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Economic gains using organic P source and inoculation with P-solubilizing bacteria in sugarcane[1]

Ganhos econômicos usando fonte orgânica de P e inoculação com bactérias solubilizadoras de P em cana-de-açúcar

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HIGHLIGHTS:

Structural equations are potential approaches to select main drivers of sugarcane yield.
β-glucosidase and alkaline phosphatase activities are the most predictive parameters selected.
The economic gains associated with bacterial inoculation and organic compost application vary according to yield scenario.

ABSTRACT: Biological agribusiness has grown substantially worldwide and requires efficient strategies to maintain or increase crop production. However, little is known about the real economic gains associated with belowground mechanisms in agriculture, including those of traditional crops such as sugarcane. This study aimed to identify potential microbiological indicators related to yield increase and value the soil microbiological services through the development of a structural equation model (SEM). The SEM was constructed based on a dataset from a previous sugarcane field experiment in which the effects of inoculation with phosphate-solubilizing bacteria (PSB) and the input of organomineral fertilizer were evaluated. The SEM indicated that the β-glucosidase and alkaline phosphatase activities were potential indicators of yield increases in four scenarios (current, plausible, optimistic, and futuristic). Increases of 158 and 195 t ha^{-1} were projected based on the β-glucosidase activity for the current and plausible scenarios, respectively. These increases resulted in economic gains of R$ 453.02 ha^{-1} (US$ 86.07 ha^{-1}) for the current scenario, and R$ 1,571.53 ha^{-1} (US$ 298.59 ha^{-1}) for the plausible scenario, considering the exchange rate from February 2022 (R$ 0.19 US$$^{-1}$). Regardless of the scenario, bacterial inoculation was associated with increased β-glucosidase or alkaline phosphatase activity and higher yields, which translates into economic gains for sugarcane farmers.

Key words: organic fertilizer, bioinoculants, soil health, bioeconomy, soil organic matter

RESUMO: O agronegócio biológico cresceu substancialmente em todo o mundo, demandando estratégias eficientes para manter ou aumentar a produção vegetal. Entretanto, pouco se conhece a respeito dos reais ganhos econômicos associados aos mecanismos que ocorrem na agricultura, incluindo cultivos tradicionais como a cana-de-açúcar. Buscou-se neste estudo encontrar potenciais indicadores microbiológicos relacionados com o aumento de produtividade e, paralelamente, valorar os serviços microbiológicos do solo por meio do desenvolvimento de uma equação estrutural (SEM). A SEM foi construída com base nos dados prévios de um experimento com cana-de-açúcar a campo, no qual os efeitos da inoculação com bactérias solubilizadoras de fosfato e utilização de fertilizante organomineral foram avaliados. A SEM indicou que as atividades de β-glucosidase e fosfatase alcalina foram potenciais indicadores relacionados ao aumento de produtividade em quatro cenários (atual, plausível, otimista e futurista). Aumentos de 158 e 195 t ha^{-1} foram projetados com base na atividade de β-glucosidase para os cenários atual e plausível, respectivamente. Estes aumentos resultaram em ganhos econômicos de R$ 453,02 ha^{-1} (US$ 86,07 ha^{-1}) para o cenário atual, e R$ 1.571,53 ha^{-1} (US$ 298,59 ha^{-1}) para o cenário plausível, considerando a taxa de câmbio de fevereiro de 2022 (R$ 0,19 US$$^{-1}$). Independente do cenário, a inoculação bacteriana esteve associada a maiores atividades de β-glucosidase ou fosfatase alcalina e também maiores produtividades, o que se traduziu em ganhos econômicos para os agricultores de cana-de-açúcar.

Palavras-chave: fertilizante orgânico, bioinoculantes, saúde do solo, bioeconomia, matéria orgânica do solo

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Introduction

Agribusiness represents approximately 27% of the Brazilian gross domestic product (GDP), which corresponds to US$ 390 billion in the world economy (CEPEA, 2021; The World Bank, 2022). However, thus far, agribusiness has been responsible for converting natural areas into cultivated regions, which leads to decreased soil health and yield stagnation (Martinelli et al., 2017) in many crops, such as sugarcane.

