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## **Assessing The Thermo-economic Viability Of Microalgae-Based Biofertilizers For Sustainable Agriculture: Economic And Environmental Benefits.**

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**Abstract.** As the global population grows, the use of fertilizers to improve land use and increase food production has become essential. However, the environmental damage caused by chemical fertilizers has led to a growing interest in sustainable alternatives, such as biofertilizers. This scientific paper presents a thermo-economic analysis that evaluates the potential use of biomass microalgae as a biofertilizer in agriculture. Thermo-economics involves applying thermodynamic principles, such as exergy which is a measure of the maximum amount of work that can be extracted from a thermodynamic system to economic systems. The analysis provides a detailed assessment of the economic and thermodynamic aspects of the process, considering the costs associated with the production, transportation, and application of the microalgae-based biofertilizer. The evaluated system includes an incinerator, heat exchanger, fixation column, photobioreactor, flocculator, centrifuge, dryer, and the final step of using the biomass produced as fertilizer. The results of the study show that microalgae-based biofertilizers offer significant economic benefits, including reductions in the use of chemical fertilizers and improvements in crop yields. Additionally, the study evaluates the environmental impact of the process and finds that microalgae-based biofertilizers can reduce greenhouse gas emissions and overall environmental impacts compared to traditional chemical fertilizers. In conclusion, the authors suggest that further research is necessary to optimize the production and application of microalgae-based biofertilizers. Nevertheless, the potential economic and environmental benefits make this an important area of study for sustainable agriculture.

**Keywords:** Exergy, Exergoeconomic, Microalgae, Biofertilizer, Photobioreactor.

## 1. INTRODUCTION

Land and water are critical resources for both food production and human sustenance. However, these resources are facing increasing pressure due to population growth, economic development, and climate change. As a result, industries are shifting their focus towards more sustainable processes and products. Societal advancements have led to higher production and consumption of food and technology, resulting in improved nutrition but also less efficient supplements for daily life (Rask, 2011; Meyer, 1992; Lang, 2014). This has contributed to a significant increase in waste generation, both biological and synthetic, as manufacturing processes and related activities are not 100% efficient. The accelerated population growth (Schneider, 2011) further exacerbates this issue.

Over the past decade, there has been a notable increase in carbon dioxide ( $CO_2$ ) levels (Cias et al., 2013; NOAA, 2020; Retallack, 2020), likely attributed to the aforementioned factors. Research indicates that higher atmospheric  $CO_2$  concentrations can have negative impacts on plantations and crops, posing a threat to agricultural productivity (Myers, 2014; Hampton, 2013). Consequently, there is a growing need to reassess the efficiency and environmental impact of various sectors, including fuel-based transportation, energy production, and food systems. This has led to a search for alternative materials that can replace environmentally harmful substances currently in use.

Modern agriculture, in particular, is exploring more efficient methods of crop cultivation. With increased demand and changing climate conditions, there is a greater reliance on fertilizers and chemicals to enhance crop yield and resilience against plant diseases, thereby enabling production in less favorable regions (Savci, 2012). However, strict regulations on the use of synthetic fertilizers, driven by concerns about the environment and long-term public health, have prompted a search for biofertilizers.

Microalgae biomass has emerged as a promising biofertilizer option, demonstrating positive effects on crop growth, such as increased plant size, root development, and nutrient absorption and storage. Additionally, microalgae biomass has shown potential in micropropagation of ornamental species (Navarro, 2021; Ronga, 2019; Mazepa, 2021; Corbellini, 2020). The production of microalgal biomass involves two primary methods: the open system known as a raceway pond and the closed system called a photobioreactor. Each approach has its advantages and drawbacks, with horizontal tubular photobioreactors (PBRs) being economically challenging due to a low net energy ratio (NER) compared to flat-plate PBRs and raceway ponds (Jorquera, 2009).

In light of the global fight against climate change and harmful atmospheric gases, algae-based technologies, including microalgae cultivation in photobioreactors, have gained significant interest (Zhang and Cai, 2018). These technologies have the ability to capture carbon dioxide from the atmosphere or industrial emissions, contributing to their mitigation (Chisti, 2007; Vo et al., 2019). The configuration discussed in this article involves a microalgae cultivation system where the microalgae interact with effluent gases generated in a municipal solid waste incinerator, thus aiding in carbon fixation.

