Nitrogen

Article

Economic Analysis of *Azospirillum brasilense* Inoculation Associated with Enhanced-Efficiency Nitrogen Fertilizers in Corn Production in the Brazilian Amazon

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Abstract: The aim of this study was to economically estimate the effect of inoculation with *Azospirillum brasilense* (*A. brasilense*) associated with enhanced efficiency nitrogen fertilizers on corn yield cultivated in the Brazilian Amazon. The experimental design used was completely randomized, in a 2 × 3 × 5 factorial scheme, resulting from the combination of the presence and absence of seeds inoculated with *A. brasilense*, three sources of N (conventional urea, urea with NBPT, *N*-(*n*-butyl)thiophosphoric triamide, and polymer-coated urea), and five doses of N (0; 50; 100; 150; and 200 kg ha^{-1} of N), with six replications. Inoculation with *A. brasilense* promoted profit in corn, regardless of dose and the source of N applied. The urea with NBPT provided better economic return compared to polymer-coated urea and conventional urea sources, and doses of N applied in topdressing that promoted the highest economic return were 100 and 150 kg ha^{-1} of N, with an estimated increase of 62.33 and 135.53 bags ha^{-1} and increase of BRL 3253.76 and BRL 7074.88 respectively, compared to the control treatment.

Keywords: nitrogen fertilization; cost–benefit ratio; biological N fixation; economic viability

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1. Introduction

The dynamics of the corn production chain have changed significantly around the world, and the grain is not only intended for animal feed, becoming an exportable commodity, as well as having the possibility of being used as an energy matrix in ethanol production [1]. According to the historical series of Brazilian grain production that began in the mid-1970s, an increase of 245% in corn grain production was estimated [2].

Technologies such as transgenic cultivars (single and triple hybrids) [3]; reduced spacing associated with higher planting density [4]; improvement in seed quality [5]; pest and disease control [6]; and soil correction and adequate fertilizer management [7], especially the application of nitrogen, have promoted high yields in the Brazilian Amazon [8].

Many studies on nitrogen fertilization associated with growth-promoting bacteria in corn are available from temperate regions; however, currently, intensification in grain production has expanded to the Amazon forest biomes [9,10], being the fastest growing agricultural frontiers. Grain cultivation in the region has promoted an increase in the application of nitrogen fertilizers, with doses recommended between 80 and 120 kg ha^{-1} of N [11], contributing to a 78% increase in the use of N fertilizers in Brazil during the last 20 years [12].

In Brazilian agricultural production, fertilizers are agricultural inputs that most impact the cost of corn production, especially nitrogen [13]; being the nutrient that most impacts the cost of corn production, N management needs to be well managed to ensure profit in agriculture [14]. Thus, in an attempt to reduce N losses, mainly through ammonia volatilization, modifications have been made to urea-containing fertilizers that include the addition of a urease inhibitor and the production of fertilizers with controlled solubility using resins or polymers [15]. Another technology that has been disseminated to improve the use of nitrogen fertilizer is N fixation by *Azospirillum brasilense* (*A. brasilense*) [16], resulting in increases in grain yield and reduced corn production costs [14].

Several studies have confirmed that *A. brasilense* promotes benefits such as the production of phytohormones such as auxins, cytokinins, and gibberellins [17], increasing root development and leading to higher nutrient and water acquisition [18], increasing N use efficiency from applied N fertilizer [19], enhancing nitrate reductase activity [20], solubilizing phosphates [21], and the contribution of N fixation to plant nutrition (an increase of 5–18% in the total N of inoculated plants) [22]. According to Galindo et al. [23], there have been few investigations of how much mineral N can be applied for successful FBN to increase yield, and it would be interesting to analyze the application of urea with the NBPT urease enzyme inhibitor to determine whether it is detrimental with respect to FBN in corn.

