism										
BRM 32111 (*Burkholderia* sp.)	3,839 b*	82.29^{ns}	6.60 b	74.47 b	15.60 ab	12.38^{ns}	22.58^{ns}	818^{ns}	1,318 a	159 b
BRM 63523 (*Serratia* sp.)	4,447 ab	85.56	6.43 b	76.90 b	12.55 ab	12.10	23.27	924	1,063 ab	190 ab
BRM 63524 (*Bacillus* sp.)	5,027 a	95.28	8.51 a	91.22 a	16.18 a	15.61	26.77	1,039	1,200 ab	205 a
Control	4,708 ab	91.38	6.61 b	78.21 b	12.08 b	14.37	22.58	1,281	940 b	164 b
Phosphorus dose										
Half	4,627^{ns}	91.59^{ns}	7.16^{ns}	81.74^{ns}	14.09^{ns}	13.89^{ns}	24.98^{ns}	918^{ns}	1,276^{ns}	181^{ns}
Full	4,383	85.67	6.78	78.65	14.11	13.34	21.93	1,113	984	177

* Means followed by the same letter do not differ by the LSD test ($p < 0.05$); ^{ns} non-significant according to the Anova.

In terms of macronutrient accumulation in upland rice dry biomass, the inoculation with BRM 63524 resulted in increased accumulation per hectare of P (28.74 %), K (16.6 %) and Ca (33.94 %), if compared to the control treatment (Table 6). For micronutrient accumulation, BRM 32111 led to the highest increase in Mn (27.65 %), whereas the greatest increase in Zn (25 %) was observed with BRM 63524. Previous studies have shown that *Bacillus* species can enhance macronutrient uptake in upland rice seedlings (Nascente et al. 2013, Fernandes et al. 2020, Cruz et al. 2023). The input of micronutrients in no-tillage systems is essential for maintaining soil fertility, supporting nutrient cycling and increasing micronutrient availability, thereby reducing dependency on mineral fertilizers (Silva et al. 2022a).

Applying the full phosphorus dose (100 %) to corn increased production costs by 5 %, when compared to using 50 % of the dose, regardless of microorganism application (Table 7). For rice, a differential cost analysis showed a similar pattern: using 100 % of the recommended phosphorus rate increased costs by 6 % when compared to the reduced rate (50 %), also regardless of inoculation (Table 8). However, the introduction of microorganisms led to only a marginal cost increase of 0.3 %, in relation to the treatments without inoculation in both crops. These results highlight the potential of microorganisms to reduce production costs, especially when used to complement synthetic fertilizers. Inoculants based on these microorganisms are low-cost, environmentally friendly and can supplement chemical fertilizers, contributing to more sustainable agricultural practices (Oliveira et al. 2020).

In general, the highest revenues in corn cultivation were observed with the application of BRM 32111 and BRM 63524 combined with

Table 7. Input costs and relative contribution to corn (AG 8088) production costs as influenced by microorganism application and phosphorus dose (50 or 100 %), averaged over the 2023 and 2024 growing seasons.

