BIOFERTILIZER PRODUCTION ENHANCES THE PERFORMANCE AND SUSTAINABILITY OF THE ANNEXED SUGARCANE BIOREFINERY

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ABSTRACT

The excessive use of fertilizers and pesticides in farming has worldwide economic and ecological consequences. Biofertilizers offer a feasible solution, lowering expenses and environmental harm while boosting yield. This research provides a technical, economic, and environmental evaluation of a biofertilizer production facility incorporated into a sugarcane ethanol biorefinery. The inclusion of biofertilizer production could enhance the biorefinery's net present value by as much as 69%. Compared to the base scenario, the integration results in environmental enhancements, reducing most impacts. The most significant stages influencing economic and environmental outcomes are solid-state fermentation and composite formulation. This research demonstrates that incorporating biofertilizers into a biorefinery is more sustainable than a standalone biorefinery, considering both environmental and technical-economic sustainability factors.

Keywords: Inoculants. Integrated biorefinery. Techno-economic analysis. Life cycle analysis.

1 INTRODUCTION

The implementation of biorefineries reflects global efforts to develop processes that take advantage of renewable resources, thus reducing dependence on the volatile oil market. These efforts are not only fundamental in combating climate change, but they have also stimulated research around the world. The use of resources such as sucrose and starch for liquid fuels production has had considerable success in countries such as Brazil, with sugarcane production, and the United States, with corn production. The growing climate crisis is driving a rapid transition to a circular, carbon-neutral economy. A fundamental step in this direction is the improvement of renewable energy sources through the advancement of technologies that fully take advantage of the energy potential of biomass, estimated between 2 and 6 TW per year [1]. The use of sugarcane serves as an excellent example of a successful biorefinery, given its ability to produce three main marketable products: sugar, ethanol, and bioelectricity, along with a wide range of derived by-products.

The development and application of new bio-based products that encourage the use of untreated nutrient sources, such as mineral rock fertilizers, could potentially alleviate the environmental problems associated with the production and use of chemical fertilizers. The production process of chemical phosphate fertilizers, which involves the acid treatment of phosphate rock, is energy-intensive and generates several byproducts that contribute to environmental pollution. The interaction between microorganisms, soil, and plants is critical for sustainable agriculture and crop yield. Biofertilizers, also known as microbial inoculants, have been available since the early 1900s, but they have recently regained the attention of both the scientific community and major corporations. Numerous formulations have been developed and applied to various crops worldwide. Soybean cultivation is the primary global user of inoculants, with Brazil leading the way. Approximately 78% of the farmed land in Brazil is pre-inoculated. Brazil's domestic market for inoculants has seen significant growth, with sales increasing from 10 million liquid doses in 2005 to over 45 million in 2018 [2].

The advancement of Brazilian agriculture is heavily reliant on the escalated utilization of fertilizers, especially phosphorus. The high phosphorus fixation capacity of Brazilian soils necessitates significant fertilizer inputs to offset the rapid immobilization of inorganic phosphorus. The intense demand for phosphorus fertilizer, coupled with a strong dependence on imports, makes Brazilian agriculture extremely vulnerable to potential phosphorus scarcities or sudden price changes. To maintain the sustainability of the country's agriculture, two approaches can be adopted: the biotechnological solubilization of phosphate rocks [3], and the application of inoculants that contain phosphate-solubilizing microorganisms found in the soil [4].

This study investigates the technical, economic, and environmental aspects of producing phosphate biofertilizer within a sugarcane biorefinery. The biofertilizer is a mixture of microorganisms, starch, and phosphate rock. A comparison was conducted between a biorefinery and another biorefinery that manufactures biofertilizer. The Net Present Value (NPV) was selected as the economic measure, while the Life Cycle Assessment (LCA) was employed to evaluate the environmental impact.