Sugarcane occupies more than 10 million hectares of arable land in Brazil, with a mean production of 757 million tons (IBGE, 2022). Among the main bottlenecks in sugarcane cultivation are the costs related to the application of synthetic fertilizers, especially macronutrients such as phosphorus (P) (Soltangheisi et al., 2019). Therefore, given the current concept of the bioeconomy and biofuel production incentives, there is considerable interest in increasing sugarcane yields through strategies such as the improvement of soil health (Bordonal et al., 2018). Despite the increasing use of phosphate-solubilizing bacteria (PSB) and organomineral fertilizers to supply phosphorus to different crops, few studies have demonstrated their direct impact on P availability, yield, and profit (Crusciol et al., 2020; Lopes et al., 2021; Silva et al., 2022).

Thus, an approach based on structural equation modeling (SEM) would be useful to provide a theoretical basis for understanding the relationships of yield with organomineral fertilizers coupled with PSB inoculation, thereby allowing for the detection of potential soil microbiological indicators (Gruda et al., 2012). Therefore, the objective of this study was to develop a SEM based on a dataset from a previous sugarcane field experiment involving the use of an organic P source and PSB inoculation to evaluate the economic gains generated by microbiological services in the soil and to determine the best predictors of sugarcane yield.

Material and Methods

The dataset used in this study comprised soil enzyme activities, leaf nutrients, and yield parameters obtained from a field experiment with sugarcane (Lopes et al., 2021; Silva et al., 2022). This experiment was monitored during the crop year 2014/2015 (cane plant) to evaluate the effects of applying an organic P source, which was prepared by composting both filter cake and ash, with or without phosphate-solubilizing bacteria (PSB) (Silva et al., 2022).

The experiment was conducted in a region of Novo Horizonte, São Paulo State, Brazil (21º 33' 59.8" S; 49º 10' 13.9" W; altitude 462 m) with an Oxisol soil (United States, 2014) that corresponds to a Latossolo Vermelho-Amarelo in the Brazilian Soil Classification System (EMBRAPA, 2018), with a sandy loam texture. Estrada-Bonilla et al. (2021) demonstrated the efficiency of the bacteria under greenhouse conditions, while Lopes et al. (2021) and Silva et al. (2022) subsequently used the bacteria in a field experiment.

Briefly, the field study demonstrated a strategy based on phosphate-solubilizing bacteria (PSB) inoculation (*Bacillus* sp. BACBR04, *Bacillus* sp. BACBR06, and *Rhizobium* sp. RIZBR01) and organic P-source application that increased the yield of sugarcane by 17.3 Mg ha^{-1} compared to the traditional mineral P-source control. The sugarcane variety planted was CTC24, and the experiment was set up in a randomized block design with the application of an organomineral fertilizer in the presence and absence of bacterial inoculation (inoculated and uninoculated treatments, respectively). An additional treatment without compost was included as a control with exclusively soluble P using triple superphosphate (TSP, 46% P_2O_5). These treatments supplied the amounts of P (150 kg ha^{-1} of P_2O_5, using TSP 46% P_2O_5), nitrogen (140 kg ha^{-1} of N, using urea 45% N), and potassium (140 kg ha^{-1} of K_2O, using potassium chloride 60% K_2O), as described by Silva et al. (2022).

The data analysis was divided into three steps (Figure 1).

First, the data were divided into three groups: 1. soil enzymes (acid and alkaline phosphatases, β-glucosidase, and arylsulfatase activities, Figure 1A); 2. Leaf nutrients (nitrogen, copper, calcium, manganese, potassium, and phosphorus, Figure 1B); and 3. Yield parameters (tons of stalk per hectare and total recoverable sugar, Figure 1C). A composite variable was obtained for each group using non-metric multidimensional scaling (NMDS), which was designated the first axis score (Yang et al., 2020) (Figure 1A).