Component	100 % P + micro ($ ha^{-1})	Participation (%)	50 % P + micro ($ ha^{-1})	Participation (%)	100 % P ($ ha^{-1})	Participation (%)	50 % P ($ ha^{-1})	Participation (%)
1. Inputs	412.38	60.67	372.34	58.21	410.76	60.57	370.72	58.10
Seeds	194.00	28.54	194.00	30.33	194.00	28.61	194.00	30.40
Inoculant	1.62	0.24	1.62	0.25	0.00	0.00	0.00	0.00
Urea	57.85	8.51	57.85	9.04	57.85	8.53	57.85	9.07
KCl	27.58	4.06	27.58	4.31	27.58	4.07	27.58	4.32
Triple superphosphate	80.07	11.78	40.04	6.26	80.07	11.81	40.04	6.27
Herbicides, insecticides and fungicides	51.25	7.54	51.25	8.01	51.25	7.55	51.25	8.04
2. Agricultural operations	81.10	11.93	81.10	12.68	81.10	11.96	81.10	12.71
Sowing	26.77	3.94	26.77	4.18	26.77	3.95	26.77	4.19
Topdressing fertilization	7.17	1.05	7.17	1.12	7.17	1.06	7.17	1.12
Pesticide application	8.25	1.21	8.25	1.29	8.25	1.22	8.25	1.29
Central pivot operation	10.55	1.55	10.55	1.65	10.55	1.56	10.55	1.65
Harvest	28.37	4.17	28.37	4.44	28.37	4.18	28.37	4.45
3. Administrative costs	100.81	14.83	100.81	15.76	100.81	14.87	100.81	15.80
Technical assistance	11.52	1.69	11.52	1.80	11.52	1.70	11.52	1.81
Management	11.54	1.70	11.54	1.80	11.54	1.70	11.54	1.81
Production credit interest	33.24	4.89	33.24	5.20	33.24	4.90	33.24	5.21
Taxes and fees	44.50	6.55	44.50	6.96	44.50	6.56	44.50	6.97
A) EOC (1 + 2 + 3)	594.29	87.43	554.25	86.64	592.66	87.40	552.63	86.61
4. Maintenance	2.17	0.32	2.17	0.34	2.17	0.32	2.17	0.34
Central pivot	2.17	0.32	2.17	0.34	2.17	0.32	2.17	0.34
5. Depreciation	41.14	6.05	41.14	6.43	41.14	6.07	41.14	6.45
Machinery and equipment	38.08	5.60	38.08	5.95	38.08	5.62	38.08	5.97
Improvements	3.06	0.45	3.06	0.48	3.06	0.45	3.06	0.48
B. TOC (A + 4 + 5)	637.60	93.80	597.56	93.41	635.98	93.79	595.94	93.40
6. Factor remuneration	42.14	6.20	42.14	6.59	42.14	6.21	42.14	6.60
Machinery and equipment	34.11	5.02	34.11	5.33	34.11	5.03	34.11	5.35
Improvements	8.03	1.18	8.03	1.26	8.03	1.18	8.03	1.26
Total cost (B + 6)	679.74	100.00	639.70	100.00	678.11	100.00	638.08	100.00

[1] EOC: effective operational cost; [2] TOC: total operational cost.

50 % of the recommended phosphorus dose, as well as with the control treatment using 100 % of phosphorus (Figure 2A). For upland rice, the highest revenues were obtained with BRM 63523 and BRM 63524 using 50 % of phosphorus, along with the control treatment with the full recommended dose (Figure 2B). These results have important economic and environmental implications, as reducing phosphorus inputs can lower production costs and minimize the environmental impacts associated with the extraction and overuse of mineral fertilizers, thereby promoting the sustainability of agricultural systems (Monteiro et al. 2024).

Economic viability was assessed through differential profit, considering the interaction among microorganisms, phosphorus doses and crop type during the off-season. It was observed that the application of certain microorganisms generated economic gains even when using only 50 % of the recommended phosphorus dose (Figure 3). For corn, BRM 63524 and BRM 32111, combined with 50 % of phosphorus, yielded additional profits of US$ 305.40 ha^{-1} and US$ 269.98 ha^{-1}, respectively, when compared to the control with 100 % of phosphorus, which represents the conventional agricultural standard (Figure 3A). These results translate to profit increases of 29.37 % for BRM 63524 and 25.96 % for BRM 32111, in relation to the use of no microorganisms and the full phosphorus dose in corn.

For rice, the application of BRM 63523 and BRM 63524 with 50 % of phosphorus resulted in additional profits of US$ 120.33 and US$ 271.90, respectively, if compared to the control with 100 % of phosphorus (Figure 3B). This corresponds to profitability increases of 12.33 % for BRM 63523 and 27.84 % for BRM 63524 relative to treatments

Table 8. Input costs and relative contribution to upland rice (BRS A502) production costs as influenced by microorganism application and phosphorus dose (50 or 100 %), in the 2024 growing season.