In the literature, there are few studies that economically demonstrate the effect of inoculation with *Azospirillum brasilense* associated with nitrogen fertilization, and none exist for the Brazilian Amazon region, since according to Kaneko et al. [14], to be viable for farmers, it is not enough for technological innovations to increase grain yield; there must be, in parallel, studies that estimate economic viability. Although research results based on agronomic parameters of crops are essential to indicate the benefits of inoculation concerning the use of nitrogen fertilizers, it is necessary to determine the potential of these technologies from an economic point of view since this is a factor of great importance for decision-making by corn producers. Thus, the aim of this study was to economically estimate the effect of inoculation with *Azospirillum brasilense* associated with nitrogen fertilizers of increased efficiency on corn yield cultivated in the Brazilian Amazon.

2. Materials and Methods

2.1. Greenhouse Experiment and Experimental Design

The experiment was conducted from January to May 2019, in a greenhouse at the Federal Rural University of the Amazon, Parauapebas city, Brazil, with geographic coordinates of 06°04′03″ South latitude and 49°04′03″ West longitude. The climate according to the Köppen classification is type Aw, tropical rainy. The soil was Red Yellow Argisol [24], with chemical characteristics in the 0–0.20 m layer as follows [25]: pH_{H2O} = 4.6; O.M. = 21.0 g dm^{-3}; [P] (Mehlich 1) = 0.3 mg dm^{-3}; [K^+] = 121.3 mg dm^{-3}; [Ca^{2+}] = 2.2 $cmol_c$ dm^{-3}; [Mg^{2+}] = 0.7 $cmol_c$ dm^{-3}; [H+Al] = 2.2 $cmol_c$ dm^{-3}; [Al^{3+}] = 0.2 $cmol_c$ dm^{-3}; CTC = 5.44 $cmol_c$ dm^{-3}; and V = 59.64%.

The experimental design used was completely randomized, in a 2 × 3 × 5 factorial scheme, resulting from the combination of the presence and absence of seeds inoculated with *Azospirillum brasilense*, three sources of N (conventional urea, urea with NBPT, and polymer-coated urea), and five doses of N (0; 50; 100; 150; and 200 kg ha^{-1} of N), with six replications.

2.2. Azospirillum Strains and Inoculation Procedure

The seeds were inoculated with the Ab-V5 (=CNPSo 2083) and Ab-V6 (=CNPSo 2084) strains of *Azospirillum brasilense* (concentration of 2 × 108 CFU mL^{-1}) at a dose of 200 mL of inoculant in 25 kg of seeds. Sowing was carried out on 12 January 2019, in pots with a volume of 15 dm^3, using the Al Bandeirante cultivar, applying the dose corresponding to

140 kg ha^{-1} of N, 100 kg ha^{-1} of P_2O_5, and 80 kg ha^{-1} of K_2O [26]. Cultural treatments were carried out according to corn requirements [27].

2.3. Analytical Procedures

The corn was harvested at the R6 phenological stage [28], and grain yield was measured [11]. For economic analysis, the values were converted into production per hectare and costs of inputs, personnel, machinery, and equipment in the region were projected, using the structure of the total operational cost of production used by the Institute of Agricultural Economics, proposed by Matsunaga et al. [29]. The effective operating cost (EOC) is made up of expenses with mechanized operations, manual operations, and materials consumed. Adding to the EOC the expenses with financial charges, other expenses, and depreciation, we have the total operating production cost (TOC). This methodology has already been used in several studies on economic evaluation in crops such as those by Kaneko et al. [14], Kappes et al. [30], Portugal et al. [31], and Galindo et al. [23].

To estimate the profitability of the involved treatments in the study, profitability analyses were carried out according to Martin et al. [32]. To this end, the following variables were determined: gross revenue (GR) (in BRL), as the product of the amount produced (in 60 kg bags) by the average sale price (in BRL); operating profit (OP), as the difference between the gross revenue and total operating cost; and the profitability index (PI), understood as the ratio between operating profit and the gross revenue, as a percentage, which is an important measure of profitability, as it shows the available rate of revenue from the activity after the payment of all operational costs.

To carry out the economic analysis, it was necessary to make a decision regarding the quantity of seeds, obtaining the estimated dose of inoculant for planting corn in an area of 1.0 ha. A total of 25 kg of seeds and a dose of 200 mL of inoculant were adopted according to the manufacturer's recommendation.

