MECHTA
International Journal Of Mechanical Engineering Technologies & Applications
ISSN 2722-3213 articles 7, pp. 83 – 99, 2025
V06 N.1

AN ANALYSIS OF LIFE CYCLE SUSTAINABILITY ASSESSMENT ON THE SUGAR PRODUCTION PROCESS IN PT X

Atikah Aulia Dina [1) ✉], Ishardita Pambudi Tama [1)], Femiana Gapsari [1)], Aliya Qurrota Ayunin [2)]

[1)] **Mechanical Engineering Department**
Universitas Brawijaya
Malang, Indonesia
atikahauliaad@gmail.com
kangdith@ub.ac.id
memi_kencrut@ub.ac.id

[2)] **Faculty Business and Economics**
University of Melbourne
aayunin@student.unimelb.edu.au

Abstract

Among the industries that have detrimental effects on the environment is the sugarcane sector. Consequently, it is possible to draw the conclusion that the sugarcane sector is not environmentally sustainable. According to the study's findings, the primary cause of all damage categories is the usage of power produced through bagasse cogeneration. With a total score of 71,2%, human health makes the largest contribution to the harm categories. It is anticipated that this research's findings will lessen PT X's environmental effect, making the company more environmentally sustainable.

Keywords: *Sustainability, Life Cycle Assessment, Sugarcane Industry*

1. INTRODUCTION

Sustainability is influenced by manufacturing, which impacts the economy, environment, and society. The life cycle of product, manufacture, use, and disposal also contributes to work employment, value creation, and customer satisfaction [1]. Assessing sustainability involves consideration of the entire product life cycle because it cannot be managed independently and requires a comprehensive approach [2]. Sustainable consumption and production patterns are important for achieving a sustainable world by increasing interest in sustainable products and impacting strategic decision-making through sustainability assessment instruments. Because poor waste management methods can alter socioeconomic connection between ecosystems and human well-being [3], companies frequently amplify existing environmental issues (e.g., pollution, trash). Life Cycle Sustainability Assessment (LCSA) is one technique to evaluate sustainability that takes all three of these factors into account. Three separate methods— Life Cycle Assessment (LCA) to analyze the effects in environment, Life Cycle Cost (LCC) for determining a product's monetary worth, and Social Life Cycle Assessment (SLCA) for analyzing its societal effects—combine to form LCSA. [4].

The sugar industry is one of largest in world. Competition amongst sugar factories arose in context of rising productivity to meet market demand as sugar business expanded. However, better care must be taken of environment in addition to boosting productivity and efficiency. According to Ramjeawon [5], Sugarcane's cultivation occurs primarily in tropical countries. The first literature to address idea of LCSA was written more than a dozen years ago. Since then, there have been many papers showcasing various LCSA techniques. But there is currently no established LCSA methodology, and suggested assessment methodologies differ. This serves as inspiration for study, which analyzes pertinent LCSA literature and provides an outline of field's current level of development in context of sugar production. summary will serve as a foundation for more scientific research in this field. PT

Corresponding Author:
✉ **Atikah Aulia Dina**
atikahauliaad@gmail.com
Received on: 2024-05-07
Revised on: 2024-06-12
Accepted on: 2024-06-13

DOI: 10.21776/MECHTA.2025.006.01.7

X is a sugar production industry in East Java. This industry will continuously commit to increasing company value according to consumer desires and produce sugar to meet consumers' needs with competitive quality and prices. This industry has a target of sugarcane milled per year, reaching 1.9 tons with a milling capacity of PT X of 12,000 canes daily. The large target for milled sugarcane will certainly result in a large amount of waste. This certainly will have a negative impact on air pollution in the environment, which is also complained by residents around the company. As an industry, it should not only strive to meet consumers' needs but also maintain sustainability and environmental sustainability, one of which is by paying attention to the product life cycle [6].

Data from 2018 to 2022 indicate that sugar sales at PT. X has experienced fluctuations every year which tended to decline. This downturn has significant implications for the company's economy, which in turn affects the social aspects of the organization, particularly in the stagnation of employee productivity. The condition suggests that PT. X is not yet sustainable, which can be seen by the environmental concerns raised by local residents affected by smoke emissions from sugar production, the inability to compete effectively with market competitors, and social challenges from employee stagnation. Research findings reported by [7] indicate that the cultivation, harvesting, and fertilizer production processes associated with sugar production contribute to 66% of the environmental impact. Additionally, electricity cogeneration and sugar production account for 20%, while the transportation of sugarcane represents the remaining 13%. Research conducted by [8] reinforces the conclusions of [7], indicating that sugarcane utilization as a raw material is recognized as the main contributor to environmental impact, followed by the utilization of sugarcane waste, known as bagasse, in the cogeneration process, and the transportation phase. Cogeneration, as defined in [9], is the process of generating two types of energy from a single primary energy source. At PT. X, this primary source is sugarcane bagasse, which fuels the boilers to produce electricity and steam. To address the social sustainability challenges at PT. X, a comprehensive questionnaire was developed to identify and classify social factors relevant to sustainable manufacturing. This involved a process of content classification and content analysis to group factors with similar meanings and relevance for application within the company. The goal was to streamline the number of factors considered and minimize redundancy.

With hundreds of employees at PT. X, there is a need for a uniform understanding of production processes among its workforce. It is crucial to consider efficiency levels and costs, which were assessed using Life Cycle Costing (LCC) obtained through interviews with PT. X representatives and Social Life Cycle Assessment (SLCA) from interviews and questionnaire distribution. The aim of this research is to analyze sustainability assessment of PT. X using the life cycle approach by utilizing LCA method, LCC method, and SLCA method.

