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Economic analysis of rhizobia and azospirilla co-inoculation in common beans

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Abstract

Background Common bean has high production cost, mainly due to the use of inputs like nitrogen fertilizers. An alternative to replace the use of nitrogen fertilizers is the co-inoculation technique. This work aimed to evaluate the economic performance of the co-inoculation of *Rhizobium tropici* and different doses of *Azospirillum brasilense* applied at the V2–V3 stage of the common bean.

Methods The economic analysis was carried out based on data from five field experiments in five locations in the state of Goiás in Brazil. Treatments consisted of absolute control (AC), N-fertilizer treatment (NfT), single inoculation of *R. tropici* (Rt), *R. tropici* + one dose of *A. brasilense* (Rt + Ab1I), *R. tropici* + two doses of *A. brasilense* (Rt + Ab2I), *R. tropici* + three doses of *A. brasilense* (Rt + Ab3I) and *R. tropici* + four doses of *A. brasilense* (Rt + Ab4I). The economic analysis was carried out based on prices and market indexes, depending on the grain yield of the different treatments.

Results The best economic performance was obtained by the co-inoculation Rt + Ab3I, which provided the highest average values of gross revenue (2.471 US\$ ha^{-1}), net revenue (2.220 US\$ ha^{-1}), and benefit–cost ratio (1.4 US\$ US\$$^{-1}$).

Conclusions Co-inoculation Rt + Ab3I also showed the lowest production costs (451 US\$ ha^{-1}), while the nitrogen treatment with 80 kg ha^{-1} of N resulted in the highest average production cost (499 US\$ ha^{-1}).

Keywords *Rhizobium tropici*, *Azospirillum brasilense*, *Phaseolus vulgaris* L., Production cost

Background

The common bean (*Phaseolus vulgaris* L.) occupied an area of around 1.5 million hectares in 2021 in Brazil, producing 2,269,861 tons (Embrapa Rice and Beans 2022), resulting from the cultivation of this crop in three harvesting seasons distributed along the same agricultural year. The first cropping season, known as waters harvest, occurs from August to March. The second cropping season, also known as dry harvest, occurs from January to July, and the third cropping season, or winter harvest, occurs from May to October (Barbosa and Gonzaga 2012). The common bean production system includes small, medium, and large producers, usually having a highly technical production system.

According to Santos et al. (2003), under Cerrado conditions, the maximum economic productivity of the common bean (2700 kg ha^{-1}) is reached by applying 167 kg ha^{-1} of N. As urea has 45% of N, this represents using 371 kg ha^{-1} of urea. Considering this dose and the area occupied by common bean in Goiás in the 2021/2022 season, it is estimated that 23,000 tons of urea per year are needed to provide N for the common bean crop. The price of a ton of urea at R\$ 6461.80 (FAEG 2022) represents an annual expenditure of around US\$ 63 million. In addition to the high acquisition cost and low efficiency, nitrogen fertilizers contribute to increased environmental risks (Ferreira et al. 2021).

In this context, searching for new technologies and cultural techniques is fundamental to reducing costs and obtaining higher productivity in production systems,

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guaranteeing profitability for common bean production. Even if partial, replacing nitrogen fertilization by co-inoculating *R. tropici* and *A. brasilense* is an alternative for reducing production costs and environmental risks in the common bean production system. According to Souza and Ferreira (2017), the co-inoculation of *R. tropici* with three doses of *A. brasilense* resulted in productivity increases, as compared to the use of nitrogen fertilization, of approximately 221 and 534 kg ha^{-1} in Goiás and Minas Gerais, respectively, resulting in a rate of return of 25% and 36%.

Although research results based on agronomic parameters of crops are essential to indicate the benefits of co-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 common bean producers.

In this sense, this work aimed to evaluate the economic aspects of the co-inoculation of *Rhizobium tropici* with different doses of *Azospirillum brasilense* applied in the phenological stage V2–V3 of common bean in different production areas.

Methods

Field experiments

The economic viability analysis study of co-inoculation technology in common bean was carried out based on data from five field trials reported by Messias et al. (2023). The trials were carried out in three municipalities in the state of Goiás in Brazil: Cristalina, Formosa, and Santo Antônio de Goiás, in four different seasons (2018 winter, 2018–2019 waters, 2019 winter, and 2019–2020 waters), with previous harvests of wheat and corn, respectively. The experiments conducted in the winter seasons (Santo Antônio de Goiás-GO/2018, Cristalina-GO/2019, and Santo Antônio de Goiás-GO/2019) used center pivot irrigation, while the experiments conducted in the water seasons (Formosa-GO/2018–19 and Santo Antônio de Goiás-GO/2019–20) were rain-fed.

The climatic characteristics as defined by the Köppen classification, the experimental areas have an Aw, tropical savannah, megathermal climate. The average annual temperature varies from 20.5 to 23 °C and the average annual precipitation ranges from 1465 to 1600 mm. The climatic conditions during the experiment periods are shown in Fig. 1.

Description of treatments, experimental design and management of experimental areas

In this work, two commercial inoculants and a registered product were used. The commercial inoculants were: Biomax Premium Turfoso Feijão, containing *R. tropici* (strain SEMIA 4077), and Biomax Premium Azum, containing *A. brasilense* (strain Ab-V5). The registered product comprises MASTERfix Feijão, containing *R. tropici* (strain 4080), and MASTERfix L Gramíneas, containing *A. brasilense* (Ab-V5 and Ab-V6).

The treatments consisted of AC—Absolute control (without inoculation and fertilization), NfT—nitrogen fertilization (80 kg N ha^{-1} of N, being 20 kg N ha^{-1} at sowing and 60 kg N ha^{-1} at the V4 stage), Rt—two doses of *R. tropici* in the seed, Rt + Ab1l—two doses of *R. tropici* in the seed + one dose of *A. brasilense* applied in V2–V3, Rt + Ab2l—two doses of *R. tropici* in the seed + two doses of *A. brasilense* applied in V2–V3, Rt + Ab3l—two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3, Rt + Ab4l—two doses of *R. tropici* in the seed + four doses of *A. brasilense* applied in V2–V3, and RP-registered product (two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3. The inoculants Biomax Premium Turfoso Feijão and Biomax Premium Azum were used in the treatments Rt, Rt + Ab1l, Rt + Ab2l, Rt + Ab3l, and Rt + Ab4l. As for the inoculants MASTERfix Feijão and MASTERfix L Gramineas used in the PR treatment.