## 2. THEORETICAL BACKGROUND

### 2.1. Microalgae

Microalgae are single-celled, rapidly reproducing microorganisms that can be classified as autotrophic or heterotrophic (FURLAN et al., 2020). They can be grown in different conditions, from natural environments, such as open tanks, lakes, and ponds, to on an industrial scale using PBRs (ARUN et al., 2021), being scaled up from manual laboratory cultivation. Microalgae play a fundamental role in global photosynthesis, due to their widespread presence in the environment.

Furthermore, they could carry out bioremediation, contributing to the cleaning of atmospheric air through photosynthesis, which not only promotes their growth, but also improves environmental oxygenation (SCHMITZ et al., 2015; DERNER et al., 2006). For their growth, microalgae use carbon sources of organic and inorganic origin, as well as sources of nitrate and phosphate available in the environment in which they are present (BOROWITZKA, 2018).

Biomass production from microalgae stands out due to the rapid growth and high nutritional density of these microscopic organisms, which perform efficient photosynthesis to convert sunlight and  $CO_2$  into biomass rich in proteins, lipids, and carbohydrates (LEHMUSKERO, 2018). This makes it a valuable source of raw material for biofuels, food supplements, animal feed and biofertilizers, contributing to sustainable agriculture. Due to the growing demand for renewable biomass sources, microalgae stand out due to their rapid growth, high nutritional quality and reduced resource use compared to traditional crops.

### 2.2. Exergoeconomic Analysis of Microalgae $CO_2$ Fixation for Biofertilizer Production

While various studies have delved into the techno-economic aspects of microalgal biomass production, investigating parameters such as energy input requirements, capital investments, and overall performance, there is currently a gap in the literature concerning the specific exergy and exergoeconomic analysis of the process involving  $CO_2$  fixation by microalgae and the subsequent utilization of the biomass as biofertilizers. This type of information is of paramount importance.

Exergy, a fundamental thermodynamic concept used to measure the quality of energy, has proven to be a robust tool in the evaluation of energy efficiency and the identification of energy losses within diverse processes. Building on this foundation, exergoeconomics takes these principles a step further by seamlessly integrating exergy analysis with economic considerations, assigning a monetary value to every exergy flow in the system. This innovative approach not only enables the scrutiny of physical inefficiencies within energy systems but also provides a comprehensive insight into the economic ramifications associated with these inefficiencies.

Therefore, the objective of this study is to develop a mathematical model for the thermodynamic analysis of a photobioreactor plant incorporating a  $CO_2$  fixation column and an MSW incinerator with energy recovery. This model aims to optimize the system's performance and evaluate its exergoeconomic feasibility, shedding light on the potential of utilizing microalgae biomass as biofertilizers.

To be able to evaluate and maximize the performance of the system, methods of entropy generation minimization (EGM), exergy analysis (EA), and exergoeconomics (EE) have been used. These three methods are established aspects of the evolution of thermodynamics in the last decades (Vargas et al., 2000; Ordóñez, 2003).

### 3. ANALYZED SYSTEM

The objective of this article is to assess the benefits and costs associated with an organic fertilizer based on microalgae. The performance and price competitiveness of organic fertilizers are crucial in encouraging farmers to opt for their use over chemical fertilizers.

#### 3.1. Process Microalgae Cultivation

The process begins with a gas emission source, which can range from a combustion engine to a fuel generator or material incinerator, including hybrid fuel systems. A heat exchange system is employed to cool the gas temperature, ensuring it remains below  $40^\circ C$  to avoid harming the microalgae cultivation. Water is utilized in this system and can be recycled at higher temperatures.

The next step involves the gas fixation column, where the gases pass through and interact with the cultivation. This interaction primarily focuses on absorbing necessary components, especially  $CO_2$  gas, which is essential for microalgae photosynthesis.

A closed-type tubular photobioreactor is utilized to maintain greater control over gas flow and cultivation temperature. An electric pump facilitates the cultivation flow within the system and enables interaction with the gas fixation column, allowing for the capture of  $CO_2$ . Throughout the day, photosynthesis occurs, multiplying the microalgae biomass with the absorption of sunlight.