Second, the structural equation model (SEM) was used to understand the causal relationship between variables according to an established a priori model (Figure 1B) and detect potential parameters related to yield increase (Kline, 2015). The maximum likelihood estimator was applied to the SEM, and the selection of soil or plant attributes that exerted significant influence on each soil composite variable was based on the positive standardized path coefficient and p-value. According to Kline (2015), the default estimation method in the SEM (maximum likelihood) assumes multivariate normality for continuous outcome variables; therefore, this method was used for the transformation of log (x + 1).

Third, four scenarios were created (current, plausible, optimistic, and futuristic) based on the increment in the soil or plant attributes selected from the SEM analysis (Figure 1C). A hypothetical linear regression was delineated for the selected SEM attribute (independent variable) and yield (dependent variable). During this step, two different levels were considered, inoculated and uninoculated (with or without inoculation with the three PSB, respectively).

Finally, the economic gain was estimated from linear equations and fixed values of production costs for the 2022 harvest (SOCIANA, 2022). The price of sugarcane stalk was set at R$ 106.02 per ton (equivalent to US$ 20.53 per ton, at the exchange rate of R$ 0.19 US$$^{-1}$ in February 2022). The final economic gain was calculated based on the difference between those obtained with and without the bacterial inoculation. Here, it was not considered the costs related to PSB inoculation, as scientific efforts are still ongoing to find efficient strategies and strains for sugarcane crops.

The statistical analyses were performed in the R program (R Core Team, 2019), using the "vegan," "lavaan," and "semPlot" packages.