The concentrations of *R. tropici* cells and different doses of *A. brasilense* applied to the seeds were as follows:: Rt = seed inoculation with *R. tropici* (2.4×10^7 cells $seed^{-1}$); Ab = spraying inoculation with *A. brasilense* in different concentrations (1 l—0.8×10^5 cells $plant^{-1}$; 2 l—1.6×10^5 cells $plant^{-1}$; 3 l—2.4×10^5 cells $plant^{-1}$; and 4 l—3.2×10^5 cells $plant^{-1}$); RP = Registered product (seed inoculation with R. tropici-2.4×10^7 cells $seed^{-1}$ and leaf inoculation with *A. brasilense*—2.4×10^5 cells $seed^{-1}$).

The common bean cultivars used were: Pérola, sown in Santo Antônio de Goiás-2018, Cristalina-2019, Santo Antônio de Goiás-2019 and Santo Antônio de Goiás-2019/20 and BRS Notável, sown in Formosa-2018/2019. All trials were conducted in a randomized block design with four replications. The plots were composed of six rows of four meters in length, using a spacing of 0.45 m, making a total of 10.8 m^2 per plot. Planting density was around 240,000 plants ha^{-1}.

According to chemical analysis of the work sites of Messias et al. (2023), with the objective of raising the basic saturation of the soil to 70% and the soil pH to 5.5, the application of lime was carried out 50 days before the experiments were set up, according to the needs of each location. According to Messias et al. (2023), phosphate (P_2O_5) and potassium (K_2O) fertilization was carried out during the sowing operation. According to the results of the soil chemical analysis and the technical recommendation for the common bean crop (Carvalho and Silveira 2021; Messias et al. 2023), the experiments conducted in Formosa-GO/2018–19

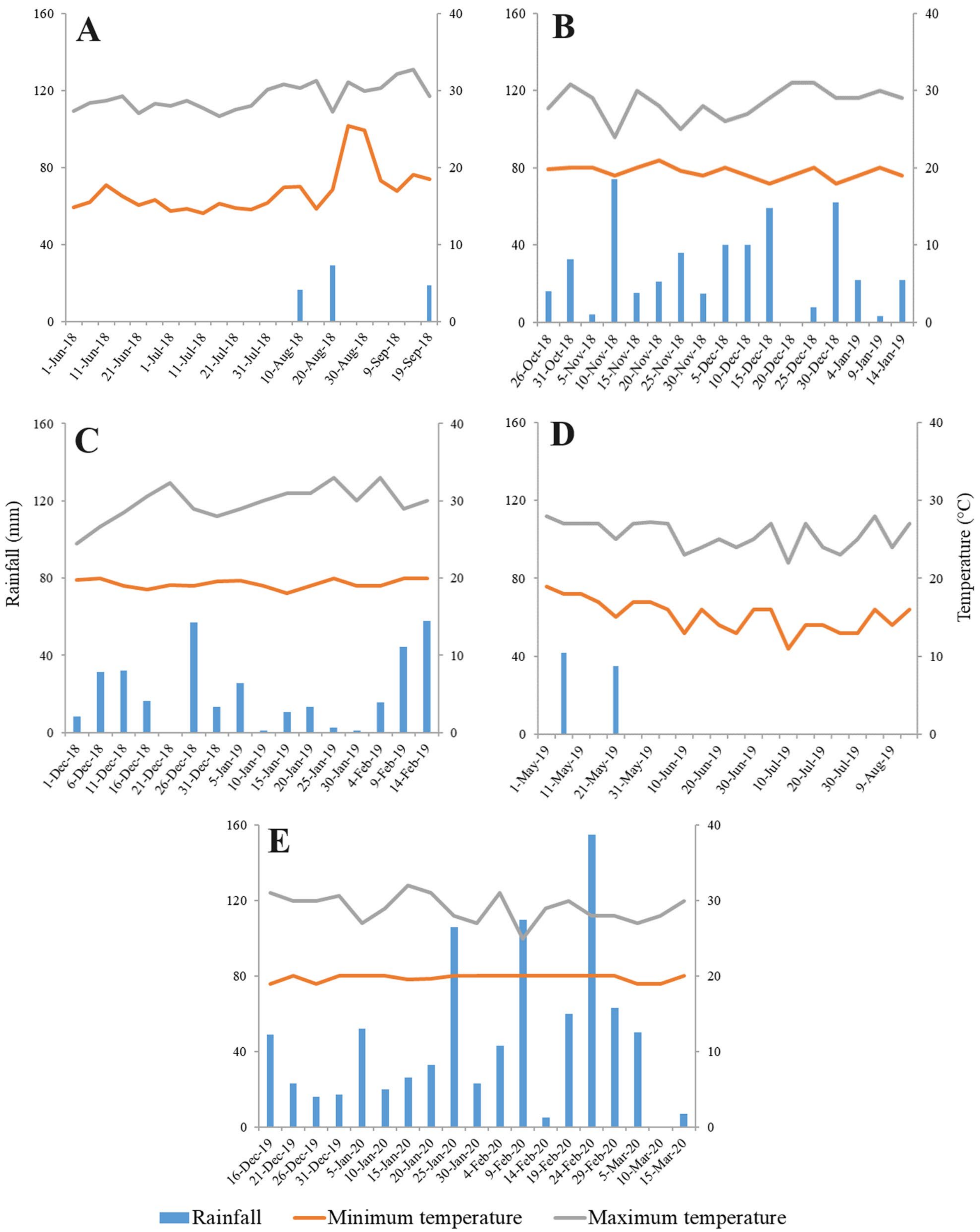

Fig. 1 Rainfall, maximum and minimum mean temperatures during the experimental periods. Santo Antônio de Goiás-GO/2018 (**A**), Formosa/2018–19 (**B**), Cristalina/2019 (**C**), Santo Antônio de Goiás-GO/2019 (**D**) and, Santo Antônio de Goiás-GO/2019–20 (**E**). *Source*: Adapted from Messias et al. (2023)

and Cristalina-GO/2019 did not require fertilization. The applications of triple susperfos were 270, 262.5 and 260 kg ha^{-1} in Santo Antônio de Goiás-GO/2018, Santo Antônio de Goiás-GO/2019 and Santo Antônio de Goiás-GO/2019–20, respectively. While, 90 and 87.5 kg ha^{-1} of potassium chloride were applied only in Santo Antônio de Goiás-GO/2018 and Santo Antônio de Goiás-GO/2019, respectively.