To facilitate the discussion, the values referring to the yields were transformed into 60 kg bags, which was the basic unit of sale by local producers. Average prices were collected at CEPEA (Center for Advanced Studies in Applied Economics) in January 2020, carrying out simulations as if each experimental treatment represented commercial crops. The cost of the bag of corn for Parauapebas city was BRL 52.20 per unit produced. As regards the N sources, the price paid by the farmer was BRL 3200.00 per ton for conventional urea, urea with NBPT, and polymer-coated urea. For the inoculant with *Azospirillum brasilense*, the cost was BRL 20.00 per dose, with only one dose being used.

3. Results

3.1. Cost of Mechanized Operations and Inputs in Corn

Table 1 shows projections of values relating to mechanized operations and inputs used in cultivation. Expenses involving tractor-driven mechanized operations, manual operations, and phytosanitary treatment were added within each item (standardized), since such values do not influence the economic analysis of the treatments involved in the present study. Therefore, only the costs of seeds, sowing fertilizer, topdressing nitrogen fertilizer, and inoculant are detailed. Adding the values of mechanized operations, manual operations, and inputs used for each treatment in the experiment, we have the effective operating cost (EOC). Adding expenses with financial charges and unaccounted expenses to the EOC, the total operating cost (TOC) was obtained.

Table 1. Cost of mechanized operations and inputs in corn.

Description	Specification	Total Value (BRL)
A. Production costing expenses		
A1. Operation with machines/implements	HM	78.09
A2. Labor	HM	85.62
A3. Corn seed	Bag (20 kg)	140.00
A4. Liming	t	32.51
A5. Sowing fertilizer	t	509.60
A6. Inoculant (*A. brasilense*)	L	20.00
A7. Fungicide	L	37.06
A8. Herbicide	L	69.25
A9. Insecticide	L	140.43
Subtotal A		1112.56
B1. Topdressing with N		
B1.1. Without N		-
B1.2. 50 kg ha^{-1} de N	t	385.18
B1.3. 100 kg ha^{-1} de N	t	770.00
B1.4. 150 kg ha^{-1} de N	t	1155.00
B1.5. 200 kg ha^{-1} de N	t	1540.74
C. Other variable costs		
C1. External transport		154.00
C2. Storage		17.60
C3. Classification and processing		88.00
C4. Taxes and fees		98.33
C5. Maintenance of machines/implements		84.99
C6. Administrative costs		109.20
Subtotal C		552.12
D. Financial expenses		
D1. Fees		86.20
Subtotal D		86.20
E. Depreciations		
E1. Improvement depreciation		2.75
E2. Depreciation of machines/implements		132.55
Subtotal E		135.30
F. Other fixed costs		
F1. Charges		8.13
F2. Fixed capital insurance		8.36
F3. Maintenance of improvements		0.69
F4. Lease		200.91
Subtotal F		218.09
G. Factor income		
G1. Expected return on capital		80.82
G2. Agricultural area		50.32
Subtotal G		131.14

3.2. Total Operating Cost, Yield, Gross Revenue, Operating Profit, and Profitability Index for Corn

Table 2 shows the yield data converted into bags per hectare and gross revenue obtained in each treatment, verifying that application of urea with NBPT at a dose of 150 kg ha^{-1} of N promoted an increase of 83 bags ha^{-1} in the presence of inoculation with *A. brasilense* compared to the absence of seed inoculation.

Table 2. Total operating cost (TOC), yield (YIELD), and gross revenue (GR) for corn.