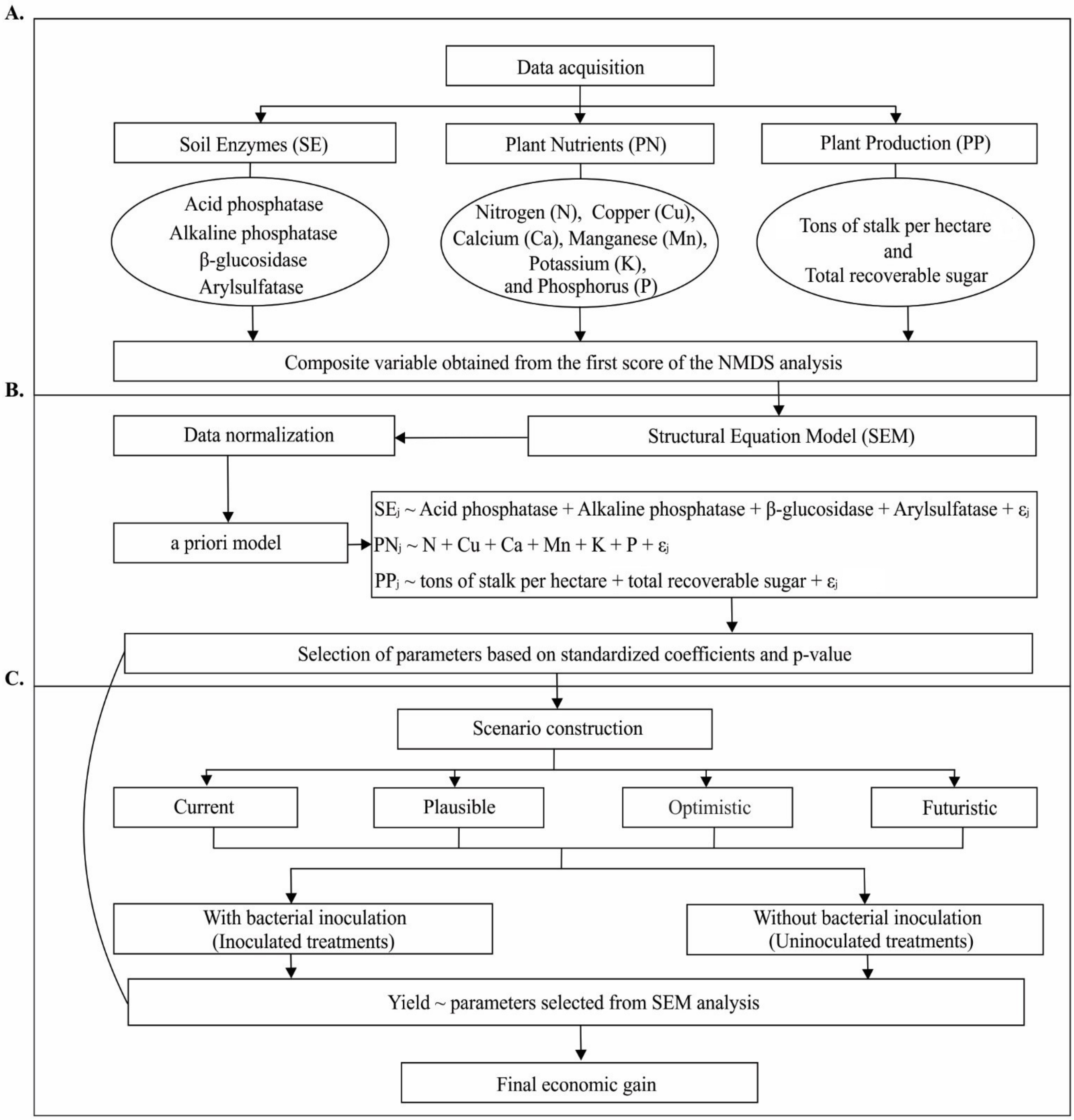


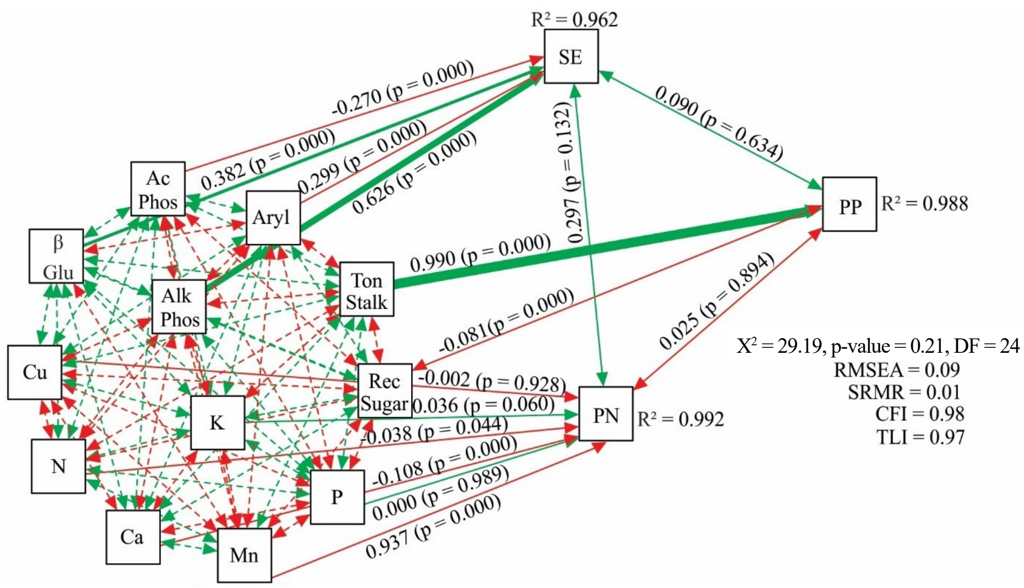
Figure 1. Workflow of the modeling procedures conducted in this study, considering (A) data acquisition and construction of composite variables, (B) establishment of a priori model, and (C) construction of scenarios and final profit

Results and Discussion

The structural equation model (SEM) approach allows for an understanding of the influence of different factors and their interactions. The aim of this study was to select the most important drivers among soil enzymes and leaf nutrients that could induce biomass increase. The SEM (Figure 2) was adequate according to the cutoff values summarized by Fan et al. (2016) (Table 1). In general, the benchmark value for the comparative fit index (CFI) and Tucker-Lewis index (TLI) is 0.9 or greater, and the values found here were 0.98 and 0.97, respectively. Other indices, such as the chi-squared test and standardized root mean square residual, were also in accordance with benchmark values.