Phytosanitary management and control was carried out using products registered for common bean (Messias et al. 2023). For weed control, in the experiments conducted in Santo Antônio de Goiás-GO/2018, Santo Antônio de Goiás-GO/2019, and Santo Antônio de Goiás-GO/2019–20 seven days before sowing (DBS) desiccation of the areas was done with the herbicide Paraquat—SL 200 g L^{-1} IA (2.0 L ha^{-1}). In the experiment from Formosa-GO/2018–19, ten DBS desiccation of the area was carried out with the herbicides Aurora—EC 400 IA g L^{-1} IA (50 mL ha^{-1}) and Roundup—SL 445 IA g L^{-1} (2.0 L ha^{-1}). In the experiment from Cristalina-GO/2019, five DBS desiccation of the area was accomplished with the herbicide Roundup—SL 445 IA g L^{-1} (2.0 L ha^{-1}). Pre-emergence herbicide application was done, between 2–3 days after sowing (DAS), in Santo Antônio de Goiás-GO/2018, Santo Antônio de Goiás-GO/2019, and Santo Antônio de Goiás-GO/2019–20, using Gramoxone—SL 200 IA g L^{-1} (2.0 L ha^{-1}). Pre-emergence application was also performed in Formosa-GO/2018–19 and Cristalina-GO/2019, using Gramocil—SC 200 g L^{-1} IA (2.0 L ha^{-1}). In Santo Antônio de Goiás-GO/2018, Santo Antônio de Goiás-GO/2018–19, Santo Antônio de Goiás-GO/2019 and Formosa-GO/2018–19, post-emergence herbicide application was done, between 20 to 30 days after emergence (DAE), using Flex—SL 250 g L^{-1} IA (1.0 L ha^{-1}) and Fusilade—EW 250 g L-1 IA (0.75 L ha^{-1}).

The experiments conducted in Santo Antônio de Goiás-GO/2018 and Santo Antônio de Goiás-GO/2018–19 witnessed the occurrence of *Bemisia tabaci*, requiring 2 applications of the insecticide Engeo Pleno—ZC 141 g L^{-1} IA (125 mL ha^{-1}). In the experiment from Formosa-GO/2018–19 the insecticides Actara—WG 250 g kg^{-1} IA (200 g ha^{-1}), Benevia—OD 100 g L^{-1} IA (500 mL ha^{-1}), and Acephate—SP 750 g kg^{-1} IA (200 g ha^{-1}) were used for the control of *B. tabaci* with 3 applications in preventive and curative control. For the control of *Etiella zinckenella*, the biological Bt insecticide (*Bacillus thuringiensis*) was used in the experiment from Formosa-GO/2018–19.

For pathogen control in the experiment from Santo Antônio de Goiás-GO/2019 the fungicides Difere—SC 588 g L^{-1} IA (1.5 L ha^{-1}), Fox—SC 150 g L^{-1} IA (400 mL ha^{-1}) and Amistar Top—SC 200 g L^{-1} IA (400 mL ha^{-1}) were used to control *Phaeoisariopsis griseola*, *Colletotrichum lindemuthianum* and *Erysiphe polygoni*.

Grain yield analysis

Grain yield (GY), expressed in kg ha^{-1}, was determined by harvesting the useful area of each plot, which was cleaned and weighed, and the values were corrected for 13% moisture.

Economic analysis

For economic analysis, all costs related to the acquisition of inputs, planting, driving, handling, and harvesting operations were computed to determine the production cost of the experiments carried out. Data for evaluating the production, cost, and value of common bean bags in the state of Goiás were obtained from the Federation of Agriculture and Livestock Site of Goiás (FAEG 2022). All amounts were obtained in Reais (R$) and converted to US Dollars (US$). The months of June and October 2018, and the months of May, June, and December 2019, were used as a reference to obtain the planting and management costs of the experiments carried out. For the common bean bag sales values, the months of September 2018 were used as references; January, August, and September 2019 and March 2020.

The economic analysis was performed as described by Sousa et al. (2020), in which gross revenue (RB), production cost (PC), net revenue (RL), and benefit–cost ratio (Rbc) were evaluated. As for the RB, it was obtained for each treatment by selling the grain yield, transformed into 60 kg bags, using as an index the values of R$ 98.09 (=US$ 24.52) bag^{-1} for the year 2018, BRL 273.95 (=USD 75.05), BRL 143.34 (=USD 34.62), and BRL 153.85 (=USD 36.98) bag^{-1} for the year 2019 and, R$ 239.27 (=US$ 46.01) bag^{-1} for 2020 (FAEG 2022). To determine the CP, all inputs consumed and operations carried out from pre-planting to harvest were considered, with values expressed in US$ ha^{-1}. The RL was obtained by subtracting the CP value from the RB. Finally, the Rcb ratio was calculated by dividing the RB value by the CP, expressing how much US$ returns per invested US$.

Statistical analysis

The data were subjected to tests of normality and homogeneity of variances for each variable and then to the analysis of variance. When a significant F test ($p \leq 0.05$) was found, the mean values were compared by the Scott–Knott test ($p \leq 0.05$) using the Sisvar software (Ferreira 2019).

Results

Grain yield analysis

The grain yield of common bean cultivated in the different areas ranged from 3,130.24 to 3,438.53 kg ha^{-1} as influenced by the evaluated treatments, resulting in a product equivalence ranging from approximately 52–57 bags of 60 kg ha^{-1} (Table 1).

Economic analysis

The production costs of the common bean crop also varied according to the treatments in each place where the experiments were conducted. In the experiments in Santo Antônio de Goiás-2018 and Formosa-2018/19, the AC treatment had the lowest production costs, equivalent to 533.84 and 375.79 US$ ha^{-1}, respectively (Table 2). For both sites, the NfT treatment had the highest values of production costs, equivalent to 595.65 and 447.32 US$ ha^{-1}, respectively (Table 2).

In Santo Antônio de Goiás-2018, the co-inoculation with Rt + Ab4l resulted in grain yield of 148 kg ha^{-1} more than the NfT treatment, resulting in a gross revenue of 61 US$ ha^{-1} more, even though no statistical difference was observed. In Formosa-2018/19, treatments with Rt + Ab1l and Rt + Ab4l co-inoculation stood out, which resulted in 143 and 88 kg ha^{-1} more than the NfT treatment, and gross revenue of 179 and 111 US$ ha^{-1} (Table 2).

It is noteworthy that all co-inoculation and single inoculation treatments with *R. tropici*, together with the absolute control, presented the lowest production cost values in Santo Antônio de Goiás-2018 and Formosa-2018/19.

Similar to what was observed in Santo Antônio de Goiás-2018 and Formosa-2018/19, in Cristalina-2019 and Santo Antônio de Goiás-2019, the AC treatment had the lowest production costs, being 393.47 and 593.13 US$ ha^{-1}, respectively. The NfT treatment showed the highest values of production costs, with 465.04 and 656.46 US$ ha^{-1}, respectively (Table 3).

