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Improvement of the Environmental Performance of Canned Pineapple Production Based on Life Cycle Assessment

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Abstract: Canned pineapple products have great potential for Indonesia's export and agricultural sectors. The purpose of this research is to conduct the Life Cycle Assessment (LCA) of canned pineapple products and to determine how to reduce their environmental impacts. The LCA method comprises goal and scope definition, inventory analysis, impact analysis, and interpretation stages. The scope of this research is gate-to-gate and covers the entire pineapple production process, starting from the arrival of raw materials at the production gate and ending with the final product from the factory. Environmental impacts are focused on global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). The findings identified various inputs and outputs in the canned pineapple production process, including pineapple raw materials, electrical energy, packaging, waste, and emissions. The functional unit (FU) of canned pineapple is 0.5873 kg/can, and it shows three environmental impacts as follows: GWP at 5.14E-02 kg-CO_2.eq/kg-canned pineapple, AP at 2.62E-04 kg-SO_2-eq/kg-canned pineapple, and EP at 2.01E-04 kg-PO^3_4-eq/kg-canned pineapple. The main emissions come from thermal power plants in factories, so improvements are proposed by renewable energy sources, such as solar photovoltaic (SPV), which achieves a reduction of 71.78% GWP, 67.94% AP, and 93.24% EP. The substitution of sub-bituminous coal with anthracite reduced 75.29% GWP and 73.48% AP but increased 88.66% EP. Coal substitution to Liquefied Natural Gas (LNG) reduced 16.79% AP and 94.49% EP but increased 44.69% GWP. The utilization of solid waste for juice production can reduce 98.91% GWP, 97.53% AP, and 97.13% EP. The utilization of liquid waste as biogas can reduce 70.92% GWP, 96.12% AP, and 95.1% EP. Substituting renewable energy from SPVs and utilizing wastewater or solid wastes can reduce the environmental impacts of GWP, AP, and EP compared to substituting bituminous coal with anthracite or LNG.

Keywords: acidification, eutrophication, global warming potential, life cycle assessment, pineapple processing.

基于生命周期评价的菠萝罐头生产环境性能改进

摘要：罐装菠萝产品在印度尼西亚的出口和农业部门具有巨大的潜力。本研究的目的是对罐装菠萝产品进行生命周期评估（生命周期评估）并研究如何减少环境影响。生命周期评估方法包括目标与范围定义、清单分析、影响分析和解释阶段。本研究的范围是“门到门”，涵盖了从原材料到达生产门到最终产品出厂的整个菠萝生产过程。环境影响主要集中在全球变暖潜力（全球升温潜能值）、酸化潜力（美联社）和富营养化潜力（EP）。分析结果识别了罐装菠萝生产过程中的各种投入和产出，包括菠萝原料、电能、包装、废物和排放物。罐

装菠萝产品的功能单位（FU）为0.5873公斤/罐，显示出以下三种环境影响：全球升温潜能值为5.14E-02千克二氧化碳当量/千克罐装菠萝，美联社为2.62E-04千克-二氧化硫-当量/千克罐装菠萝，EP为2.01E-04千克磷酸三十四当量/千克罐装菠萝。主要排放来自工厂的热电厂，因此提出了使用可再生能源如太阳能光伏（特殊目的公司）来改善，能够减少71.78%的全球升温潜能值、67.94%的美联社和93.24%的EP。用无烟煤代替次烟煤可以减少75.29%的全球升温潜能值和73.48%的美联社，但EP增加了88.66%。将煤替换为液化天然气（液化天然气）可以减少16.79%的美联社和94.49%的EP，但全球升温潜能值增加了44.69%。将固体废物用于果汁生产可以减少98.91%的全球升温潜能值、97.53%的美联社和97.13%的EP。将液体废物转化为沼气可以减少70.92%的全球升温潜能值、96.12%的美联社和95.1%的EP。与用无烟煤或液化天然气替代次烟煤相比，使用特殊目的的公司可再生能源以及利用废水或固体废物可以更有效地减少全球升温潜能值、美联社和EP的环境影响。
关键词：酸化、富营养化、全球变暖潜力、生命周期评估、菠萝加工.

1. Introduction

Canned pineapple is processed from fresh pineapple (*Ananas Comosus*), available as cross-slice or other shapes without cores, in a sugar solution with or without other permitted food additives [1]. According to the Indonesian Central Bureau of Statistics [2], national pineapple production reached 1,795,982 tons, with a harvest productivity of 20,785 tons/hectare in 2017. By 2021, Indonesia had produced 2,886,417 tons of pineapple, becoming one of the world's leading pineapple producers, with the highest production of 705,883 tons in 2021 [3].