The hypothesized relationships among the variables defined in the a priori model (Figure 1B) were checked and identified as valid; therefore, the model coefficients were estimated. One exception was the root mean square error of approximation (RMSEA) of 0.09, which is recommended to be below 0.06. However, Savalei (2012) suggested that RMSEA is often insensitive to multiple omitted cross-loadings, and is a function of model size.

The standardized root mean square residual (SRMR) was 0.01, which was considered adequate according to the reference value (SRMR < 0.09) (Fan et al., 2016). RMSEA and SRMR are indexes that indicate the fit of the model and vary between 0 and 1, where 0 indicates a perfect fit and 1 indicates a lack of fit



SE - Soil enzymes; PP - Plant production; PN - Plant nutrients; Ac Phos - Acid phosphatase activity; Alk Phos - Alkaline phosphatase activity; Aryl - Arylsulfatase activity; β-Glu - β-Glucosidase activity; Ton Stalk - Ton of stalk per hectare; Rec Sugar - Total recoverable sugar. Leaf nutrients (N, P, K, Ca, Mn, and Cu). X^2 - Chi-squared test; DF - Degrees of freedom; RMSEA - Root mean square error of approximation; SRMR - Standardized root mean square residual; CFI - Comparative fit index; TLI - Tucker-Lewis index. Numbers adjacent to the arrows indicate the standardized path coefficients and p-values for each direct relationship. Green and red signify positive and negative relationships, respectively. The double-headed arrows denote the covariance results, whereas the forward arrows indicate the regression results. R^2 denotes the proportion of variance explained for each composite variable and attributes considered in the a priori model

Figure 2. Structural equation model showing the direct (solid arrows) and indirect (dashed arrows) pathways based on the a priori model

Table 1. Model evaluation indexes obtained and reference values according to Fan et al. (2016)

Fit measure	This study	Benchmark
Chi-squared test (p-value)	0.21	> 0.05
Comparative fit index (CFI)	0.98	> 0.95
Tucker-Lewis index (TLI)	0.97	> 0.90
Root mean square error of approximation (RMSEA)	0.09	< 0.06
Standardized root mean square residual (SRMR)	0.01	< 0.09

(Fan et al., 2016). The interpretation of RMSEA and SRMR is contrary to the coefficient of determination (R^2), that is, when the coefficient of determination is 1, the RMSEA or SRMR is 0 (Barnston, 1992).

When working with the SEM, there is no simple universally acceptable index to determine the quality of the modeling. For example, Xu et al. (2018) used the comparative fit index (CFI) and SRMR, whereas Li et al. (2020) used the fit quality index (GFI) and RMSEA. However, generally a combination of at least two fit indices is preferred (Hu & Bentler, 1999). In this study, the modeling was considered excellent according to the cut-off values recommended for four indices (X^2, SRMR, CFI, and TLI). The SEM approach has been used successfully in the sugarcane sector to detect the interactions between socioeconomic factors and the production system (Nacife et al., 2019), and here it was used to detect potential parameters related to yield increase.

According to the a priori model proposed here, the greatest contributions to soil enzymes and leaf nutrients were from alkaline phosphatase and β-glucosidase activities (Figure 2). β-glucosidase is an enzyme secreted primarily by microorganisms, especially bacteria, that participates in the carbon cycle (more precisely, in the final step of cellulose degradation). Alkaline phosphatase is also secreted by soil microbes and is involved in phosphorus cycling, which is particularly relevant in tropical and subtropical soils, where this nutrient is mostly unavailable to plants due to its fixation into soil colloids (Ahmed et al., 2017). Hence, nutrient cycling (carbon and phosphorus), one of the main soil ecosystem services, was directly related in this model.