2 MATERIAL & METHODS

Process models were developed using the EMSO software. All equipment was designed based on mass and energy balance equations, considering thermodynamic and physical properties, efficiency, and process performance indicators like conversions and productivity. Furthermore, equations representing the economic and environmental performance of the process were incorporated into the EMSO simulation script files for simultaneous resolution with the process equations.

This research evaluated the viability of producing biofertilizers within an annexed sugarcane biorefinery. The biofertilizer standalone production has been previously analyzed, detailed in an earlier publication, where more information can be found [5]. The scenario was designed to cater to approximately 1% of Brazil's biofertilizer consumption, which is around 50,000 tons annually. The primary ingredients of the biofertilizer are phosphate rock, corn starch, and microorganisms. The inoculum production process occurs in a submerged cultivation environment. Cultivation takes place in polypropylene bags, reflecting the commercial method for cultivating microorganisms, through solid-state fermentation (SSF), using rice as a substrate. After the SSF cultivation, the spores are separated from the culture medium, and the solid residue is sent to the boiler as solid fuel. The spores are encapsulated in a gel made of starch, glycerol, and water. The process involves blending the encapsulated material with processed phosphorus rock. This blend is then homogenized and extruded to create the final product.

The economic evaluation considered the implications of building and operating the industrial plant. The dimensions of the equipment were established based on the energy and mass balances derived from EMSO simulations. Capital expenditures (Capex) were projected based on the costs of procured equipment. The calculated investments were adjusted using the chemical engineering plant cost index (CEPCI). Operational expenditures (Opex) were projected based on the costs of raw materials. The chosen economic metric was the net present value (NPV). The Life Cycle Assessment (LCA) methodology employed a cradle-to-gate approach. The primary input datasets were supplied by Ecoinvent via the SimaPro 9.0 software. The biorefinery's outputs include ethanol, excess electricity, sugar, and biofertilizer. Economic allocation was utilized to address the multifunctionality. The Life Cycle Impact Assessment (LCIA) was conducted using the CML-IA baseline V3.04 (World 2000) method.

3 RESULTS & DISCUSSION

The impact of incorporating the biofertilizer production into an annexed biorefinery was assessed by examining the process and economic performances. The outcomes for the base case and the integration of the biofertilizer production scenario are presented in Table 1.

Table 1 Process and economic performances of the case study.

	Base case	Biofertilizer
Process performance		
Anhydrous ethanol (L/TC [a]) a	47.46	47.45
Sugar (kg/TC)	69.78	69.77
Surplus Electricity (kWh/TC)	183.34	183.01
Economic performance		
Capex (MM US$)	372.50	405.56
Opex (MM US$)	172.91	212.34
NPV (MM US$)	63.49	107.69
IRR %	13.18	14.33

[a] TC – ton of sugarcane

Table 1 indicates that the process performance is nearly unaffected by the integration of biofertilizer production, primarily due to the process scale. The base case processes 4 million tons of sugarcane bagasse annually, while the biofertilizer scenarios handle 50 thousand tons of biofertilizer. Consequently, all material and energy needs for biofertilizer production are relatively minor compared to the base case. The portion of treated juice diverted to sugar-ethanol production has a minimal impact. The surplus electricity experiences a more notable decrease than other process performance metrics, mainly due to the electricity and thermal demands, especially for phosphorus rock processing and preparations, and the evaporator used for humidity control of the formulated biofertilizer. On the other hand, the economic performance is significantly affected by the integration of biofertilizer production, with both Capex and Opex being higher than the base case.

The biofertilizer price was set at 1.10 US$/kg, as determined in a previous study, given that this type of biofertilizer is a new market entrant [5]. For context, from January to October 2021, Brazil imported over 33 million tons of chemical fertilizers at an average cost of US$ 0.3 per kg [5]. During the same period, the country imported over 350 thousand tons of plant growth regulators, including fungicides, herbicides, insecticides, rodenticides, and disinfectants, at an average price of US$9.29 per kg [5]. Despite increased Capex and Opex, the NPV is significantly higher than the base case, with a 69% increase as shown in Table 1. The internal rate of return (IRR) is also higher as expected. Under the RenovaBio policy, Brazil has implemented a carbon credit system, known as CBios. As a result, the economic success is intrinsically linked to the environmental effectiveness of the process.