The demand for canned fruit and vegetable products is increasing by 1%-2% per year in the European market, where the comparative competitiveness of Indonesian canned pineapple is equivalent to that of the Philippines and Thailand [4]. The Sustainability Report (2020) [5] states that 9.1-9.4 million cans of Indonesian pineapples are exported to over 60 countries, with the main marketing regions: America, Europe, Asia-Pacific, and the Middle East. The Asia-Pacific region has emerged as a leading pineapple producer, contributing 41% of global pineapple production in 2021, with significant contributions from Indonesia, the Philippines, and India. Indonesia leads the region at 2.88 million metric tons, closely followed by the Philippines at 2.86 million metric tons and India at 1.7 million metric tons.

This production dominance is associated with the increasing demand for pineapples, especially in countries like China, which imported pineapples worth USD 172 million in 2020, mainly from neighboring countries like the Philippines and Taiwan [6]. In Europe and North America, the demand for fresh pineapples is increasing, driven by consumer health awareness and a shift toward vegan diets. Pineapple needs in both regions are met through imports, mainly from Costa Rica and the Philippines. In 2021, Costa Rica exported pineapples worth USD 1.0 million worldwide, with the United States, the Netherlands, Belgium, Spain, and Italy as the main importers. Europe and North America account for more than 50% of the world's total pineapple imports. This connection also affects the canned pineapple market because the increasing demand for fresh pineapple can boost the production and consumption of canned pineapple, especially in regions with high imports of fresh pineapple [7].

The production process of canned pineapple involves various stages that produce ready-to-consume canned pineapple products. These stages involve energy consumption and resource use that result in emissions with measurable environmental impacts, such as Global Warming Potential (GWP), acidification (AP), and eutrophication (EP) [8]. Emission assessments can be conducted using the Life Cycle Assessment (LCA) method.

The research on canned pineapple is essential and interesting. Indonesia is a leading producer of pineapples, making significant contributions to both fresh and canned pineapple markets. The canned pineapple industry is crucial to the national economy, especially considering the substantial export volume to over 60 countries. Furthermore, there is growing demand for canned fruits and vegetables in international markets, particularly in Europe, where Indonesian canned pineapple competes with products from the Philippines and Thailand. Understanding the environmental impact of production can help enhance competitiveness. The production of canned pineapple involves various stages that consume energy and resources, leading to emissions with environmental impacts, such as GWP, AP, and EP. Assessing and mitigating these impacts is essential for sustainable production. Previous LCA studies on pineapple products from Thailand provide a benchmark for evaluating Indonesian products. Conducting similar assessments of Indonesia's canned pineapple can highlight areas for improvement and ensure global market competitiveness.

LCA is a method used to evaluate the environmental impacts associated with all stages of a product's life cycle, process, and services. This method is used to evaluate the environmental consequences of canned pineapple production, from the delivery of pineapple raw materials to the production area to the finished product leaving the factory (gate-to-gate). LCA analysis of pineapple products in Thailand with a cradle-to-factory-gate scope for fresh pineapple production yields 72 g-CO_{2-eq}/kg pineapple and 738 g-CO_{2-eq}/can for canned pineapple products [9]. 1.12 kg-CO_{2-eq} for pineapple in syrup. To support global market competition, Indonesian pineapple products must conduct LCA analysis and process production improvement efforts that support the sustainability of the natural environment.

The findings of this research can be applied in several ways. Identifying the environmental hotspots in the production process will guide producers in implementing more sustainable practices, reducing emissions, and optimizing resource use. The results can inform policymakers about the environmental impacts of the canned pineapple industry and aid in the creation of regulations and incentives to promote sustainable pineapple production. Providing transparent information about the environmental impact of canned pineapple products can enhance consumer awareness and drive demand for sustainably produced goods. Demonstrating a commitment to sustainability through LCA can improve the market positioning of Indonesian canned pineapple in competitive international markets, particularly where environmental credentials are increasingly valued by consumers and importers. By addressing these criteria and applying the findings, this research aims to support the sustainable development of the canned pineapple industry in Indonesia, ensuring it remains competitive and environmentally responsible in the global market.

The purpose of this research is to conduct a life cycle assessment (LCA) of canned pineapple products and to determine how to reduce their environmental impacts. The scope of this research is gate-to-gate and covers the entire pineapple production process, starting from the arrival of raw materials at the production gate and ending with the final product from the factory. Environmental impacts focus on global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP).