Interestingly, β-glucosidase and phosphatase activities were shown to be equally the most responsive attributes in a study by Mambu et al. (2018). Those authors conducted a field experiment using a similar approach in which they evaluated the effects of organomineral fertilizer application. The results demonstrated that integrative methods based on structural equations can be used to support the selection of potential microbial indicators related to yield; therefore, the attributes selected in this study can be considered predictors of sugarcane yield (Adetunji et al., 2017).

After selecting the main drivers from the SEM, linear regressions were constructed with yield data inoculated or uninoculated with the PSB consortium. The constructed regressions using yield as the dependent variable were significant ($p \leq 0.05$) only in the presence of bacterial inoculation, regardless of enzyme type. Even though a larger adjustment was not possible with these regressions, the interpretations were supported by structural equation modeling.

The increase in enzyme activity (β-glucosidase or alkaline phosphatase) equally increased sugarcane yield, especially in the presence of bacteria (more evident for β-glucosidase activity, $y = 1.477x + 135.70$; $R^2 = 0.2$). This finding corroborates the results observed in a similar study, which found a greater yield in the presence of bacterial inoculation (Lopes et al., 2021; Prataviera et al., 2021; Silva et al., 2021). The trend of increasing sugarcane yield, when considering the activity of alkaline phosphatase, was more pronounced in the absence of bacteria, although not significantly ($y = 0.2405x + 144.10$; $R^2 = 0.12$).

The β-glucosidase and alkaline phosphatase activities estimated for each scenario (current, plausible, optimistic, and futuristic), with or without bacterial inoculation, were used to project the economic gain associated with each nutrient cycle (carbon and phosphorus, respectively), and the difference between those with bacteria and those without was the final economic gain or profit. Inoculation was not included in the modeling, but it is expected to be introduced once the inoculation of sugarcane with PSB is more advanced.

In the current scenario, for β-glucosidase activity, a yield of up to 158 t ha^{-1} was estimated in the presence of bacterial inoculation, whereas the yield was 154 t ha^{-1} without bacterial inoculation, generating an economic gain of R$ 453.02 ha^{-1} (US$ 86.07 ha^{-1}) with the introduction of bacteria. For alkaline phosphatase activity, the yield was estimated to reach 157 t ha^{-1} with bacterial inoculation and 156 t ha^{-1} without bacterial inoculation, generating an economic gain of R$ 66.47 ha^{-1} (US$ 12.63 ha^{-1}) (Table 2).

The profit obtained in the current scenario, that is, considering the sum of carbon and phosphorus cycling was R$ 519.50 ha^{-1} (US$ 98.70 ha^{-1}) (Table 3).

Within the plausible scenario of β-glucosidase activity, it was estimated that a yield of up to 195 t ha^{-1} could be achieved with the inoculation of bacteria, whereas without bacterial

Table 2. Economic gains expressed in Brazilian Reais (R$) and American Dollars (US$) based on estimated increases in the enzyme activity (β-glucosidase and alkaline phosphatase), with or without bacterial inoculation in four scenarios (current, plausible, optimistic, and futuristic)