An LCA was performed to assess the environmental performance of biofertilizer production when incorporated into an annexed sugarcane biorefinery. The environmental impacts were calculated, and the outcomes are depicted in Figure 1. As previously stated, a biorefinery is a multi-product system. Therefore, in this study, we used economic allocation as the allocation rule to distribute environmental impacts among co-products based on their economic value. The main product of the biorefinery is anhydrous ethanol, so all environmental impacts were computed with this product as the basis.

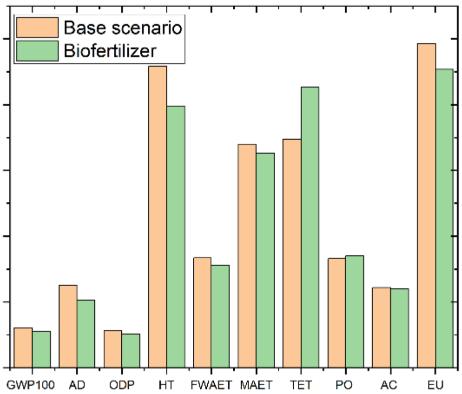

Figure 1 - Midpoint indicators for the scenarios assessed in this work with economic allocation. GWP100: Global Warming Potentials 100 years' horizon, in kg CO_2 eq./ US$ ethanol; AD: Abiotic depletion, in 10^3 kg Sb eq./ US$ ethanol; ODP: Ozone layer depletion, in 10^7 kg CFC-11 eq./ US$ ethanol; HT: Human toxicity, in 10^1 kg 1,4DB eq./ US$ ethanol; FWAET: Freshwater aquatic ecotoxicity, in 10^1 kg 1,4DB eq./ US$ ethanol; MAET: Marine aquatic ecotoxicity, in 10^{-2} kg 1,4DB eq./ US$ ethanol; TET: Terrestrial ecotoxicity, in 10^3 kg 1,4DB eq./ US$ ethanol; PO: Photochemical oxidation, in 10^4 kg C_2H_4 eq./ US$ ethanol; AC: Acidification, in 10^2 kg SO_2 eq. / US$ ethanol; and EU: Eutrophication, in 10^3 kg PO_4^{-3} eq./ US$ ethanol.

Figure 1 shows that the integration of biofertilizers reduced environmental impacts, except for Terrestrial Ecotoxicity (TET). TET refers to the harm inflicted on land ecosystems by toxic substances. The increased TET impact is mainly due to the Solid-State Fermentation substrate (rice), maize starch used in gel formation, and phosphate rock used in the formulation. This is largely because fertilizers and pesticides used in rice and starch production can negatively impact the environment. Moreover, phosphate rock, a key agricultural phosphorus source, can contribute to TET through its mining and extraction processes. The integration of biofertilizer production has resulted in positive economic results, which directly influence environmental performance due to economic allocation. Among the four biorefinery products, biofertilizer sales have become the third largest income source. As a result, a decrease in the environmental impact associated with ethanol is anticipated, given its reduced contribution to the total impact.

4 CONCLUSION

This study explored the large-scale production of composite granule biofertilizers, integrated with a first-generation sugarcane ethanol and sugar biorefinery. The objective was to conduct a techno-economic-environmental analysis of an industrial biofertilizer production facility in conjunction with an annexed sugarcane ethanol biorefinery. The economic analysis reveals that the inclusion of biofertilizer production can boost the NPV of the sugarcane biorefinery by 69%. In terms of environmental impact, all scenarios show an improvement over the base case, except for TET. The increased TET impact is mainly due to the SSF substrate (rice), maize starch used in gel preparation, and phosphate rock used in the formulation. These findings could stimulate the production of industrial biofertilizers, playing a pivotal role in the shift towards a sustainable, low-carbon bioeconomy.

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