2. Methods

2.1. Research Location

This study was conducted at a canned pineapple agroindustry in Indonesia.

2.2. Types and Sources of Data

The research uses both primary and secondary data. Primary data were collected from interviews with company officials and relevant stakeholders. Secondary data were gathered from company documents, including input and output data, data on the use of raw materials, additives, energy, machinery and equipment at each production stage, as well as waste data generated from the production process and from previous research findings.

2.3. Research Stages

The LCA method is carried out according to the LCA framework in ISO 14040:2016, which comprises four stages: goal and scope definition, lifecycle inventory analysis, lifecycle impact assessment, and result interpretation. These stages form the basis for developing improvement recommendations. The research stages are illustrated in Fig. 1.

2.3.1. Goal and Scope

At this stage, the purpose and scope of the LCA study for the canned pineapple industry are defined using both primary and secondary data obtained through research questionnaire interviews and literature review.

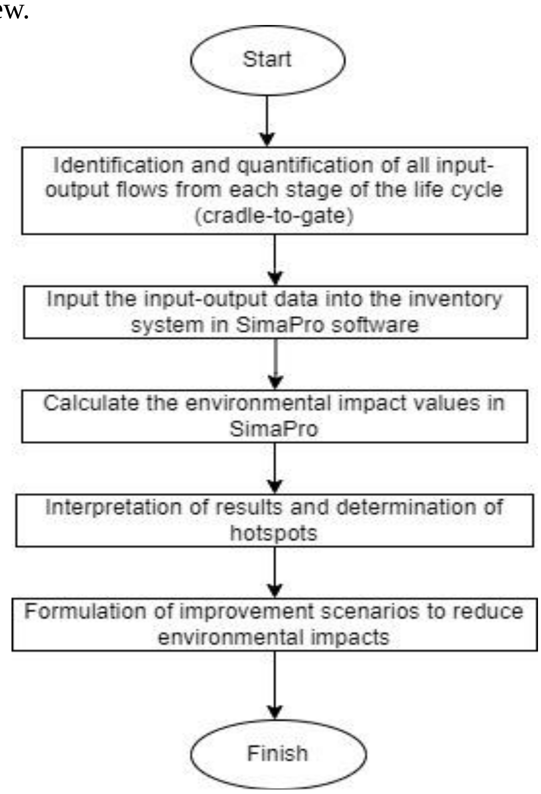


Fig. 1 Flow chart of the research stages (Developed by the authors)

According to ISO14040:2006 [10], the functional unit is the quantified performance of a product system used as a reference unit in LCA studies. The most common functional unit for food products is the mass. Observations were made to understand the life cycle scope of canned pineapple production through direct observation and interviews.

2.3.2. Inventory Analysis

Inventory analysis involves identifying the inputs and outputs of the product throughout its life cycle in accordance with ISO 14044:2006 standards. Data collection was conducted through interviews, field observations, and inventory forms. The primary and secondary data include all input flows (raw materials, additives, and energy) and output flows (products, by-products, waste, and emissions) throughout the production process in canned pineapple agroindustry. The material balance from input and output materials was analyzed using material flow analysis based on the flowchart of canned pineapple production.

2.3.3. Environmental Impact Analysis

The primary objective of environmental impact analysis is to evaluate potential environmental impacts based on inventory analysis results. SimaPro software, a leading LCA data processing tool with a comprehensive database, facilitates this evaluation by assessing the environmental impacts of products. It uses methodologies like CML 2001 and the Eco-indicator 99 for impact analysis, enabling accurate decision-making. The inventory data is linked to specific environmental impact categories and analyzed using SimaPro, which focuses on GWP, AP, and EP among the potential impacts considered.

2.3.4. Interpretation of Results

The final stage of LCA is interpretation, where data from SimaPro are analyzed and translated into potential impact categories. These results are then aligned with relevant literature to produce appropriate recommendations. This stage encompasses the results analysis, cause of impact analysis, identification of key issues, conclusions, explanation of study limitations, and recommendations and evaluations. Based on the hotspot of several impacts, scenarios for mitigation impacts were developed to improve the life cycle performance. The reduction of environmental impacts will be discussed by the operational activities that produce the largest emissions.

3. Results and Discussion

3.1. Life Cycle of Canned Pineapple Production

The canned pineapple production process involves several stages using fresh pineapple from the company's plantations as raw material. The company produces 15 types of pineapple products, which are divided into two categories: pure pineapple and mixed fruit pineapple products, with three different packaging types: pouch, cup, and can.