2. METHODS

PT. X in East Java is the location of this case study research project. As its primary product, PT X makes sugar. The reason the sugarcane sector was selected for examination was due to its perceived detrimental effects on the environment, as was previously indicated [9]. The reason the sugarcane sector was selected for study was due to its perceived detrimental effects on the environment, as was indicated in the previous section [10]. So that the detrimental effect can be minimized, this study attempts to evaluate PT X's environmental impact through LCA. Therefore, in an effort to lessen the adverse effect, this research attempts to evaluate PT X's environmental impact using LCA. The initial phase of this research consists of data gathering and literature review. The method of assessing using LCA is the next step. It involves four steps: defining the scope and objectives, creating a life cycle inventory, conducting a life cycle assessment, conducting a LCA, and doing a LCA. steps for interpretation, life cycle impact assessment, and inventory. Simapro software is now being utilized to carry out the assessment.

The last stage is called the conclusion stage, and it entails making recommendations for enhancements based on the findings of the stage before it as well as offering ideas for additional research. Figure 1 shows how this study process progresses.

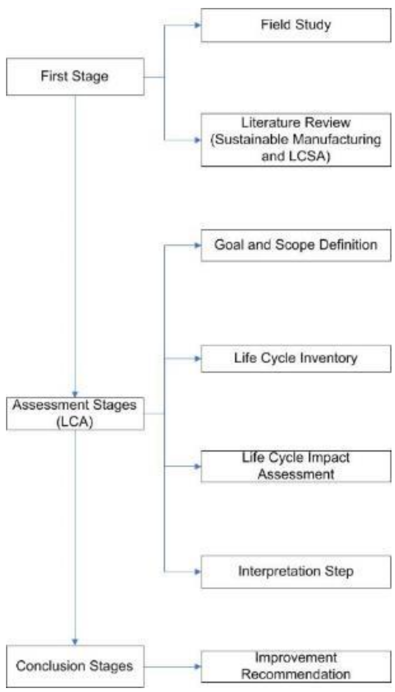

Figure 1. Flow the Research Methodology

Sugar Production Process

The milling process is the initial stage in the manufacture of sugarcane. This phase involves utilizing a crusher roller to mill the previously cleaned sugarcane, producing bagasse and raw juice as the end products. The boiler that will be used to run the cogeneration process of electricity will run on bagasse as fuel. Juice clarity is the following stage that will handle the raw juice in the meantime. Sand, soil, and ground rock are examples of soluble and insoluble impurities that should be eliminated in this phase if they weren't eliminated by preliminary screening. Heat and lime are the clarifying agents used in the procedure. This procedure yields clear juice and filter cake. While the clear juice is the input used in the evaporation process, the filter cake will be sold as fertilizer. Reducing the water by vacuum evaporation is the goal of this method. The end result of this operation will be a thick syrup, which will then be crystallized. Making the viscous syrup into massecuite is a process called crystallization. By applying high speed centrifugal action in the centrifugal separation process, massecuite will be separated into raw sugar crystals and molasses. Once dry sugar crystals are sorted by size using vibrating screens and packed into a container, the next process is referred to as the dryer and packer. The sugar production process flow in PT. X is represented in Figure 2.

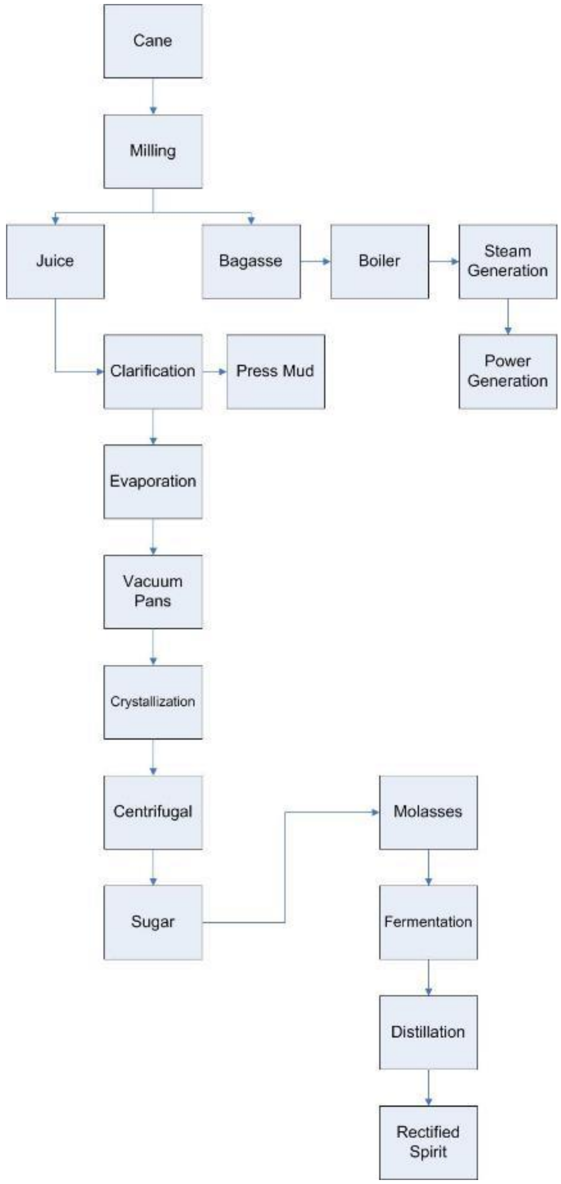

Figure 2. Sugar Production Process

2.1. Life Cycle Assessment (LCA)

The assessment process related to the environmental impacts was conducted using the Life Cycle Assessment method with the assistance of SimaPro software [11]. Data input in this stage will later be adjusted to the Ecoinvent database in the SimaPro software. After finding the quantification of environmental impact resulting from PT X, an analysis was conducted according to the results of the measurements. The output resulting from the analysis conducted was in the form of a category assessment based on the impact measurements conducted from the software, whether they were included in safe, moderate, sufficient, or dangerous categories. If the analysis results showed a safe, moderate, and sufficient category, an attempt was made to maintain or improve the assessment. If the analysis results show a dangerous category, a solution to identify the causes will be made, and a solution related to the problems will be found.