Scenario	Estimation[1]	With bacteria			Without bacteria			Economic gain With – Without bacteria	
		(t ha^{-1})[2]	(R$)[3]	(US$)[4]	(t ha^{-1})[2]	(R$)[3]	(US$)[4]	(R$ ha^{-1})[5]	(US$ ha^{-1})[6]
					β-glucosidase activity				
Current	5	143	15,169.87	2,882.28	143	15,164.25	2,881.21	5.62	1.07
	10	150	15,952.83	3,031.04	148	15,723.51	2,987.47	229.32	43.57
	15	158	16,735.79	3,179.80	154	16,282.76	3,093.73	453.02	86.07
Plausible	20	165	17,518.74	3,328.56	159	16,842.02	3,199.98	676.73	128.58
	30	180	19,084.66	3,626.09	169	17,960.53	3,412.50	1,124.13	213.58
	40	195	20,650.58	3,923.61	180	19,079.04	3,625.02	1,571.53	298.59
Optimistic	50	210	22,216.49	4,221.13	191	20,197.55	3,837.53	2,018.94	383.60
	60	224	23,782.41	4,518.66	201	21,316.06	4,050.05	2,466.34	468.61
	70	239	25,348.32	4,816.18	212	22,434.57	4,262.57	2,913.75	553.61
Futuristic	80	254	26,914.24	5,113.71	222	23,553.09	4,475.09	3,361.15	638.62
	90	269	28,480.15	5,411.23	233	24,671.60	4,687.60	3,808.56	723.63
	100	283	30,046.07	5,708.75	243	25,790.11	4,900.12	4,255.96	808.63
					Alkaline phosphatase activity				
Current	30	153	16,271.84	3,091.65	151	16,042.31	3,048.04	229.53	43.61
	40	155	16,445.29	3,124.61	154	16,297.29	3,096.48	148.00	28.12
	50	157	16,618.74	3,157.56	156	16,552.27	3,144.93	66.47	12.63
Plausible	60	158	16,792.19	3,190.52	159	16,807.24	3,193.38	- 15.05	- 2.86
	70	160	16,965.64	3,223.47	161	17,062.22	3,241.82	- 96.58	- 18.35
	80	162	17,139.09	3,256.43	163	17,317.20	3,290.27	- 178.11	- 33.84
Optimistic	90	163	17,312.54	3,289.38	166	17,572.18	3,338.71	- 259.64	- 49.33
	100	165	17,485.98	3,322.34	168	17,827.16	3,387.16	- 341.17	- 64.82
	110	167	17,659.43	3,355.29	171	18,082.14	3,435.61	- 422.70	- 80.31
Futuristic	120	168	17,832.88	3,388.25	173	18,337.11	3,484.05	- 504.23	- 95.80
	130	170	18,006.33	3,421.20	175	18,592.09	3,532.50	- 585.76	- 111.29
	140	171	18,179.78	3,454.16	178	18,847.07	3,580.94	- 667.29	- 126.79

[1]Three estimations of enzyme activity were used for each scenario; [2] Yield (t ha^{-1}) was calculated based on the linear regression equation for β-glucosidase activity (with bacteria: y = 1.477x + 135.70; without bacteria: 1.055x + 137.757) and for alkaline phosphatase (with bacteria: 0.1636x + 148.571; without bacteria: 0.2405x + 144.099); [3]Economic gain considering sugarcane production produced at the current estimation based on price per ton of stalk set at R$ 106.02 (US$ 20.53); [4]Economic gain converted to American Dollars considering the exchange rate of R$ 0.19 $US\$^{-1}$ in February 2022;[5]Economic gain per hectare obtained with the bacterial inoculation expressed in Brazilian Reais (R$); [6]Economic gain per hectare obtained with the bacterial inoculation expressed in American Dollars (US$)

Table 3. Profit per hectare obtained with bacterial inoculation considering the sum of the gains with β-glucosidase and alkaline phosphatase activities in the four scenarios

Scenario	Estimation[1]	β-glucosidase (β)		Estimation[2]	Alkaline phosphatase (P)		Final profit (β + P)	
		(R$)	(US$)		(R$)	(US$)	(R$)	(US$)
Current	5	5.62	1.07	30	229.53	43.61	235.15	44.68
	10	229.32	43.57	40	148.00	28.12	377.33	71.69
	15	453.02	86.07	50	66.47	12.63	519.50	98.70
Plausible	20	676.73	128.58	60	- 15.05	-2.86	661.67	125.72
	30	1,124.13	213.58	70	- 96.58	-18.35	1,027.55	195.23
	40	1,571.53	298.59	80	- 178.11	-33.84	1,393.42	264.75
Optimistic	50	2,018.94	383.60	90	- 259.64	-49.33	1,759.30	334.27
	60	2,466.34	468.61	100	- 341.17	-64.82	2,125.17	403.78
	70	2,913.75	553.61	110	- 422.70	-80.31	2,491.05	473.30
Futuristic	80	3,361.15	638.62	120	- 504.23	-95.80	2,856.92	542.81
	90	3,808.56	723.63	130	- 585.76	-111.29	3,222.80	612.33
	100	4,255.96	808.63	140	- 667.29	-126.79	3,588.67	681.85