In Cristalina-2019, the co-inoculation treatments Rt + Ab1l and Rt + Ab3l resulted in grain yield of 505 and 284 kg ha^{-1} more than the NfT treatment, resulting in gross revenue of 291 and 164 US$ ha^{-1} more than NfT treatment (Table 3). These same treatments (Rt + Ab1l and Rt + Ab3l) showed grain yield of 286 and 419 kg ha^{-1} and gross revenue of 176 and 258 US$ ha^{-1} more than the NfT treatment in Santo Antônio de Goiás-2019.

As in Santo Antônio de Goiás-2018 and Formosa-2018/19, the treatments of co-inoculation, single inoculation with *R. tropici*, and the absolute control also showed the lowest production cost values in Cristalina-2019 and Santo Antônio de Goiás-2019.

In the experiment conducted in Santo Antônio de Goiás-2019/20, the absolute control treatment had the lowest value of production costs, equivalent to 279.90 US$ ha^{-1}, while the treatment with nitrogen fertilization had the highest values of production costs. production, with 329.57 US$ ha^{-1} (Table 4).

In Santo Antônio de Goiás-2019/20, the Rt and RP treatments showed grain yield of 452 and 349 kg ha^{-1} and gross revenue of 346 and 268 US$ ha^{-1} more than the NfT treatment (Table 4). As well as in the experiments conducted in Santo Antônio de Goiás-2018, Formosa-2018/19, Cristalina-2019, and Santo Antônio de Goiás-2019, the co-inoculation treatments (*R. tropici* and *A. brasilense*), single inoculation with *R. tropici*, absolute control, and nitrogen fertilization resulted in lower production cost values in Santo Antônio de Goiás-2019/20.

The five experiments and treatments effects show that grain yield, gross revenue, and production cost ranged from 2,518.81 to 4,152.99 kg ha^{-1}, from 1,111.16 to 4,275.54 US$ ha^{-1}, and from 292.85 to 609.47 US$ ha^{-1}, respectively. The average cost of production in the experiment conducted in Santo Antônio de Goiás-2019 was higher than in Santo Antônio de Goiás-2018, Formosa-2018/19, Cristalina-2019 and Santo Antônio de Goiás-2019/20, with an average value of 609 US$ ha^{-1}. The average gross revenue presented a value of 4.275.54 US$ ha^{-1} in Formosa-2018/19, being higher than that

Table 1 Effect of nitrogen fertilization, single inoculation with *R. tropici*, and co-inoculation of *R. tropici* and *A. brasilense* via foliar spraying on grain yield of common bean. Average data of five field experiments

Treatments[1]	Grain yield[2] (kg ha^{-1})		Product equivalence (bags 60 kg ha^{-1})	
AC	3355.69	a	55.93	a
NfT	3338.15	a	55.64	a
Rt	3364.44	a	56.07	a
Rt + Ab1l	3360.84	a	56.01	a
Rt + Ab2l	3130.24	b	52.17	b
Rt + Ab3l	3438.53	a	57.31	a
Rt + Ab4l	3300.89	a	55.01	a
RP	3345.98	a	55.77	a
Average	3329.34		55.49	

Santo Antônio de Goiás-GO—winter/2018; Formosa-GO—waters/2018–19; Cristalina-GO—winter/2019; Santo Antônio de Goiás-GO—winter /2019; Santo Antônio de Goiás-GO—waters/2019–20

[1] AC—Absolute control (without inoculation and fertilization), NfT—nitrogen fertilization (80 kg N ha^{-1} of N, being 20 kg N ha^{-1} at sowing and 60 kg N ha^{-1} at the V4 stage), Rt—two doses of *R. tropici* in the seed, Rt + Ab1l—two doses of *R. tropici* in the seed + one dose of *A. brasilense* applied in V2–V3, Rt + Ab2l—two doses of *R. tropici* in the seed + two doses of *A. brasilense* applied in V2–V3, Rt + Ab3l—two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3, Rt + Ab4l—two doses of *R. tropici* in the seed + four doses of *A. brasilense* applied in V2–V3, and RP-registered product (two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3

[2] Average values of grain yield as reported by Messias et al. (2023). Means followed by the same letter within the same column do not differ by the Scott–Knott test ($p \leq 0.05$)

Table 2 Economic analysis of common bean cultivated with different nitrogen supply treatments, conducted in the 2019 winter season in Santo Antônio de Goiás-GO and the 2018–19 waters season in Formosa-GO municipality

Treatments[1]	Grain yield[2]		Product equivalence		Gross revenue		Production cost
	kg ha^{-1}		bags 60 kg ha^{-1}		US$ ha^{-1}		US$ ha^{-1}
Santo Antônio de Goiás-2018							
AC	2741.89	a	45.70	a	1120.63	a	533.84
NfT	2977.26	a	49.62	a	1216.83	a	595.65
Rt	2681.45	a	44.69	a	1095.93	a	535.09
Rt + Ab1l	2369.27	b	39.49	b	968.34	b	544.54
Rt + Ab2l	2225.58	b	37.09	b	909.61	b	546.29
Rt + Ab3l	2808.13	a	46.80	a	1147.71	a	548.04
Rt + Ab4l	3125.46	a	52.09	a	1277.40	a	549.79
RP	2820.69	a	47.01	a	1152.84	a	548.04
Average	2718.72		45.31		1111.16		550.16
Formosa-2018/19							
AC	3438.12	b	57.30	b	4.300.79	b	375.79
NfT	3465.04	b	57.75	b	4.334.46	b	447.32
Rt	3361.36	b	56.02	b	4.204.77	b	377.16
Rt + Ab1l	3607.94	a	60.13	a	4.513.22	a	387.65
Rt + Ab2l	3168.65	b	52.81	b	3.963.71	b	389.57
Rt + Ab3l	3360.36	b	56.01	b	4.203.52	b	391.49
Rt + Ab4l	3553.49	a	59.22	a	4.445.11	a	393.40
RP	3388.54	b	56.48	b	4.238.77	b	391.49
Average	3417.94		56.97		4.275.54		394.23

[1] AC—Absolute control (without inoculation and fertilization), NfT—nitrogen fertilization (80 kg N ha^{-1} of N, being 20 kg N ha^{-1} at sowing and 60 kg N ha^{-1} at the V4 stage), Rt—two doses of *R. tropici* in the seed, Rt + Ab1l—two doses of *R. tropici* in the seed + one dose of *A. brasilense* applied in V2–V3, Rt + Ab2l—two doses of *R. tropici* in the seed + two doses of *A. brasilense* applied in V2–V3, Rt + Ab3l—two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3, Rt + Ab4l—two doses of *R. tropici* in the seed + four doses of *A. brasilense* applied in V2–V3, and RP-registered product (two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3

[2] Average values of grain yield as reported by Messias et al. (2023). Means followed by the same letter within the same column do not differ by the Scott–Knott test ($p \leq 0.05$)

of Santo Antônio de Goiás-2018, Cristalina-2019, Santo Antônio de Goiás-2019 and Santo Antônio de Goiás-2019/2020.