- Energy Consumption

Energy consumption in PT X includes electrical energy produced by plants, which is managed by the company, and electrical energy produced by the State. The ratio of energy use is 95% : 5%, where the company produces 95% of the electricity using sugar cane bagasse as a boiler fuel. Meanwhile, 5% of electricity is obtained from the State Electricity Company and assumed using coal as fuel.

According to the data in the field, the electrical energy required to process 1 ton of sugarcane into sugar is 2,572.45 kWh.

- Life Cycle Inventory (LCI)

In this stage, the input used during the sugar production process was defined. The input was in the form of the amount of raw materials and energy used. This stage resulted in a quantitative description of all raw materials and energy from the observed system under study. The results of LCI were the results of the analysis of input data streams in the chemical compounds and primary energy source, referred to as basic streams, and the value will be calculated. Table 1 is following represents the total quantity of input that has been modified using the simapro software.

Table 1. Input Data Used in Simapro Software

Sugar Production Process			
No	**Data Input**	**SimaPro Database**	**Amount**
1	Sugarcane	Sugarcane (IN) sugarcane production	1 ton
2	Water	Water Ultrapure	55 kg
3	Limestone	Limestone, Crushed	2.5 kg
4	Phosphoric Acid	Phosphoric Acid, Industrial Grade	0.01 kg
5	Sulfur	Sulfur Dioxide	2.3 kg
6	Electricity of State Electricity Company	Coal cogeneration, high voltage electricity, and heat.	60.55 kWh
7	Electricity of Steam-Electric Power Station	Electricity, high voltage, treatment of bagasse	2,572.45 kWh

2.2. Life Cycle Costing (LCC)

The method used to analyze economic aspects was Life Cycle Costing with comparison of PT. X cost in excel. This method could determine the sustainability level based on economic aspects by carrying out comprehensive calculations. Thus, the output resulting from this method is expected to represent the sustainability level of a company as a whole.

- Goal and Scope Definition

1) This aims to calculate the economic impact during the sugar production process.
2) The scope employed encompassed gate-to-gate, which involved various stages of sugar production processes
3) The functional unit used is one ton of sugarcane in the rupiah currency.

The limitation with cost calculation carried out was the cost of raw materials and energy, labor costs, maintenance costs, and waste processing costs.

- Life Cycle Inventory

In this step, the input data that will be utilized to calculate the economic impact of PT. X various sugar production procedures is defined. The necessary data include labor and maintenance expenditures, as well as the costs of raw materials and energy. At this point, costs are calculated using the scope that was employed. A number of PT. X production operations are included in the gate-to-gate scope of the environmental and economic impact assessment. Table 2 shows the costs used can cover the costs incurred to produce 1 ton of sugarcane.

Table 2. Production Cost of 1 ton of Sugarcane

Energi Costs/ 1 ton Sugarcane	Rp. 2,000,000
Labor Costs/ 1 ton Sugarcane	Rp. 40,000
Maintenance Costs/ 1 ton Sugarcane	Rp. 22,000
Waste Treatment Cost/ 1 ton Sugarcane	Rp. 2,500
TOTAL/ 1 ton Sugarcane	**Rp. 2,064,500**

After analyzing, the energy cost is the largest energy in the company cost. Table 3 describes the comparison of electricity used by PT. X.

Table 3. Energy Cost in PT. X

Electricity of State Electricity Company (5%)	Rp. 90,525
Electricity of Steam-Electric Power Station (95%)	Rp. 1,726,175
Total	**Rp. 1,816,700**

2.3. Social Life Cycle Assessment (SLCA)

In order to achieve this goal, a questionnaire distributed to employees of PT. X containing social indicators that would be measured was distributed to respondents [12]. The data obtained from the questionnaire was processed to determine a company's sustainability level. The calculation was conducted using the Social Life Cycle Assessment method. Figure 3 explains the concept of this LCSA research to achieve sustainable manufacturing.

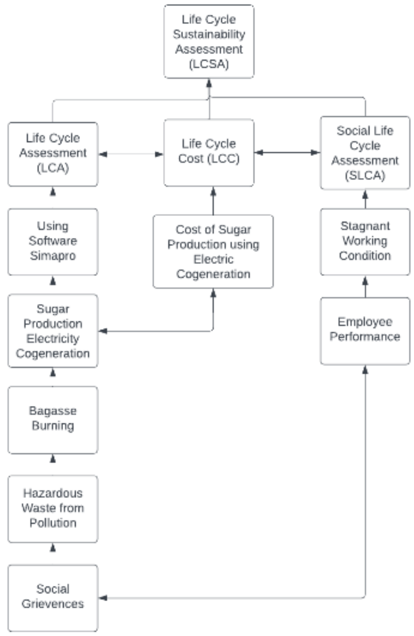

Figure 3. LCSA Concept of This Research

3. RESULTS AND DISCUSSION

3.1. Environmental Aspect with LCA

- Life Cycle Impact Assessment (LCIA)

The resources and energy listed in the previous stage will be tallied and evaluated using IMPACT 2002+ in this step with ecoinvent database. IMPACT 2002+ was selected because of its ability to link life cycle inventory input data to the impact category (midpoint) and then classify it into the damage category (endpoint). The assessments tree diagram is displayed in Figure 4.