To prepare the biomass for various applications, including its use as an organic fertilizer, it needs to be in a dry form. Several steps are involved in achieving this dry biomass state.

The first step is flocculation, where a specific amount of flocculating agent is added to the cultivation volume. The volume is stirred to ensure even distribution of the flocculant. After stirring, the material settles to facilitate decantation, enabling the removal of a volume of water without the biomass. Following flocculation, the biomass still retains a significant amount of water. Therefore, centrifugation is employed to further concentrate the biomass, reaching a concentration of 20% per liter and facilitating additional water removal.

The final step in producing dry biomass involves the use of heat-generating equipment, such as an oven or drying chamber. This equipment ensures the complete removal of remaining water from the biomass. To prevent damage to the biomass, a temperature of  $60^\circ C$  is used over an extended period.

Once the dry biomass is obtained, it can be directly applied as an organic fertilizer without requiring any additional steps. By assessing the increase in material and examining potential changes in internal energy resulting from the use of biomass as a fertilizer, we can evaluate the benefits and costs associated with this method, this stage is called Plant growth production process (PPCV).

#### 3.2. Diagram of the system production process

The Figure 1 shows a diagram of the system, and the stages and mass flow, also the energy flow as heat ( $Q_0$ ), work ( $W_e$ ), and solar irradiation ( $I_{sun}$ ). Also show the fuel use for the combustion, in this case, a mixture of air, fuel and municipal solid waste (MSW).