Regarding net revenue, different responses were observed for treatments in each location (Fig. 2).

In Santo Antônio de Goiás-2018, the highest values of net revenue were observed in treatments Rt + Ab4l, NfT, RP, and Rt + Ab3l with 728, 621, 605, and 600 US$ ha^{-1}, respectively, while treatments Rt and AC presented values of 561 and 587 US$ ha^{-1}, respectively (Fig. 2A). Co-inoculation Rt + Ab4l was very efficient since it resulted in 106, 167, 123, and 141 US$ ha^{-1} more than NfT, Rt, RP, and AC treatments, respectively.

In Formosa-2018/19, the highest values of net revenue were observed in the co-inoculation treatments Rt + Ab1l and Rt + Ab4l, resulting in 238 and 165, 298 and 224, 201 and 127, and 278 and 204 US$ ha^{-1} more than NfT, Rt, AC, and RP treatments, respectively (Fig. 2B).

In Cristalina-2019 (Fig. 2C) and Santo Antônio de Goiás-2019 (Fig. 2D), the co-inoculation treatments Rt + Ab3l and Rt + Ab1l had the highest net income values, with 2.030 and 2.160 US$ ha^{-1} and 2.046 and 1.967 US$ ha^{-1}, respectively. In Cristalina-2019, the co-inoculation treatments Rt + Ab1l and Rt + Ab3l resulted in 345 and 214 US$ ha^{-1}, 178 and 47 US$ ha^{-1}, and 194 and 64 US$ ha^{-1} more than the NfT, Rt and RP treatments, respectively (Fig. 2C). In Santo Antônio de Goiás-2019, the co-inoculation treatments Rt + Ab3l and Rt + Ab1l resulted in 308 and 229 US$ ha^{-1}, 309 and 229 US$ ha^{-1}, 394 and 315 US$ ha^{-1} and 413 and 334 US$ ha^{-1} more than the NfT, Rt, AC, and RP treatments, respectively (Fig. 2D).

In the experiment conducted in Santo Antônio de Goiás-2019/20, the highest values of net income were observed in treatments Rt, RP, and AC, with 1.915, 1.826, and 1.831 US$ ha^{-1}, respectively (Fig. 2E). It is noteworthy that the Rt treatment was the most efficient of the three treatments, due to its high net revenue value, with values of 395, 88, and 84 US$ ha^{-1} more than the NfT, RP, and AC treatments, respectively.

Table 3 Economic analysis of common bean cultivated with different nitrogen supply treatments, conducted in the 2019 winter season in Cristalina-GO and Santo Antônio de Goiás-GO

Treatments[1]	Grain yield[2]		Product equivalence		Gross revenue		Production cost
	kg ha^{-1}		Bags 60 kg ha^{-1}		US$ ha^{-1}		US$ ha^{-1}
Cristalina-2019							
AC	4204.32	b	70.07	b	2426.12	b	393.47
NfT	3952.58	b	65.88	b	2280.85	b	465.04
Rt	4132.82	b	68.88	b	2384.86	b	402.24
Rt + Ab1l	4457.09	a	74.28	a	2571.98	a	411.50
Rt + Ab2l	3993.66	b	66.56	b	2304.55	b	413.19
Rt + Ab3l	4236.52	a	70.61	a	2444.70	a	414.88
Rt + Ab4l	4120.99	b	68.68	b	2378.03	b	416.57
RP	4125.95	b	68.77	b	2380.89	b	414.88
Average	4152.99		69.22		2396.50		416.47
Santo Antônio de Goiás-2019							
AC	3641.66	b	60.69	b	2.244.67	b	593.13
NfT	3884.70	b	64.75	b	2.394.48	b	656.46
Rt	3783.82	b	63.06	b	2.332.29	b	594.34
Rt + Ab1l	4170.60	a	69.51	a	2.570.70	a	603.67
Rt + Ab2l	3870.79	b	64.51	b	2.385.90	b	605.35
Rt + Ab3l	4304.06	a	71.73	a	2.652.96	a	607.04
Rt + Ab4l	3416.40	b	56.94	b	2.105.82	b	608.72
RP	3634.09	b	60.57	b	2.240.00	b	607.04
Average	3838.27		63.97		2.365.85		609.47

[1] AC—Absolute control (without inoculation and fertilization), NfT—nitrogen fertilization (80 kg N ha^{-1} of N, being 20 kg N ha^{-1} at sowing and 60 kg N ha^{-1} at the V4 stage), Rt—two doses of *R. tropici* in the seed, Rt + Ab1l—two doses of *R. tropici* in the seed + one dose of *A. brasilense* applied in V2–V3, Rt + Ab2l—two doses of *R. tropici* in the seed + two doses of *A. brasilense* applied in V2–V3, Rt + Ab3l—two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3, Rt + Ab4l—two doses of *R. tropici* in the seed + four doses of *A. brasilense* applied in V2–V3, and RP-registered product (two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3

[2] Average values of grain yield as reported by Messias et al. (2023). Means followed by the same letter within the same column do not differ by the Scott–Knott test ($p \leq 0.05$)

Table 4 Economic analysis of common bean cultivated with different nitrogen supply treatments, conducted in the 2019/20 waters season in Santo Antônio de Goiás-GO

Treatments[1]	Grain yield		Product equivalence		Gross revenue		Production cost
	kg ha^{-1}		Bags 60 kg ha^{-1}		US$ a^{-1}		US$ ha^{-1}
AC	2752.47	a	45.87	a	2110.84	a	279.90
NfT	2411.15	b	40.19	b	1849.09	b	329.57
Rt	2862.73	a	47.71	a	2195.40	a	280.86
Rt + Ab1l	2199.28	b	36.65	b	1686.61	b	288.34
Rt + Ab2l	2392.51	b	39.88	b	1834.79	b	289.69
Rt + Ab3l	2483.60	b	41.39	b	1904.65	b	291.03
Rt + Ab4l	2288.10	b	38.14	b	1754.72	b	292.38
RP	2760.63	a	46.01	a	2117.10	a	291.03
Avereage	2518.81		41.98		1931.65		292.85