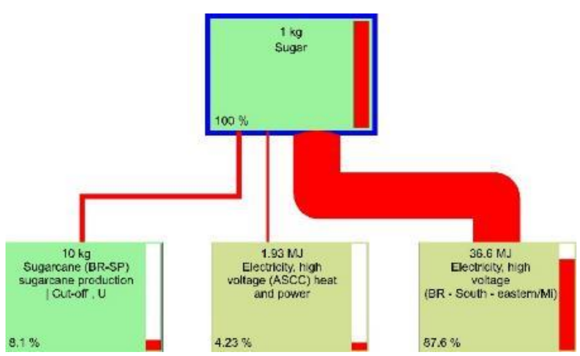

Figure 4. Tree Diagram

Figure 4 illustrates how the sugar production process in PT. X affects the environment. It starts with the use of electricity produces from bagasse (87.6%), which is followed by the use of electricity generated from the use of sugarcane (8.1%), which is assumed to be coal (4,23%). The halfway assessment findings are displayed in figure 5.

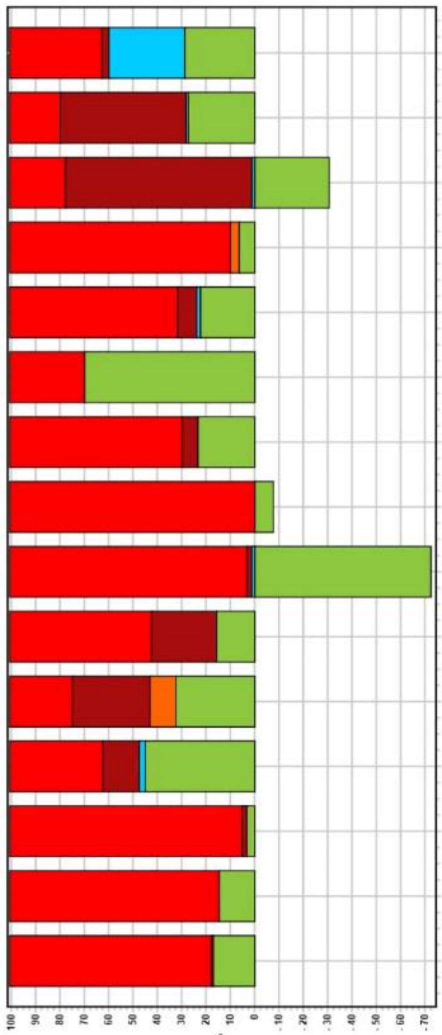

Figure 5. Impact Category of Sugar Production Process (midpoint).

As seen in Figure 4, practically every effect category in the midway is significantly impacted by the consumption of energy produced by bagasse cogeneration. The usage of sugarcane affects practically every affects practically every effect category in addition to bagasse cogeneration. The usage of coal-derived electricity was sthe source of the following impact category. The evaluation results for the damage impact (endpoint) are as follows.

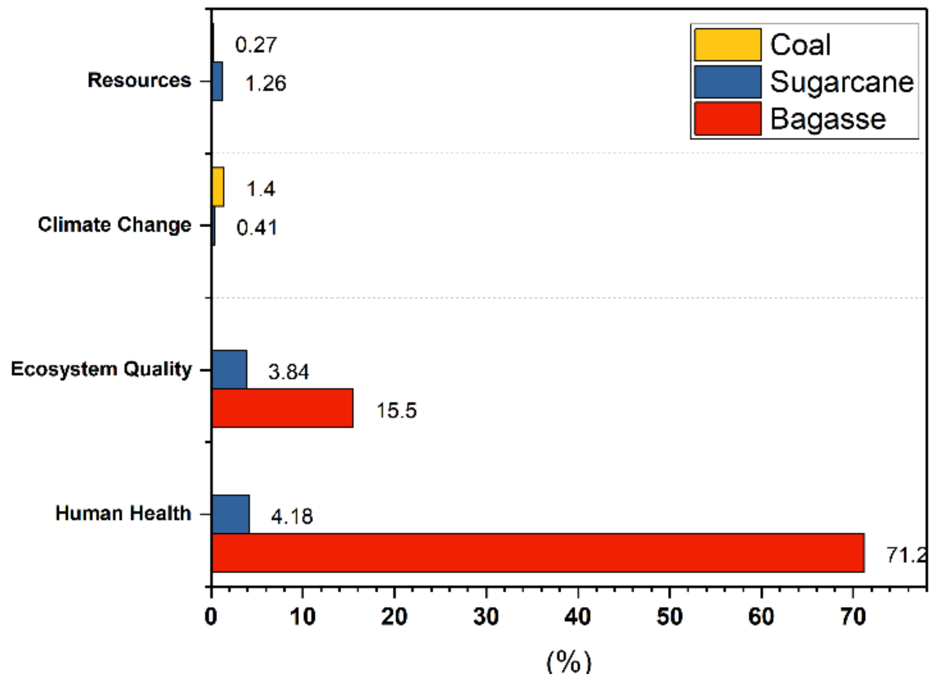

Figure 6. Calculation Outcomes in LCIA

The endpoint calculation outcomes in Figure 6 revealed that the most substantial harm arising from the sugar production process is inflicted upon human health (76%), predominantly attributable to the utilization of electrical energy derived from the cogeneration process utilizing sugarcane bagasse (71.2%) and the utilization of sugarcane as raw materials for sugar production (4.18%). Furthermore, ecosystem quality (19.4%) is the primary factor affected by the utilization of electricity generated from the energy cogeneration process (15.5%) and the use of sugarcane (3.84%). Moreover, the next damage is resources (2.37%), in which the main contributor is the use of State Electricity Company (1.26%) and the use of sugarcane (0.627%). The next damage category is climate change (1.27%), in which the main contributor is the use of State Electricity Company (1.4%) and cogeneration electrical energy (0.41%).

- Interpretation Step

Using sugarcane bagasse waste as sugarcane fuel is one form of efficiency the company can carry out. However, in practice, using sugarcane bagasse waste as raw material for boilers actually has other impacts on the environment. From the data results above showed that the electrical cogeneration process using sugarcane bagasse resulted in waste in the form of ash from combustion. Besides having an environmental impact, combustion has also become one of the social problems, with complaints from the surrounding community. Therefore, additional examination to minimize waste is necessary to enhance the sustainability of the sugar production process.