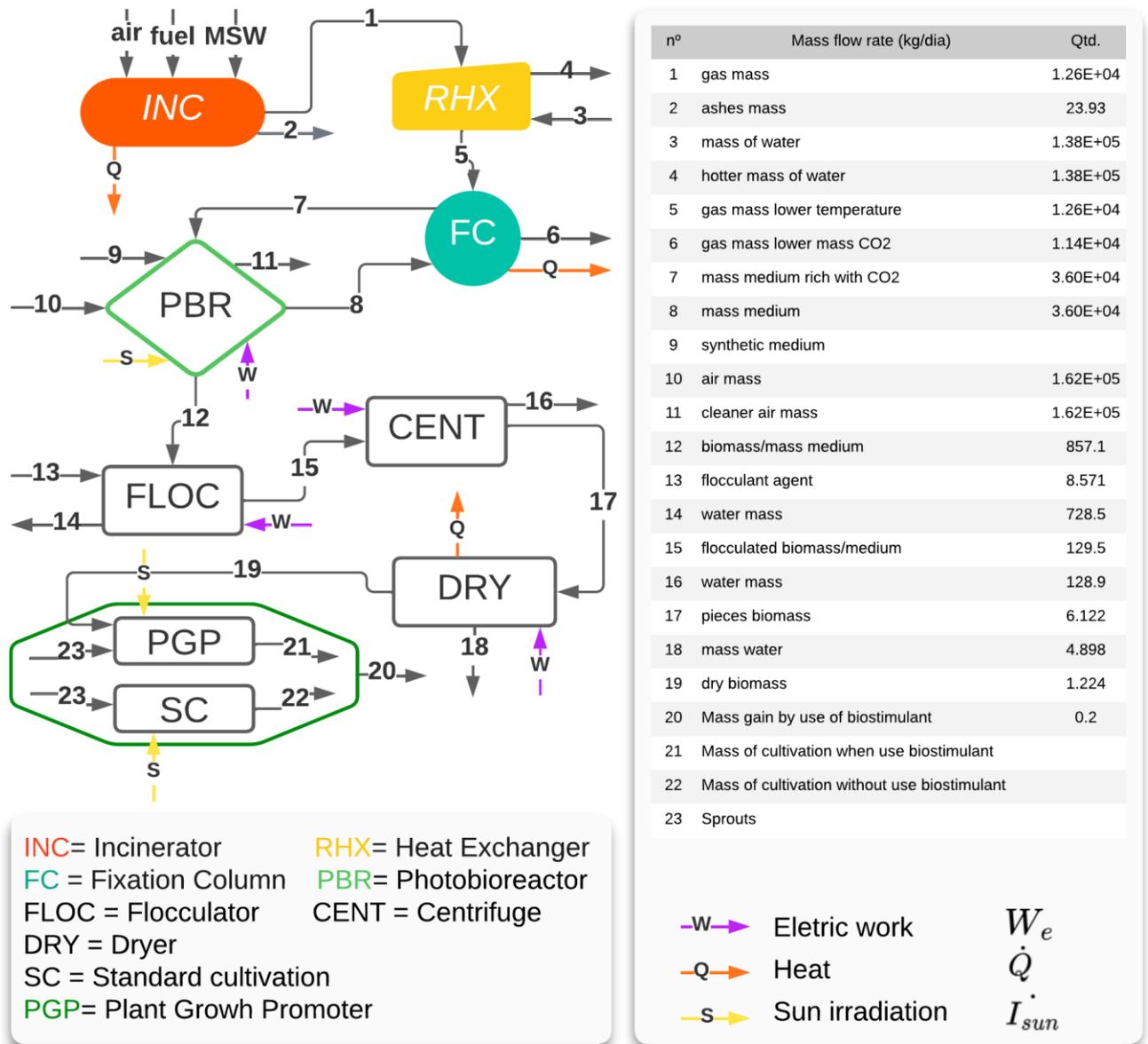


Figure 1. Schematic diagram of the system under analysis

#### 4. EXERGY

Exergy is a fundamental concept used to measure the maximum potential work or useful energy that can be obtained from a system. It serves as a valuable tool for assessing the efficiency and sustainability of various processes and systems. By analyzing the exergy of a system, we can determine its theoretical maximum efficiency and identify areas for improvement in energy utilization.

In the context of this study, the analysis of the system involves conducting energy, mass, and exergy balances under steady-state conditions. The mass balance equation (Eq. 1) is employed to ensure that the total mass entering the system equals the total mass exiting the system (Bejan, 1996).

$$\Sigma m_{in} = \Sigma m_{out} \tag{1}$$

Where m is the mass flow rate ( $\text{kg} \cdot \text{s}^{-1}$ ), the subscript "in" refers to what enters the stage, and the subscript "out" refers to what leaves the stage of the observed system.

The energy balance equation (Eq. 2) accounts for the heat transfer rate (Q), work done (W), and enthalpy (h) associated with the mass entering and leaving the system. This balance provides insights into the energy flows within the system (Bejan, 1996).

$$Q + \Sigma m_{in} * h_{in} = W + \Sigma m_{out} * h_{out} \quad (2)$$

The exergy balance equation (Eq. 3) focuses on the exergy rate (E), which quantifies the maximum work potential of the system, and the rate of exergy destruction ( $E_D$ ). This balance considers the exergy associated with the mass entering and leaving the system, as well as the work performed. By analyzing exergy flows, we can determine the efficiency of the system in terms of maximizing useful work.

$$E_q + \Sigma E_{in} = W + \Sigma E_{out} - E_D \quad (3)$$

To calculate the exergy rate (Eq. 4), the specific exergy ( $e_x$ ) is multiplied by the mass flow rate ( $m_x$ ). The specific exergy (e) is determined using Equation 5, which considers various properties such as specific internal energy (u), volume (v), entropy (s), kinetic energy ( $V^2/2$ ), and potential energy (gz). The subscripts "0" denote the reference or initial state for these properties (Bejan, 1996).

$$E_x = m_x * e_x \quad (4)$$

$$e = (u - u_0) + p_0(v - v_0) - T_0(s - s_0) + \frac{v^2}{2} + gz \quad (5)$$

## 5. THERMOECONOMIC

Thermoeconomics is a powerful methodology that combines the principles of thermodynamics and economics to evaluate and optimize energy systems. Its primary objective is to determine the most efficient and cost-effective ways to utilize energy resources in the production of goods and services while considering economic and social needs. This approach involves analyzing the trade-offs between different energy sources, technologies, and their environmental impacts.

Exergetic and exergoeconomic analyses play crucial roles in assessing the thermodynamic and economic performance of processes and systems. These analyses provide valuable insights into the efficiency, cost-effectiveness, and sustainability of energy utilization. By quantifying the exergy flows and associated costs within a system, thermoeconomics enables the identification of opportunities for process optimization and the efficient utilization of natural resources.