[1] AC—Absolute control (without inoculation and fertilization), NfT—nitrogen fertilization (80 kg N ha^{-1} of N, being 20 kg N ha^{-1} at sowing and 60 kg N ha^{-1} at the V4 stage), Rt—two doses of *R. tropici* in the seed, Rt + Ab1l—two doses of *R. tropici* in the seed + one dose of *A. brasilense* applied in V2–V3, Rt + Ab2l—two doses of *R. tropici* in the seed + two doses of *A. brasilense* applied in V2–V3, Rt + Ab3l—two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3, Rt + Ab4l—two doses of *R. tropici* in the seed + four doses of *A. brasilense* applied in V2–V3, and RP-registered product (two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3

[2] Average values of grain yield as reported by Messias et al. (2023). Means followed by the same letter within the same column do not differ by the Scott–Knott test ($p \leq 0.05$)

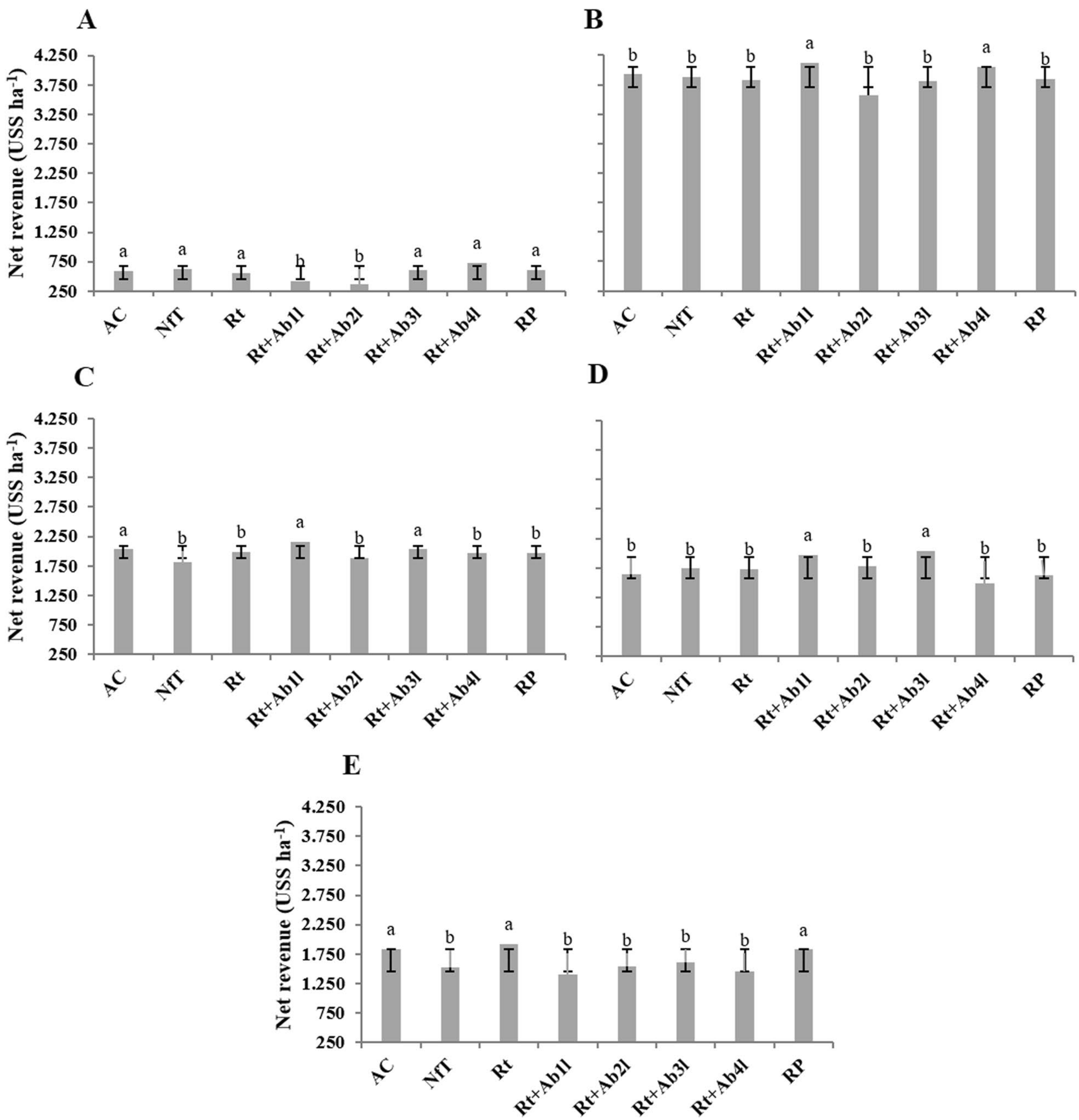

Fig. 2 Net income of common bean cultivated with different nitrogen supply treatments, conducted in Santo Antônio de Goiás-2018 (**A**), Formosa-2018/19 (**B**), Cristalina-2019 (**C**), Santo Antônio de Goiás-2019 (**D**) and Santo Antônio de Goiás-2019/20 (**E**). AC—Absolute control (without inoculation and fertilization), NfT—nitrogen fertilization (80 kg N ha^{-1} of N, being 20 kg N ha^{-1} at sowing and 60 kg N ha^{-1} at the V4 stage), Rt—two doses of *R. tropici* in the seed, Rt + Ab1l—two doses of *R. tropici* in the seed + one dose of *A. brasilense* applied in V2–V3, Rt + Ab2l—two doses of *R. tropici* in the seed + two doses of *A. brasilense* applied in V2–V3, Rt + Ab3l—two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3, Rt + Ab4l—two doses of *R. tropici* in the seed + four doses of *A. brasilense* applied in V2–V3, and RP—registered product (two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3. Means followed by the same letter do not differ by the Scott–Knott test ($p \leq 0.05$)

For the benefit–cost ratio, the responses were similar to those for net revenue in all experiments conducted (Fig. 3).