In this study, the impact categories evaluated using the IMPACT 2002+ method encompassed resources, climate change, ecosystem quality, and human health. The utilization of electrical energy from sugarcane bagasse as fuel significantly affects all four damage categories. The human health category contributed 71.2% of the total impact of 76.9%. This category consolidates assessment findings related to photochemical oxidation, ozone layer depletion, ionizing radiation, respiratory effects, and human toxicity [13]. Consequently, it can be concluded that the utilization of electrical energy from sugarcane bagasse as fuel has environmental implications, particularly in the atmospheric domain, which could lead to long-term consequences such as ozone layer depletion and adverse effects on human health, such as respiratory issues induced by inorganic substances.

3.2. Economic Aspect Using LCC

- Life Cycle Impact Assessment (LCIA)

After calculations, it was discovered that energy prices were the most expensive, and the outcome was the pie chart in Figure 7. It displays the expenditures in Table 2.

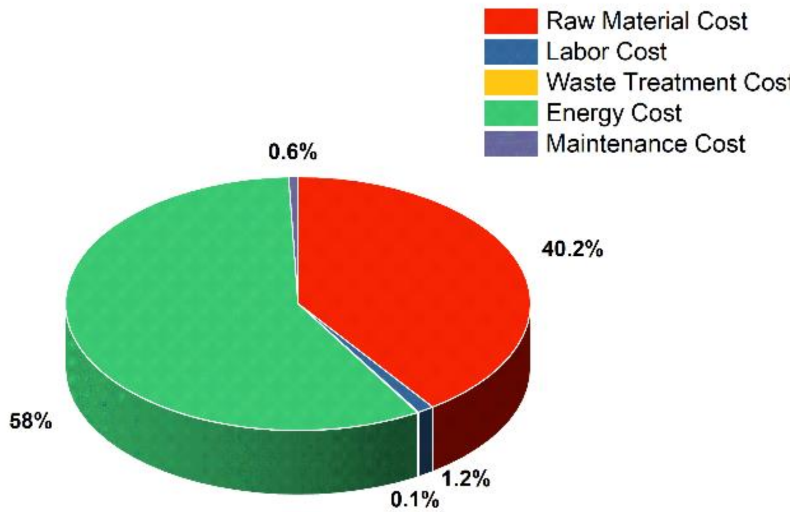

Figure 7. Costs Used to Produce 1 Ton of Sugarcane.

- Interpretation Step

After analyzing table 3 and figure 7, energy cost is the biggest cost. The proportion of using electrical energy in table 3 at PT X was segmented into two main sources: 5% of electricity from the State Electricity Company and 95% of electricity produced by PT X. The electrical energy produced by PT X is a cogeneration process of electrical energy by utilizing sugarcane bagasse waste as boiler fuel to further be able to produce steam and electrical energy. The aim of LCC is to determine the economic impact of a series of sugar production processes. The results of calculating economic impact using LCC showed that energy costs were the main contributor to economic impact.

- Analysis of the Economic Impact on the Sugar Production Process

One of the causes of the high use of electrical energy in the sugar production process is the use of various equipment and machines that use electrical energy as a driving source. This causes high energy costs in the sugar production process. Realizing the high electrical energy required, PT X took the initiative to use sugarcane bagasse as fuel for the electrical cogeneration process. According to [14], electrical cogeneration is a process of generating two types of energy using one main energy source. In PT X, the main energy source used was sugarcane bagasse, which was used as boiler fuel to generate steam and electricity. The research conducted by [14] demonstrated that sugarcane bagasse possesses an energy potential of 381,818,182 kJ per hour, sufficient to generate steam in a boiler with a capacity of 100,000 kg per hour at 45 bar and 400°C. This steam can then be utilized to produce electricity, generating up to 11 MW through the turbine and generator conversion process. Moreover, the electrical cogeneration process also has quite high effectiveness compared to conventional power plants. The electrical cogeneration process has an effectiveness of 90%, so it is able to benefit the company [15].

In one day, PT X can process 12,000 tons of sugarcane into 1,200 tons of sugar, where 12,000 tons of sugarcane can produce ±25-30% sugarcane bagasse. Thus, it can be stated that PT X is able to produce ±3000-3600 tons of sugarcane bagasse per day. The energy cogeneration process using sugarcane bagasse that PT X has carried out showed that the calorific value for 1 ton of sugarcane bagasse is kJ/kg, where if converted, it can produce 7,600 kJ/kg where converted, it can produce 2 tons of steam, and electrical energy of 200kWh. If compared, the use of coal can produce 2,500kWh of electricity. Thus, it can be stated that the higher the calorific value, the higher the potential for electrical energy generated. If compared between the two types of fuel, the efficiency of coal is much better than sugarcane bagasse. However, considering that in practice, biomass fuel of sugarcane bagasse can meet the milling operational needs with the provision that the milling operation is based on the installed capacity, which is 12,000 TCD (Ton Cane per Day), and there are no constraints to stopping milling operations and high content of sugarcane fiber. Therefore, it can be stated that the amount of sugarcane bagasse exceeds the need for an electrical energy supply in PT X and is able to provide positive economic benefits. On the other hand, the remaining sugarcane bagasse produced will be stored in bagasse storage in an open area with a roof, ensuring that it is protected and dry so that fermentation that can cause odors and risks of fire does not occur.

Therefore, the assessment of economic impact in this study had a positive impact on the economic aspect. However, one other assessment pillar, which is the environment, still generated a negative impact. Thus, it can be stated that the sugar production process in PT X is still not sustainable, considering the aim of sustainability development is to stabilize the three sustainability pillars: economy, society, and environment [16].