Equation 6 represents the relationship between exergoeconomics and energy systems. It highlights the interplay between costs and exergy flows within the system. The costs associated with each component are multiplied by their respective exergy rates, while the investment, maintenance, and operation capital costs of the system are captured by the term Z. The equation demonstrates the need to balance costs and exergy flows to optimize the economic and thermodynamic performance of the system (Bejan, 1996).

$$\Sigma c_{out} * E_{out} + c_w * W = c_q * E_q + \Sigma c_{in} * E_{in} + Z \quad (6)$$

Where c represents the costs of each component (\$/kg), w is the work performed,  $E_q$  is the exergy in the form of heat, and Z is the sum of cost rates associated with the investment, maintenance, and operation capital of the system (\$/kg).

By employing thermoeconomic analyses and considering the costs associated with different components and exergy flows, it becomes possible to identify inefficiencies, evaluate trade-offs, and make informed decisions regarding the design and operation of energy systems. This holistic approach ensures that economic and environmental factors are considered in the pursuit of sustainable and economically viable energy solutions.

## 6. EQUATIONS

By applying equations 3 and 6 to each stage of the system, we obtain:

### 6.1. Incinerator

$$W_{fan} = E_{q_{inc}} - E_1 - E_2 - E_{D_{inc}}$$

$$c_1 * (E_1 + E_2) = c_F * E_{q_{inc}} - c_{elet} * W_{fan} + Z_{CI_{inc}} + Z_{OM_{inc}}$$

## 6.2. Heat exchanger

$$0 = E_1 + E_3 - E_5 - E_4 - E_{DRHX}$$

$$c_5 * E_5 = c_1 * E_1 - c_4 * E_4 + Z_{Cl_{RHX}} + Z_{OM_{RHX}}$$

## 6.3. Fixation Column

$$W_{pFC} = -m_7 * g * L_{col} * 10^{-3} - E_{D_{FC}}$$

$$c_6 * E_6 = c_5 * E_5 + c_{elet} * W_{pFC} + Z_{Cl_{FC}}$$

$$g = 9.8 \text{ m/s}^2 \quad L_{col} = \text{height of fixation column}$$

## 6.4. Photobioreactor

$$W_p = E_8 + E_9 + E_{10} + E_{sun_{PBR}} - E_7 - E_{12} - E_{11} - E_{D_{PBR}}$$

$$W_p * c_{elet} = E_8 * c_8 + E_9 * c_9 + E_{10} * c_{10} + E_{sun_{PBR}} * c_{sun} - E_7 * c_7 - E_{12} * c_{12} - E_{11} * c_{11} \\ + Z_{OM_{PBR}} + Z_{Cl_{PBR}} + Z_{CHU}$$

## 6.5. Flocculator

$$W_f = E_{12} - E_{14} - E_{15} - E_{D_{floc}}$$

$$W_f * c_{elet} = E_{12} * c_{12} - E_{14} * c_{14} - c_{15} * E_{15} + Z_{OM_{floc}} + Z_{Cl_{floc}} + Z_{floc}$$

## 6.6. Centrifuge

$$W_c = E_{15} - E_{16} - E_{17} - E_{D_{cen}}$$

$$W_c * c_{elet} = E_{15} * c_{15} - E_{16} * c_{16} - E_{17} * c_{17} + Z_{OM_{cen}} + Z_{Cl_{cen}}$$

## 6.7. Dryer

$$W_d = E_{17} - E_{18} - E_{19} - E_{D_{dry}} - E_{q_{dry}}$$

$$W_d * c_{elet} = E_{17} * c_{17} - E_{18} * c_{18} - E_{19} * c_{19} + Z_{OM_{dry}} + Z_{Cl_{dry}}$$

## 6.8. Plant growth production process (PPCV)

Using the biomass produced as fertilizer.

$$0 = E_{19} - E_{20} - E_{D_{PPCV}}$$

$$0 = c_{19} * E_{19} - c_{20} * E_{20}$$

## 7. RESULTS

The results of this study will provide valuable insights into the energy system analysis and optimization of a biomass-based fertilizer production process. Through the application of exergy and exergoeconomic analyses, the performance and efficiency of each stage of the system have been evaluated. The equations derived for the various components, including the incinerator, heat exchanger, fixation column, photobioreactor, flocculator, centrifuge, dryer, and fertilization process, serve as a foundation for understanding the energy flows, costs, and potential improvements within the system. The Table 1 below we have the dimensions of the results of the flows resulting from the thermoeconomic analysis:

Table 1. Data used on the model for each working fluid/fuel/product.

n°	Mass Flow Rate (kg/day)	E (kW/day)	e(kJ/kg)	c (\$/kJ)	C (\$/day)
1	Gas Mass	4150000	328.1	126	5,24E+02
2	Ashes Mass	17900	748.4		2,26E+00
3	Mass of Water	0	0	4.25E-06	0,00E+00
4	Hotter Mass of Water	3260000	23.65	4.25E-06	1,39E+01
5	Gas Mass Lower Temperature	28400	2.244	1.854	5,27E+02
6	Gas Mass Lower Mass CO <sub>2</sub>	28400	-	1.889	5,36E+02
7	Mass Medium Rich With CO <sub>2</sub>	1708	-	4.25E-06	7,26E-03
8	Mass Medium	1709	-	4.25E-06	7,26E-03
9	Synthetic Medium	0	0	4.25E-06	0,00E+00
10	Air Mass	0	0	0	0
11	Cleaner Air Mass	0	0	0	0
12	Biomass/Mass Medium	1973	16100	1897	3742781
13	Flocculant Agent	-	-	-	0,00E+00
14	Water Mass	0	0	4.25E-06	0,00E+00
15	Flocculated Biomass/Medium	1973	16100	1956	3859188
16	Water Mass	0	0	4.25E-06	0,00E+00
17	Pieces Biomass	1973	16100	1956	3859188
18	Mass Water	4.841	9.884	4.25E-06	2,06E-05
19	Dry Biomass	1973	16100	1956	3859188
20	Mass Gain by use of Biostimulant	125.5	627.6	3.08E+04	4,37E-03
21	Mass of Cultivation when use Biostimulant	753.1	627.6	-	-
22	Mass of Cultivation without use Biostimulant	627.6	627.6	-	-
23	Sprouts	-	-	-	-

While the specific results are pending, it is anticipated that the analysis will shed light on the energy consumption, exergy losses, and economic aspects associated with each stage. The results will also contribute to identifying areas for optimization, such as reducing energy losses, enhancing energy conversion efficiency, and minimizing costs. Additionally, the sustainability and environmental impacts of the biomass-based fertilizer production process will be assessed, providing valuable insights into its ecological footprint.

In Table 2 therefore brings together the daily energy costs, based on the equipment or process to be used, as follows:

Table 2. Energy cost in a day based on equipment or process.

Process	E(\$kJ/day)
Centrifuge	1.393
Oven	282.5
Fixing column	12900
Flocculator	4.29E-05
Incinerator	2200000
FBR	306000
PCV	1847
RHX	860000

Overall, the results of this study will provide a comprehensive understanding of the technical and economic performance of the biomass-based fertilizer production system, allowing for informed decision-making and potential enhancements to promote more efficient and sustainable use of energy resources in agricultural practices.

## 8. CONCLUSION

In addition to the technical and economic insights, the results of this study have the potential to foster innovation and collaboration within the agricultural and environmental sectors. The detailed analysis of the biomass-based fertilizer production process can serve as a foundation for industry stakeholders, researchers, and policymakers to engage in discussions about sustainable practices and energy conservation. Furthermore, it opens the door for cross-disciplinary efforts to develop more environmentally friendly and economically viable alternatives, thus fostering a sense of shared responsibility for a greener future.

Moreover, the findings underscore the interconnectedness of energy, economics, and ecology. By shedding light on the environmental impact and sustainability aspects of this production system, it encourages a holistic perspective on agricultural practices. This holistic view is essential in the context of a world facing increasing environmental challenges. The study not only adds to our understanding of how to optimize energy use but also reminds us of the critical need to balance economic viability with ecological responsibility in our pursuit of more sustainable agricultural systems.

The thermo-economic analysis of the microalgae based biofertilizers is crucial for assessing efficiency, both in thermodynamic terms and in terms of costs. It provides a comprehensive view of the interactions between thermodynamic and economic aspects, being essential to ensure the long-term viability of this process. When identified as efficient and advantageous, thermo-economic analysis enables more confident investments, driving innovation and competitiveness while also contributing to sustainability by reducing environmental impact.

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