N Doses (kg ha^{-1})	Without *Azospirillum brasilense*								
	Conventional Urea			Polymer-Coated Urea			Urea with NBPT		
	TOC	YIELD	GR	TOC	YIELD	GR	TOC	YIELD	GR
	BRL	60 kg ha^{-1}	BRL	BRL	60 kg ha^{-1}	BRL	BRL	60 kg ha^{-1}	BRL
0	2215.32	84.93	4433.31	2215.32	87.93	4590.10	2215.32	89.72	4683.32
50	2600,50	82.36	4299.42	2600.50	61.74	3222.61	2600.50	106.25	5546.16
100	2985.32	96.17	5020.29	2985.32	116.44	6078.29	2985.32	131.27	6852.27
150	3370.32	106.83	5576.57	3370.32	145.52	7595.94	3370.32	137.34	7169.30
200	3756.06	137.09	7156.28	3756.06	146.68	7656.63	3756.06	146.76	7661.00
Mean	2291.44	101.48	5297.17	2291.44	111.66	5828.72	2291.44	122.27	6382.41
N Doses (kg ha^{-1})	With *Azospirillum brasilense*								
	Conventional Urea			Polymer-Coated Urea			Urea with NBPT		
	TOC	YIELD	GR	TOC	YIELD	GR	TOC	YIELD	GR
	BRL	60 kg ha^{-1}	BRL	BRL	60 kg ha^{-1}	BRL	BRL	60 kg ha^{-1}	BRL
0	2235.32	99.97	5218.39	2235.32	94.69	4942.72	2235.32	95.98	5010.41
50	2620.50	114.94	5999.74	2620.50	151.03	7883.68	2620.50	158.54	8275.66
100	3005.32	140.79	7349.45	3005.32	154.35	8057.08	3005.32	147.26	7687.07
150	3390.32	150.83	7873.25	3390.32	149.58	7807.92	3390.32	220.46	11,508.12
200	3776.06	138.44	7226.58	3776.06	154.83	8082.08	3776.06	182.47	9525.15
Mean	3005.50	128.99	6733.48	3005.50	140.89	7354.69	3005.50	160.94	8401.28

In general, treatments with the presence of inoculation with *Azospirillum brasilense* promoted an increase in grain yield and gross income. Economically analyzing the effects of N sources and doses, it was observed that the dose of 150 kg ha^{-1} of N, regardless of the N source, provided a higher value of BRL 1155.56 in TOC (Table 2) compared to the application of a dose of 50 kg ha^{-1} of N.

The lowest grain yield, of 85 bags ha^{-1}, was obtained in treatment without N and the absence of *A. brasilense* (control treatment). In Table 2, the importance of seed treatment was verified, in which a dose of 150 kg ha^{-1} of N using urea with NBPT in the presence and absence of seed inoculation promoted the production of 137 and 220 bags ha^{-1}; thus, *A. brasilense* promoted increases of 83 bags ha^{-1}.

Based on information obtained in the present study, an increase in TOC was found with an increase in N doses, as well as an increase in gross revenue following the increases obtained in corn grain yield. Meanwhile, inoculation with *Azospirillum* promoted an increase in TOC of BRL 20.00 on average, totaling an increase of 1% compared to the absence of inoculation in seeds.

Corn fertilized with urea with NBPT and inoculation with *Azospirillum* promoted increases of BRL 5526.83 ha^{-1} in operating profit (Table 3), totaling a profitability 62.5% higher compared to the treatment without seed inoculation. Furthermore, urea with NBPT was economically superior to conventional urea and polymer-coated urea, increasing the operating profit.

Table 3. Operating profit (OP) and profitability index of corn affected by doses and sources of nitrogen, with or without inoculation with *Azospirillum brasilense*.

N Doses (kg ha^{-1})	Without *Azospirillum brasilense*					
	Conventional Urea		Polymer-Coated Urea		Urea with NBPT	
	OP (BRL)	PI (%)	OP (BRL)	PI (%)	OP (BRL)	PI (%)
0	2349.04	52	2505.83	54	2599.05	55
50	1829.97	42	753.16	23	3076.71	55
100	2166.02	43	3224.02	53	3998.00	58
150	2337.30	41	4356.67	57	3300.30	54
200	3531.27	49	4031.62	53	4035.99	52
N Doses (kg ha^{-1})	**With *Azospirillum brasilense***					
	Conventional Urea		**Polymer-Coated Urea**		**Urea with NBPT**	
	OP (BRL)	**PI (%)**	**OP (BRL)**	**PI (%)**	**OP (BRL)**	**PI (%)**
0	3114.12	59	2838.45	57	2906.14	58
50	3510.29	58	5394.23	68	5786.21	70
100	4475.18	60	5182.81	64	4812.80	62
150	4613.98	58	4278.65	54	8248.85	72
200	3581.57	49	4437.07	54	5880.14	62

The best economic yields were obtained through nitrogen fertilization in topdressing using urea with NBPT, showing increasing profits up to a dose of 150 kg ha^{-1} of N in topdressing, verifying an operational profit of BRL 8248.85 and participation of 71% in the total gross revenue obtained (Table 3).