3.3. Social Aspect (Social Life Cycle Assessment)

The following is table 4, which is a social indicator that will be used as an indicator in the assessment of social aspects.

Table 4. Social Aspect in Questionnare

Indicators	Description	Reference
Labor Wages	The average salary given to workers in the industry	[16]
Convenient and Accessible Work Location	The availability of banking facilities, schools. markets, and public transport.	[17]
Leave Offered	The employee experiences the physical exertion, fatigue, and individual work becomes significant	[17]
Employee Welfare	Scheme to employees and their families	[17]
Appraisal	Schemes adopted by the industry, such as variable payments, incentives, rewards, promotion, etc	[17]
Comfort at Workplace	A healthy working environment, adequate ventilation, and lighting arrangements	[17]
Effect Emission and Waste	Causing health problems, injury, and unhealthy atmosphere	[17]
Effect of Noise Level	Causing dizziness and can cause disease and hypersensitivity	[17]
Exposure to Toxic Chemicals	Prolonged exposure may lead to respiratory illnesses, skin irritations, eye discomfort, and various lung ailments	[17]
Occupational Hazard	Risks due to sharp tools, high currents, heat, cold, etc	[17]
Safety	Safety policies and measures are necessary because accidents can lead to fatal consequences	[17]

Training and Development	Ensuring the efficiency of manufacturing operations and enhancing employee productivity	[17]
Employee Involvement	Involving employees in decision-making processes can enhance procedures and instill a feeling of ownership within the organization	[17]

Analysis and measurement of social aspects were conducted by distributing a questionnaire on the implementation of sustainable manufacturing indicators to the employees of PT. X. The questionnaire aimed to identify and classify social factors into categories such as Skill Development (SD), Work Safety (WS), Work Environment (WE), and Work Conditions (WC). Factors such as labor wages, work location accessibility, leave policies, employee welfare, and appraisal were classified under WC; comfort at the workplace and noise level effects under WE; emissions, waste effects, exposure to toxic chemicals, occupational hazards, and safety under WS; and training and development, along with employee involvement, under SD. After distributing questionnaires and analyzing 10 employees of PT. X.

- Work Condition (WC)

The work condition dimension is represented at Table 4 by 5 statement items. Statement 1 there were 2 respondents agreed. Statement 2 there were 4 respondents agreed, and 2 respondents strongly agreed. Statement 3 there were 6 respondents agreed, and 2 respondents strongly agreed. Statement 4 there were 4 respondents agreed, and 2 respondents stated that they agreed, and 3 respondents stated that they strongly agreed.

Table 4. Aspect in Work Condition

Factor	Code	Questionnaire Statement
Convenient and Acceasible Work Location	WC1	PT. X is located in an easily accessible location
Leave Offered	WC2	PT. X provides employees with sick leave and necessities
Employee Welfare	WC3	PT. X pays attention to employee welfare and job satisfaction
Appraisal	WC4	PT. X provides appreciation and rewards for good employee performance
Labour Wages	WC5	The salary provided by PT. X is in accordance with the requirements

- Work Environment (WE)

The work environment dimension is represented at Table 5 by 6 statement items.
Statement 1 there were 7 respondents agreed.
Statement 2 there were 6 respondents agreed.
Statement 3 there were 3 respondents agreed.
Statement 4 there were 6 respondents agreed.
Statement 5 there were 2 respondents agreed, and 1 respondent strongly agreed.
Statement 6 there were 2 respondents agreed, and 6 respondents strongly agreed.

Table 5. Aspect in Work Environment

Factor	Code	Questionnaire Statement
Comfort at Workplace	WE1	PT. X has good room lighting
	WE2	PT. X has good ventilation
	WE3	PT. X has an abnormal level of air humidity that disturbs health
	WE4	PT. X provides adequate parking lot and facilities
	WE5	PT. X has a comfortable interior and exterior design
Effect of Noise Level	WE6	Noise generated from machinery or equipment during the production process is disruptive

- Work Safety

The work safety dimension is represented at Table 6 by 4 statement items. Statement 1 there was 1 respondent who agreed, and 5 respondents strongly agreed. Statement 2 there were 3 respondents agreed, and 5 respondents strongly agreed. Statement 3 there were 3 respondents agreed, and 5 respondents strongly agreed. Statement 4 there were 3 respondents stated that they agreed, and 1 respondent stated that they strongly agreed.

Table 6. Aspect in Work Safety

Factor	Code	Questionnaire Statement
Safety	WS1	The number of work accidents that occur during the production process of PT. X is high
Exposure to Toxic Chemical	WS2	PT. X provides Personal Protective Equipment (PPE) during the production process
Effect Emissions and Waste	WS3	The production process at PT. X already has an appropriate Standard Operational Production (SOP)
Occupational Hazardz	WS4	The risk level of hazards in the production process at PT. X is high

- Skill Development

The skill development dimension is represented at Table 7 by 4 statement items. Statement 1 there were 4 respondents agreed, and 1 respondent strongly agreed. Statement 2 there were 5 respondents agreed, and 1 respondent strongly agreed. Statement 3 there were 5 respondents agreed, and 2 respondents strongly agreed. Statement 4 there were 4 respondents agreed.

Table 7. Aspect in Skill Development

Factor	Code	Questionnaire Statement
Training and Development	SD1	PT. X provides training employees for performance skills
	SD2	Training provided by PT. X has a significant impact on employee development
Employee Involvement	SD3	The level of worker satisfaction at PT. X is high
	SD4	The absence rate of workers at PT. X is high

From the calculation of distributing questionnaires to 10 employees of PT X, it can be concluded that the social aspects of PT X are in the "good" category.