Component	100 % P + micro (US$ ha^{-1})	Participation (%)	50 % P + micro (US$ ha^{-1})	Participation (%)	100 % P (US$ ha^{-1})	Participation (%)	50 % P (US$ ha^{-1})	Participation (%)
1. Inputs	308.32	53.56	268.29	50.09	306.70	53.43	266.66	49.94
Seeds	89.95	15.62	89.95	16.79	89.95	15.67	89.95	16.84
Inoculant	1.62	0.28	1.62	0.30	0.00	0.00	0.00	0.00
Urea	57.85	10.05	57.85	10.80	57.85	10.08	57.85	10.83
KCl	27.58	4.79	27.58	5.15	27.58	4.81	27.58	5.17
Triple superphosphate	80.07	13.91	40.04	7.47	80.07	13.95	40.04	7.50
Herbicides, insecticides and fungicides	51.25	8.91	51.25	9.57	51.25	8.93	51.25	9.59
2. Agricultural operations	81.10	14.09	81.10	15.14	81.10	14.13	81.10	15.19
Sowing	26.77	4.65	26.77	5.00	26.77	4.66	26.77	5.01
Topdressing fertilization	7.17	1.25	7.17	1.34	7.17	1.25	7.17	1.34
Pesticide application	8.25	1.43	8.25	1.54	8.25	1.44	8.25	1.54
Central pivot operation	10.55	1.83	10.55	1.97	10.55	1.84	10.55	1.97
Harvest	28.37	4.93	28.37	5.30	28.37	4.94	28.37	5.31
3. Administrative costs	100.81	17.51	100.81	18.82	100.81	17.56	100.81	18.88
Technical assistance	11.52	2.00	11.52	2.15	11.52	2.01	11.52	2.16
Management	11.54	2.01	11.54	2.16	11.54	2.01	11.54	2.16
Production credit interest	33.24	5.77	33.24	6.21	33.24	5.79	33.24	6.22
Taxes and fees	44.50	7.73	44.50	8.31	44.50	7.75	44.50	8.33
A) EOC (1 + 2 + 3)	490.23	85.16	450.19	84.05	488.61	85.11	448.57	84.00
4. Maintenance	2.17	0.38	2.17	0.41	2.17	0.38	2.17	0.41
Central pivot	2.17	0.38	2.17	0.41	2.17	0.38	2.17	0.41
5. Depreciation	41.14	7.15	41.14	7.68	41.14	7.17	41.14	7.70
Machinery and equipment	38.08	6.61	38.08	7.11	38.08	6.63	38.08	7.13
Improvements	3.06	0.53	3.06	0.57	3.06	0.53	3.06	0.57
B. TOC (A + 4 + 5)	533.54	92.68	493.51	92.13	531.92	92.66	491.88	92.11
6. Factor remuneration	42.14	7.32	42.14	7.87	42.14	7.34	42.14	7.89
Machinery and equipment	34.11	5.92	34.11	6.37	34.11	5.94	34.11	6.39
Improvements	8.03	1.40	8.03	1.50	8.03	1.40	8.03	1.50
Total cost (B + 6)	575.68	100.00	535.65	100.00	574.06	100.00	534.02	100.00

[1] EOC: effective operational cost; [2] TOC: total operational cost.

without phosphate-solubilizing microorganisms and with the full phosphorus dose. These findings indicate that the application of the isolates allowed for reduced phosphorus inputs while increasing yield per area, highlighting their potential as bio-inputs in upland rice cultivation.

Corn cultivation with BRM 32111 and BRM 63524 and 50 % of the recommended phosphorus dose proved more profitable than rice, regardless of phosphorus dosage or microorganism use (Figure 3). However, rice associated with BRM 63524 and BRM 63523 and 50 % of phosphorus outperformed corn