4. Discussion

The Brazilian corn producer has obtained low profits due to considerable increases in the crop's production costs, caused by commercial prices of corn not being quoted in dollars like soybeans, and the inputs applied in large quantities in its cultivation, such as conventional urea [33].

The expenses of nitrogen fertilization in topdressing were estimated, on average, to vary from 14% to 41% of the TOC for doses of 50 to 200 kg ha^{-1} of N, respectively. Coelho et al. [34] found that for the production of 61 and 97 bags ha^{-1}, 77 and 100 kg ha^{-1} of N were extracted from the soil, respectively.

Treatments inoculated with *Azospirillum brasilense* showed a decrease in N use efficiency as N doses increased. Sala et al. [35] associated an increase in grain yield with the inoculation with *Azospirillum brasilense*, but there is no proof of the possibility of reducing the N dose in topdressing [36–39].

Inoculation with *Azospirillum* increased the gross revenue compared to the absence of inoculation by BRL 1436.31, BRL 1525.31, and BRL 2018.87 in conventional urea, polymer-coated urea, and urea with NBPT, respectively. Kaneko et al. [14] reported the high cost of N fertilization by topdressing compared to seed inoculation, which has a low investment cost. Also, according to Pedroso [40], nitrogen fertilizer costs represent around 29.83% of the total cost of crop production.

The treatment with inoculation at a dose of 150 kg ha^{-1} of N in topdressing obtained a higher gross income than the treatments studied, since it promoted a greater number of bags being produced. For Troeh and Thompson [41], high yield demands a greater use of fertilizers. In the present study, increases in yield were found in the order of 83 bags ha^{-1} for the treatment with the application of 150 kg ha^{-1} of N, using urea with NBPT and *A. brasilense*, compared to the absence of seed inoculation, resulting in a difference of BRL 4332.60 in gross revenue.

Kappes et al. [42], working with doses of N and seed inoculation in corn, found an increase of 9.4% in grain yield. Similar results were obtained by Novalkowski et al. [43], in which corn production was higher with *A. brasilense* inoculation compared to the control treatment. Hungria et al. [36] obtained increases in corn production with an increase in yield in the order of 24 to 30%, corresponding to 662 to 823 kg ha^{-1}.

From the results obtained, benefits were found in corn yield, showing greater profitability and economic return with the inoculation of *A. brasilense* in corn seeds and associated N doses, regardless of the N source, reinforcing that inoculation can be an economically viable alternative, as it combines a low cost with greater profitability, which has motivated the dissemination of the technique for adoption by rural farmers [23].

5. Conclusions

In view of the low economic cost, ease of application, and high probability of a positive response to corn crops, even those associated with different N application levels, inoculation with *Azospirillum brasilense* is shown to be a key technology for improving plant-soil N management, leading to more sustainable corn production under the edaphoclimatic conditions of the Brazilian Amazon.

The inoculation of corn seeds with *Azospirillum brasilense* promotes greater profitability, regardless of the N source (conventional urea, polymer-coated urea, and urea with NBPT) and N doses (0; 50; 150; and 200 kg ha^{-1} of N).

The use of conventional urea and polymer-coated urea is less interesting in economic terms; therefore, it is recommended to use the presence of *Azospirillum brasilense* at a dose of 150 kg ha^{-1} of N using urea with NBPT, promoting the best economic return in corn cultivation in the edaphoclimatic conditions of the Brazilian Amazon.

The inoculation practice could also benefit corn producers in the Brazilian Amazon by reducing the dependency of N fertilizer applications and may be considered an appropriate strategy for improving N use efficiency. Future research is encouraged to assess the effects of agronomic practices, climate changes, plant growth-promoting rhizobacteria inoculation in different agroecosystems, and the interaction of microorganisms and plant hormones.

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