4. RECOMMENDATION

These recommendation s were developed based on the evaluations finding demonstrate that cogeneration of electricity from sugarcane bagasse has a significant negative environmental impact. The effectiveness of employing bagasse in the power cogeneration process will therefore be the main focus of the improvement recommendations in order to lessen any negative effects. As a company that uses bagasse in the cogeneration of electrical energy, PT. X has taken the lead in employing a wet scrubber dust collector system to lessen the amount of residual ash left behind after burning. To effectively reduce air pollution and remove particles or gases from industrial waste gas streams, use a wet scrubber [18]. Often, the most cost-effective method of extracting gas and particle matter from gas streams is to use a wet scrubber [19]. By using extremely thin liquid in liquid droplets, this tool's operating mechanism removes undesirable contaminants from the gas stream. When in contact with liquid droplets, the majority of tiny particles will adhere to them. The scrubber works on the basis of transferring particulates by the inertial force of droplets and particles.

Wet scrubbers offer advantages over dry scrubbers, including gas absorption, dust collection, mist control, hot gas cooling, and varied collection efficiency, making them ideal air pollution controllers [18]. Wet scrubbers are efficient in capturing ash but have weaknesses like high corrosion risk, water pollution, and particle contamination. Installation issues can affect their performance, despite their high efficiency. Issues include pressure drop, droplet accumulation, fan fan buildup, boiler wear, ash collection efficiency reduction, and community complaints due to blockage and fan wear [19]. Some of these weaknesses and problems are factors that cause the use of wet scrubber in PT X to not be optimal. Therefore, various suggestions can be devised to enhance the effectiveness of the wet scrubber:

1. Regular replacement of porous plates/pipes

Wet scrubbers are highly effective dust collector tools, with ash collection effectiveness varying based on particle size distribution and scrubber type. With optimal design, sub-micron particles can be separated by over 99%, with physical condition also influencing effectiveness [20]. The effectiveness of wet scrubbers decreases due to damage to dust collector plates and pipes, high corrosion potential, and porous plates. Regular replacement is recommended to optimize use. The tool's old age also contributes to its decreased effectiveness.

2. Rechecking the wet scrubber design

The scrubber's performance relies on the size distribution of impurity particles in the gas stream, with impaction being the dominant capture mechanism [21]. Wet scrubber design significantly impacts ash capture effectiveness, necessitating regular rechecks based on performance parameters influencing the design. The design parameters include:

- Waste gas stream rate, temperature, and humidity

Wet scrubbers measure producer gas stream rate, which affects venturi system and scrubbing liquid volume. They operate at lower rates than baghouses or esps due to liquid injection. Temperature and humidity also influence the design, with high evaporation rates increasing water consumption. High temperatures limit particle removal applications.

- Gas velocity and pressure drop

Elevated gas velocity in relation to liquid droplets enhances particle momentum, enabling the collection of smaller particles via impaction. Nevertheless, this results in increased energy requirements, pressure drop, and operational expenses for the scrubber.

- Liquid-to-gas (l/g) ratio

The liquid-to-gas ratio (l/g) represents the proportion of injected liquid to incoming gas, improving collection effectiveness by increasing droplet density. The ideal liquid flow rate ranges from 7-10 gallons per 1000 cubic feet, maintaining consistent efficiency at a steady pressure drop. However, augmenting the l/g ratio could escalate operational expenses due to the utilization of substantial volumes of scrubbing liquid and pumps.

- Droplet size

Optimizing droplet size is crucial to maximize particle collection efficiency. Smaller droplets possess a larger surface-to-volume ratio, enabling them to capture more particles per injected volume. However, excessively small droplets may experience momentum transfer from the gas stream, diminishing the relative velocity between the droplet and the particle. Consequently, low velocity leads to reduced collection efficiency.

5. CONCLUSION

The study analyzed sustainability by identifying the main contributors to the triple bottom line: environment, economy, and society. The LCA method was used for environmental impact assessment, LCC for economic impact, and SLCA for social impact assessment. Results showed in Figure 6 that the sugar production process's use of electrical energy from sugarcane bagasse, sugarcane, and coal generated the largest environmental impact. Human health and ecosystem quality also had the largest environmental impact. The results of this study have similarities with several previous studies. The study revealed pollution in Figure 5 from sugarcane bagasse burning, and PT X attempted to reduce it by installing a filtering system, but it's ineffective. The study suggests PT X is not environmentally sustainable and calls for further efforts. PT X, an industry involved in cogeneration of electrical energy, has implemented a wet scrubber dust collector system to minimize ash from combustion. This apparatus utilizes fine liquid droplets to extract pollutants from gas streams. By harnessing the inertial force of particulates and droplets, the scrubber facilitates the transfer of particulates from the gas stream to the liquid phase. This occurs through the interaction of particulates with liquid droplets, packing material, and plate jets.

ACKNOWLEDGMENTS

The author would like to thank all parties and participants in this research.

REFERENCES

[1] ABID HALEEM, MOHD JAVAID, RAVI PRATAP SINGH, RAJIV SUMAN, MOHD ASIM QADRI, “A Pervasive Study on Green Manufacturing Towards Attaining Sustainability,” Green Technologies and Sustainability, vol. 1, Issue 2., 2023. https://doi.org/10.1016/j.grets.2023.100018

[2] NGUYEN THI HANH, HUYNH THI THANH BINH, NGUYEN VAN SON, NGUYEN THI TRANG, PHAN NGOC LAN, “Optimizing Wireless Sensor Network Lifetime Through K-Coverage Maximization and Memetic Search,” Sustainable Computing: Informatics and Systems, vol. 40., 2023. https://doi.org/10.1016/j.suscom.2023.100905

[3] PUCKETT, BRIAN J., AND ERICA E. RYHERD. "Evaluating manufacturing environment soundscapes." The Journal of the Acoustical Society of America 145.3 (2019): 1753-1753. https://doi.org/10.1121/1.5101422

[4] FINKBEINER, MATTHIAS, *et al*. "Towards life cycle sustainability assessment." Sustainability 2.10 (2010): 3309-3322. https://doi.org/10.3390/su2103309