In the experiment conducted in Santo Antônio de Goiás-2018, the highest benefit–cost ratio values were observed in treatments Rt + Ab4l (0.58 US$ US$$^{-1}$), Rt + Ab3l (0.52 US$ US$$^{-1}$) and RP (0.53 US$ US$$^{-1}$),

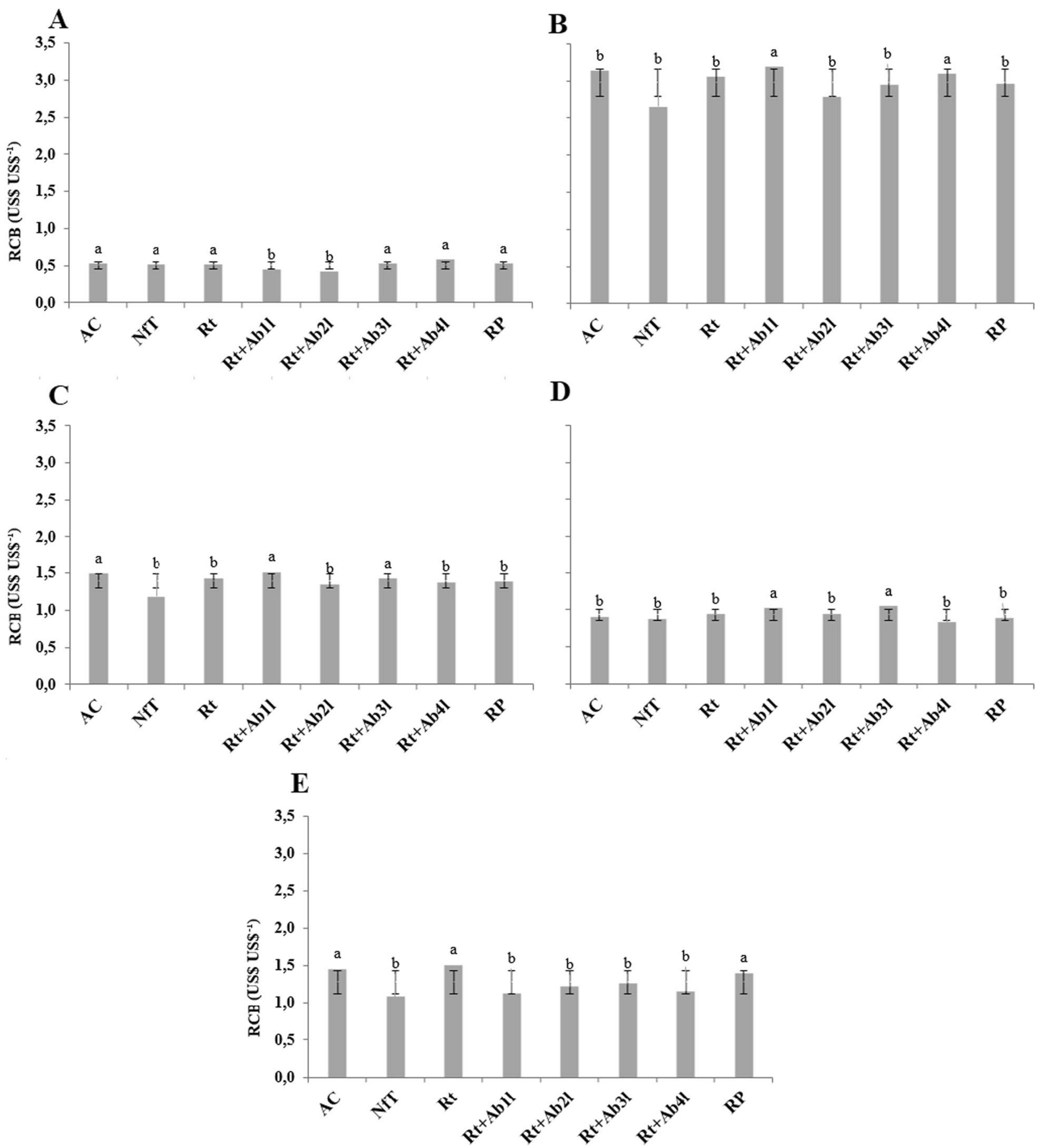

Fig. 3 Benefit–cost ration of common bean cultivated with different nitrogen supply treatments, conducted in Santo Antônio de Goiás-2018 (**A**), Formosa-2018/19 (**B**), Cristalina-2019 (**C**), Santo Antônio de Goiás-2019 (**D**) and Santo Antônio de Goiás-2019/20 (**E**). AC—Absolute control (without inoculation and fertilization), NfT—nitrogen fertilization (80 kg N ha^{-1} of N, being 20 kg N ha^{-1} at sowing and 60 kg N ha^{-1} at the V4 stage), Rt—two doses of *R. tropici* in the seed, Rt + Ab1l—two doses of *R. tropici* in the seed + one dose of *A. brasilense* applied in V2–V3, Rt + Ab2l—two doses of *R. tropici* in the seed + two doses of *A. brasilense* applied in V2–V3, Rt + Ab3l—two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3, Rt + Ab4l—two doses of *R. tropici* in the seed + four doses of *A. brasilense* applied in V2–V3, and RP—registered product (two doses of *R. tropici* in the seed + three doses of *A. brasilense* applied in V2–V3. Means followed by the same letter do not differ by the Scott–Knott test ($p \leq 0.05$)

being higher than the values observed for Rt, NfT, and AC (Fig. 3A). In the experiment conducted in Formosa-2018/19, the highest benefit–cost ratio values were observed in the co-inoculation treatments Rt + Ab1l (3.19 US\$ US\$$^{-1}$), Rt + Ab4l (3.10 US\$ US\$$^{-1}$) and TA (3.14 US\$ US\$$^{-1}$ being superior in relation to NfT, Rt and RP treatments (Fig. 3B).

On the other hand, in the experiments conducted in Cristalina-2019 (Fig. 3C) and Santo Antônio de Goiás-GO (Fig. 3D), the co-inoculation treatments Rt + Ab3l and Rt + Ab1l showed the highest benefit–cost ratio values. In Cristalina-2019, the values of the benefit–cost ratio of the co-inoculation treatments Rt + Ab1l (1.51 US\$ US\$$^{-1}$), Rt + Ab3l (1.42 US\$ US\$$^{-1}$) and AC (1.49 US\$ US\$$^{-1}$) were higher when compared to NfT, Rt and RP treatments (Fig. 3C). In Santo Antônio de Goiás-2019, the values of the benefit–cost of the co-inoculation treatments Rt + Ab3l (1.05 US\$ US\$$^{-1}$) and Rt + Ab1l (1.02 US\$ US\$$^{-1}$) were higher when compared to NfT, Rt, AC and RP treatments (Fig. 3D).

In Santo Antônio de Goiás-2019/20, the highest values of the benefit–cost ratio were observed in treatments Rt (1.50 US\$ US\$$^{-1}$), RP (1.40 US\$ US\$$^{-1}$) and AC (1.45 US\$ US\$$^{-1}$) (Fig. 3E). It is noteworthy that, in terms of net revenue, the Rt treatment was the most efficient of the three treatments due to its high benefit–cost ratio, being superior to the NfT, RP, and AC treatments.

Considering the averages of the five sites, the values for net income and benefit–cost ratio behaved similarly to those for gross income, in which the NfT treatment presented the lowest values, ranging from 621 to 3.887 US\$ US\$$^{-1}$ and from 0.51 to 2.65 US\$ US\$$^{-1}$, respectively. Still considering the average of the five locations, variation was observed for net revenue and benefit–cost ratio, which range from 561 to 3.881 US\$ ha^{-1} and 0.50 to 2.98 US\$ US\$$^{-1}$.