[1]Three estimations of β-glucosidase activity were considered for each scenario; [2]Three estimations of alkaline phosphatase activity were considered for each scenario

inoculation, the yield was estimated to be 180 t ha^{-1}. For alkaline phosphatase activity, the yield was estimated to reach 162 t ha^{-1} with bacterial inoculation and 163 t ha^{-1} without bacterial inoculation, that is, there was no economic gain in this scenario for alkaline phosphatase activity (Table 2). However, when considering profit, the gain was estimated at R$ 1,393.42 ha^{-1} (US$ 264.75 ha^{-1}) (Table 3).

In the optimistic scenario, for β-glucosidase activity, a yield of up to 239 t ha^{-1} was estimated in the presence of bacterial inoculation, while without bacterial inoculation, the estimate was 212 t ha^{-1}, generating an economic gain of R$ 2,913.75 ha^{-1} (US$ 553.61 ha^{-1}) with bacterial inoculation (Table 2). For alkaline phosphatase activity, no economic gain was estimated; however, the profit was estimated at R$ 2,491.05 ha^{-1} (US$ 473.30 ha^{-1}) (Table 3). Dias et al. (2021) revealed that under a simulation of high-input conditions (well-watered and well-fertilized), sugarcane yields were similar to the present results.

In the futuristic scenario, for β-glucosidase activity, a yield of up to 283 t ha^{-1} was estimated in the presence of bacterial inoculation, whereas without bacterial inoculation, it was estimated to be 243 t ha^{-1}, generating an economic gain of R$ 4,255.96 ha^{-1} (US$ 808.63 ha^{-1}) when bacteria were introduced (Table 2). Similar to the plausible, optimistic, and futuristic scenarios, alkaline phosphatase activity did not generate an economic gain; however, when considering profit, there was an estimated gain of R$ 3,588.67 ha^{-1} (US$ 681.85 ha^{-1}) (Table 3).

Currently, there are 10 million hectares cultivated with sugarcane in Brazil, which could translate to an economic gain of R$ 5.2 billion yr^{-1} (US$ 987 million per year) if the gains estimated for the current scenario were directly proportional in all planted areas. Although this direct proportionality cannot be inferred, since yield is a function of a myriad of biotic and abiotic factors, the results highlight the importance of biological management based on compost application and bacterial inoculation in the field. Other models have been proposed for sugarcane data considering distinct climatic conditions; however, this is challenging, particularly because of the uncertainty in the simulated model across various locations (Marin et al., 2017).

Farmers are currently more receptive to the use of bioinoculants, mainly due to the possibility of obtaining high-quality products, which results in a reduction in production costs when compared with conventional agricultural management (Bordonal et al., 2018). In addition, studies that demonstrate economic gains in different scenarios based on the practice of biological management, such as with the inoculation of bacteria, can support this trend, guaranteeing better results for producers.

Conclusions

1. There is a direct relationship between microbiological indicators (enzymatic activity and sugarcane yield), which demonstrates that these indicators are potential predictors of yield. However, this hypothesis must be proven under different edaphoclimatic conditions.

2. Regardless of the scenario, the increase in sugarcane yield coupled with the increase in β-glucosidase was converted into economic gains when bacteria were inoculated, whereas alkaline phosphatase activity brought economic gain only in the current scenario.

3. The economic return resulting from bacterial inoculation and compost application in sugarcane is expected to increase the adoption of these practices.

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