[5] FOOLMAUN, RAJENDRA KUMAR, and TOOLSEERAM RAMJEAWON. "Life cycle sustainability assessments (LCSA) of four disposal scenarios for used polyethylene terephthalate (PET) bottles in Mauritius." Environment, development and sustainability 15 (2013): 783-806. https://doi.org/10.1007/s10668-012-9406-0

[6] NIRWANTO, HANSONO, “Analisis Life Cycle Bioetanol Berbasis Singkong Daun Tandan Kosong Kelapa Sawit di Indonesia,” Thesis Teknik Bioproses, 2012. https://lib.ui.ac.id/detail.jsp?id=20292458

[7] T. RAMJEAWON, “Life Cycle Assessment of Electricity Generation from Bagasse in Mauritius,” vol. 16, 2008. https://doi.org/10.1016/j.jclepro.2007.11.001

[8] MEZA-PALACIOS, RAMIRO, ALBERTO A. AGUILAR-LASSERRE, LUIS F. MORALES-MENDOZA, JORGE R. PÉREZ-GALLARDO, JOSÉ O. RICO-CONTRERAS, and ALEJANDRO AVARADO-LASSMAN. “Life Cycle Assessment of Cane Sugar Production: The Environmental Contribution to Human Health, Climate Change, Ecosystem Quality and Resources in México.” Journal of Environmental Science and Health, Part A 54, no. 7: 668–78, 2019. https://doi.org/10.1080/10934529.2019.1579537

[9] A. WIBOWO, “Perancangan Sistem Pembangkit Kogenerasi pada Pabrik Gula Kapasitas 4000 tcd, Studi Kasus Revitalisasi Pabrik Gula Modjo Sragen,” vol. 11, no.2, pp. 98-103, 2016. https://doi.org/10.36289/jtmi.v11i2.61

[10] R. MEZA-PALACIOS, A. A. AGUILAR-LASSERRE, L. F. MORALES-MENDOZA, J. R. PEREZ-GALLARDO, J. O. RICO-CONTRERAS, and A. AVARADO. “Toxic / Hazardous Substances and Environmental Engineering Life Cycle Assessment of Cane Sugar Production: The Environmental Contribution to Human Health, Climate Change, Ecosystem Quality and Resources in Mexico.” J. Environ. Sci. Heal. Part A, vol. 0, no. 0, pp. 1-11, 2019. https://doi.org/10.1080/10934529.2019.1579537

[11] MARTA STAROSTKA-PATYK, “New Products Design Decision Making Support by SimaPro Software on the Base of Defective Products Management,” Procedia Computer Science, vol. 65, 2015. https://doi.org/10.1016/j.procs.2015.09.051

[12] DUBOIS-IORGULESCU, A. M., SARAIVA, A. K. E. B., VALLE, R., & RODRIGUES, L. M. “How to define the system in social life cycle assessments? A critical review of the state of the art and identification of needed developments,” The

International Journal of Life Cycle Assessment, 23, 507-518. 2018. https://doi.org/10.1007/s11367-016-1181-y

[13] HUMBERT, SEBASTIEN & SCHRYVER, AN & BENGOA, XAVIER & MARGNI, MANUELE & JOLLIET, OLIVIER. 2014. IMPACT 2002+: User Guide. 45 https://www.researchgate.net/publication/305444126_IMPACT_2002_User_Guide

[14] A. WIBOWO, "Perancangan Sistem Pembangkit Kogenerasi pada Pabrik Gula Kapasitas 4000 tcd, Studi Kasus Revitalisasi Pabrik Gula Modjo Sragen," vol. 11, no.2, pp. 98-103, 2016. https://doi.org/10.36289/jtmi.v11i2.61

[15] QAZI, U., JAHANZAIB, M., AHMAD, W., & HUSSAIN, S. "An institutional framework for the development of sustainable and competitive power market in Pakistan," Renewable and Sustainable Energy Reviews, 70, 83-95, 2017. https://doi.org/10.1016/j.rser.2016.11.152

[16] FATIMAH, YUN ARIFATUL, "Remanufacturing as a Potential Means of Attaining Sustainable Industrial Development in Indonesia," Thesis for the Degree of Doctor of Philosophy, 2014 https://api.semanticscholar.org/CorpusID:106606688

[17] DIGALWAR, ABHIJEET K., DAMBHARE, SUNIL and SARASWAT, SANTOSH, "Social Sustainability Assessment Framework for Indian Manufacturing Industry," Materials Today: Proceedings, 2020. https://doi.org/10.1016/j.matpr.2019.12.226

[18] A. BHARGAVA, "Wet Scrubbers – Design of Spray Tower to Control Air Pollutants Wet Scrubbers – Design of Spray Tower to Control Air," Int. J. Environ. Plan. Dev, vol. 2, no. 1, pp. 68-73, 2016. https://www.researchgate.net/publication/305441375_Wet_Scrubbers_-_Design_of_Spray_Tower_to_Control_Air_Pollutants

[19] A. MANN, "Final Report Submitted to Sugar Research Australia," 2017.

https://creativecommons.org/licenses/by-nc/4.0/

[20] BIANCHINI, A., PELLEGRINI, M., ROSSI, J., & SACCANI, C. "Theoretical model and preliminary design of an innovative wet scrubber for the separation of fine particulate matter produced by biomass combustion in small size boilers," Biomass and bioenergy, 116, 60-71, 2018. https://doi.org/10.1016/j.biombioe.2018.05.011

[21] KHAIRUMIZAN, P. Skripsi: Studi Eksperimental Implementasi Venturi Srubber Pada Sistem Gasifikasi Batubara. Universitas Indonesia: Depok, 2008. https://lib.ui.ac.id/detail?id=124882&lokasi=lokal