Discussion

Grain yield analysis

These results demonstrated that common bean grain yield differed significantly between treatments, with an average of 30 bags more than the national average, with approximately 24 bags ha^{-1} (Embrapa Rice and Beans 2022). In addition, it was 21 bags higher than the average for small properties in the municipality of Goianésia-GO (Ferreira et al. 2020), which can be explained by the technological level used in each production system.

Although family farming accounts for about 60% of the national common bean production (Souza 2015), the crop productivuty is still limited in these production systems due to the low use of inputs and technologies, such as improved genotypes, biological products, and fertilizers (Birachi et al. 2011; Ferreira et al. 2020), unlike commercial production systems, which are highly technical.

On average, the Rt + Ab3l treatment resulted in about 57 bags ha^{-1}, which, although not significantly different, was two bags ha^{-1} more than the NfT treatment (Table 1). The authors Hungria et al. (2013) and Souza and Ferreira (2017) report the positive effect of co-inoculation with *R. tropici* and *A. brasilense* on the grain yield of the common bean, which is possibly associated with the synergism between the two bacteria when combined, providing better results than inoculation only with *R. tropici* (Bárbaro et al. 2008; Ferreira et al. 2020).

Economic analysis

In the system that uses nitrogen fertilizers, inputs represented around 54% of the total, agricultural operations represented 26% and other costs represented 20% (Oliveira et al. 2023). In our present study, as well as in other studies that carry out an economic evaluation of the application of biotechnology, it was found that the use of nitrogen fertilizers increased bean production costs (Soares et al. 2016).

These results of production cost, net revenue and cost–benefit ratio are linked to the efficiency of the co-inoculation technique with *R. tropici* and *A. brasilense*, arising mainly from the mechanisms of action of the two bacteria, especially *R. tropici* providing nitrogen via biological nitrogen fixation and *A. brasilense* improving nutrient absorption through the role of phytohormones. The fact that the economic gains from the use of inoculants are associated with being cheap and easily accessible to the producer, regardless of their level of technology, in addition to being partially or totally efficient, equal to nitrogen fertilizers. Nitrogen fertilizers, in addition to having a high cost per hectare for producers, also have logistics costs, from the place of purchase to the moment of application to the crops, making them one of the most expensive inputs in the common bean production system.

Regarding the production costs of the common bean in the different places where the experiments were conducted, the AC treatment presented the lowest values, ranging from 280 to 593 US\$ ha^{-1}. In contrast, the NfT treatment showed the highest values, ranging from 330 to 656 US\$ ha^{-1}. This is because nitrogen fertilizers are one of the most expensive inputs in common bean production systems. Working with N doses, Gerlach et al. (2013) observed that the application of 90 kg ha^{-1} of N resulted in 14% of the total cost.

The economic analysis showed that, compared to the NfT, single inoculation with *R. tropici* and AC treatment, Rt + Ab3l and Rt + Ab1l presented higher mean gross revenue, with values of 56, 28, and 30 US\$ ha^{-1} and 47, 20 and 22 US\$ ha^{-1}, respectively. These results corroborate those of Ferreira et al. (2020), in which co-inoculation increased gross revenue compared to N-fertilizer treatment.

In this study, the Rt + Ab3l treatment increased the average gross revenue by 2470.71 US$ ha^{-1}, in addition to the lowest average production cost values, with 450 US$ ha^{-1}. Soares et al. (2016), working with the cultivar BRSMG Majestoso, inoculated with the CIAT 899 strain, reported that the combination of inoculation with the application of N-urea could contribute to greater profitability in the common bean crop, depending on the location.

It is worth mentioning the importance of inoculating *A. brasilense* combined with other microorganisms or nitrogen fertilization, mainly in legumes, including grasses (Ferreira et al. 2020). Galindo et al. (2017), working with inoculation of *A. brasilense* and nitrogen doses in corn, showed that the use of inoculation is more profitable, mainly due to the high cost of nitrogen fertilizers.

In the present study, the Rt + Ab3l treatment showed mean values of net revenue and benefit–cost ratio of 104 US$ ha^{-1} and 0.18 US$ US$$^{-1}$, respectively, more than the NfT treatment. These results corroborate those of Ferreira et al. (2020), in which co-inoculation with *R. tropici* and *A. brasilense* promoted the best economic performance, which resulted in a return rate of 13% under a family farming production system. Other authors reported that the inoculation with *R. tropici* presented higher grain yield and lower production cost, generating net revenue and benefit–cost ratio of 15.8% and 7.8%, respectively, superior to the treatment with nitrogen fertilization (Sousa et al. 2020).

All these results demonstrate the importance of using *R. tropici* in common bean inoculation. In addition, current works show the use of *R. tropici* combined with *A. brasilense* as an efficient strategy to increase profitability in common bean production systems. Galindo et al. (2018), studying co-inoculation with *Bradyrhizobium japonicum* and *A. brasilense* in two soybean cultivars, observed that the technique was economically viable for both cultivars.

Conclusions

The co-inoculation technique with *R. tropici* and *A. brasilense* promotes high grain production, reducing the use of nitrogen fertilizers and, mainly, savings in the common bean production system.

Treatment with nitrogen fertilizer resulted in the highest grain production, however, on the other hand, it was the one that resulted in the highest production cost, whose average value for the five locations was equivalent to US$ 499 ha^{-1}.

Co-inoculation with two doses of *Rhizobium tropici* and three doses of *Azospirillum brasilense* in bean plants provided the highest average values of gross revenue (2.471 US$ ha^{-1}), net revenue (2.220 US$ ha^{-1}) and cost–benefit ratio (1.4 US$ US$$^{-1}$), in addition to having the lowest average production cost of 451 US$ ha^{-1}. Co-inoculation with *Rhizobium tropici* and *Azospirillum brasilense* is an alternative for common bean production systems in countries that have edaphoclimatic characteristics similar to those of the present study, promoting the reduction of environmental impacts and reduction of production costs resulting from the use of nitrogen fertilizers, reduction of emissions agricultural GHG.

Abbreviations

EMBRAPA	Brazilian Agricultural Research Company
FAEG	Federation of Agriculture and Livestock of Goiás

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Author contributions

MM implemented, conducted, and collected data from the experiments besides performing the statistical analysis and writing the manuscript. PCA did the translation the manuscript into English. EPBF did study planning, statistical analysis, and support in writing the document, and all authors commented on manuscript versions. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interest.

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