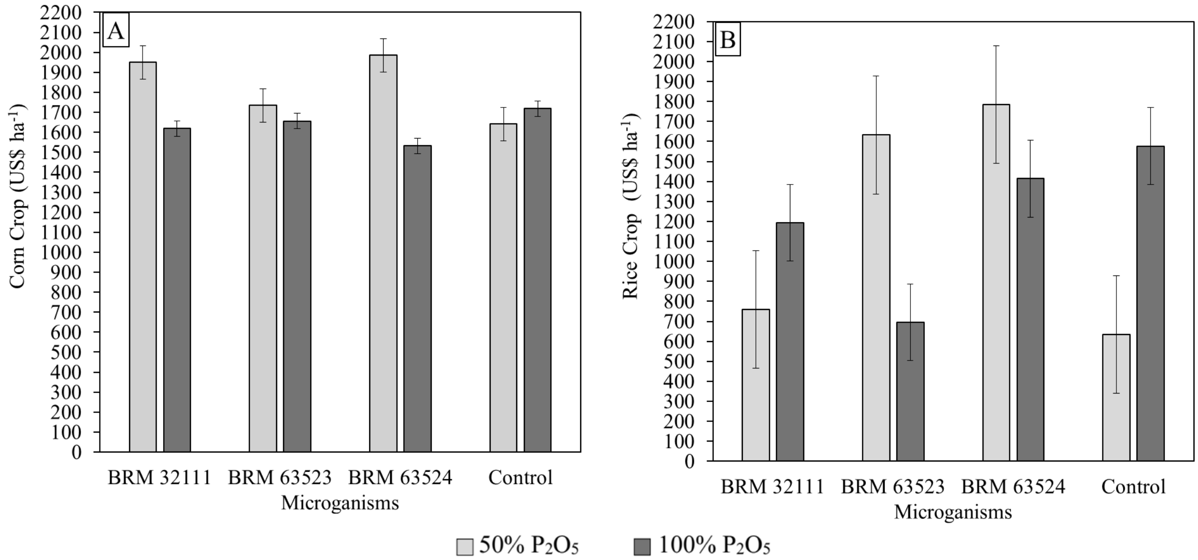

Figure 2. Calculated differential revenue for each treatment in relation to AG 8088 corn crop (A) and BRS A502 upland rice crop (B) plants grown in the off-season as a function of the application of BRM 32111, BRM 63523, BRM 63524 and control (without microorganisms), and the phosphorus dose (50 and 100 %). Results obtained by multiplying the yield within the interaction of factors (microorganism x phosphorus dose - Tables 3 and 4) by the deflated price of corn and rice in the last five years. The average deflated price of 60 kg bag^{-1} in the Goiás state over the last five years was US$ 11.01 for corn crop and US$ 19.35 for rice crop.

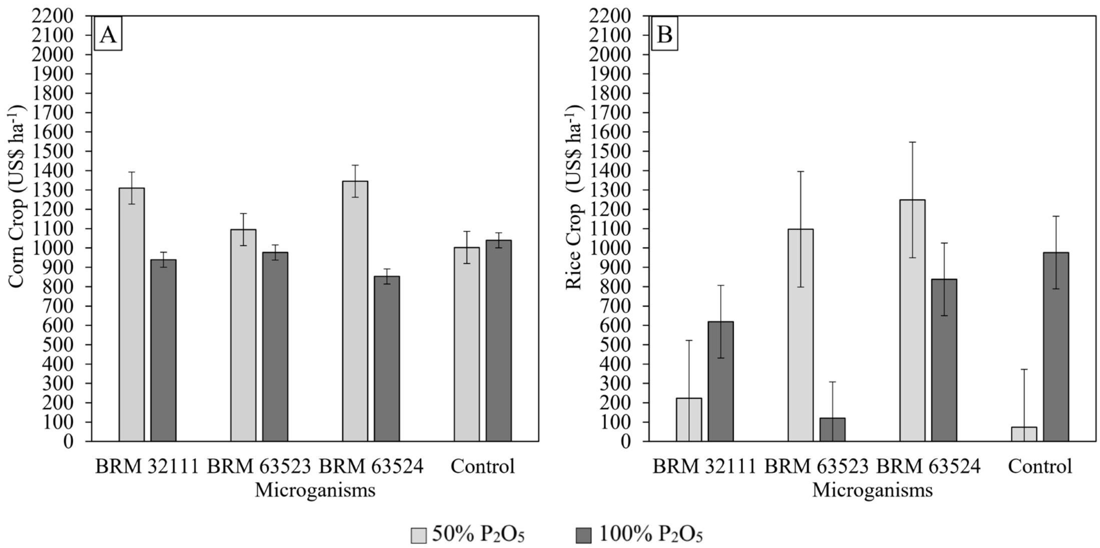

Figure 3. Differential profits in relation to AG 8088 corn (A) and BRS A502 upland rice (B) plants cultivated in the off-season, depending on the application of BRM 32111, BRM 63523, BRM 63524 and control (without microorganisms), and phosphorus dose (50 and 100 %). Results obtained by subtracting the differential revenue from the differential cost.

under the conventional system (no microorganisms; 100 % of phosphorus), generating profits 20.1 and 5.5 % higher, respectively. Including rice in crop rotation or succession enhances production systems by promoting agricultural diversification, reducing pest and disease pressure, and improving soil quality (Lacerda & Nascente 2021). In this context, upland rice emerges as a strategic alternative, interrupting pest and disease cycles while contributing to soil recovery and agricultural sustainability.

CONCLUSIONS

1. Inoculation with the BRM 63524 isolate increased the dry biomass and accumulation of macronutrients such as P, K and Mg in corn, along with micronutrients such as Cu and Zn, demonstrating its potential to improve nutrition and reduce dependence on synthetic fertilizers. For upland rice, the isolate promoted the accumulation of P, K, Ca, Zn and Mn, despite the variability in the yield response;
2. The use of the BRM 32111 (10,624 kg ha^{-1}) and BRM 63524 (10,817 kg ha^{-1}) rhizobacteria resulted in the highest corn yields, even with only 50 % of the phosphorus dose, ensuring the highest profits among the treatments. For rice, BRM 63523 (5,062 kg ha^{-1}) and BRM 63524 (5,532 kg ha^{-1}) also achieved the highest yields with half the recommended dose, securing a greater profitability, when compared to the other treatments.

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