In this study, the focus is on pure pineapple products in Z-type packaging with a net weight of 587.3 g, which undergoes various production stages. Data from 2022 indicate that pineapple accounts for approximately 38.8% of the company's total production and 40% of the total canned pineapple production. The product's life cycle assessment analyzed three environmental impacts generated during the production of canned pineapple Z. The results help identify significant environmental impacts (GWP, AP, and EP) and develop recommendations for reducing them. The life cycle of canned pineapple is illustrated in Fig. 2.

The canned pineapple production process includes several key stages, from raw material preparation to final product packaging. The process starts by selecting and harvesting ripe, quality pineapples, which are then washed to remove dirt and residue. The pineapples are peeled and cut into desired sizes, and the hard center is typically removed. This process is often mechanized to improve efficiency. The cut pineapples are blanched to remove enzymes that could affect taste, color, and texture during storage. Finally, they are typically added to syrup or sugar solutions to preserve their taste, texture, and color.

The pineapples mixed with syrup are then canned to ensure no air is trapped to maintain product quality. The filled cans were heated at high temperatures to sterilize or kill microorganisms and extend the shelf life.

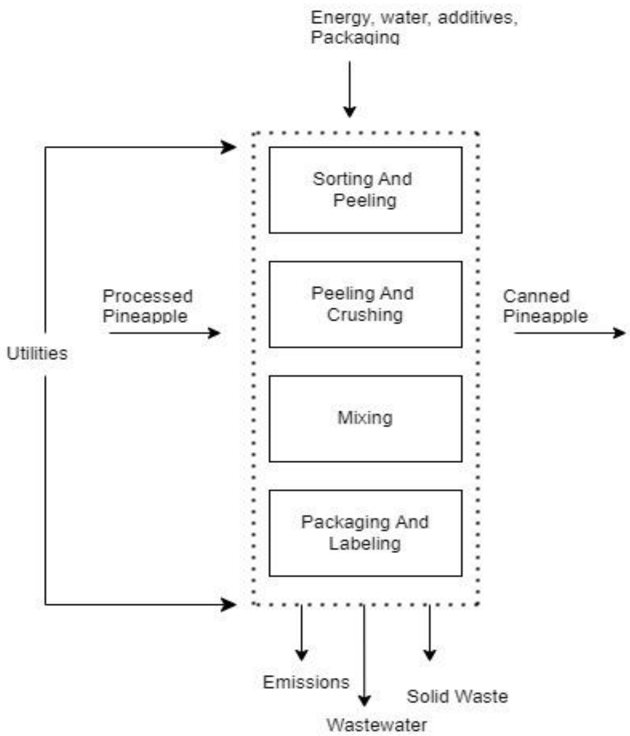


Fig. 2 Life cycle of canned pineapple production (Developed by the authors)

After cooling, the canned pineapple is stored in a cool dry place before distribution. Quality inspections precede packaging and labeling for distribution. Each step in the canned pineapple production process is crucial to ensure the final product is safe, hygienic, and high in quality, relying on modern technology and strict quality control to ensure consistency and safety.

3.2. Goals and Scope of Life Cycle Assessment (LCA)

The goal and scope phase are crucial in LCA research on canned pineapple, focusing on observing and processing data to describe the product, process, or activity. The study establishes the study limits and assesses the environmental impacts of the canned pineapple production life cycle. The LCA aims to identify emissions throughout the production life cycle and analyze potential environmental impacts, such as GWP, AP, and EP, by proposing alternative improvement recommendations to reduce environmental impacts. The scope, or boundary, of the LCA for canned pineapple products is gate-to-gate, covering the process from industrial production to the final product with a functional unit (FU) of one can of pineapple weighing an average of 587.3 g (0.5873 kg).

3.3. Inventory Analysis

Before presenting inventory data, it is crucial to recognize that the information collected for the canned pineapple production process is based on data from 2022. Table 1 presents various aspects related to production, including energy consumption, raw material usage, emissions, and other outputs associated with the production process. This information is vital for life cycle analysis because it provides a clear picture of the environmental impacts of canned pineapple production. The complete details of the inventory data for the canned pineapple production process at a FU using 2022 data are presented in Table 1.

Table 1 Inventory data of the subsystems involved in the canned pineapple production (Z) process in 2022 (Developed by the authors)

Data	Unit	Volume
Input		
Pineapple	kg	1.9706
Water	kg	4.5873
Media	kg	0.1408
Can package	kg	0.0751
Label	kg	0.0027
Electricity (State)	kWh	0.000076
Biodiesel	kg	0.0004713
LPG	kg	0.0001
Electricity (Coal-fired power plant)	kWh	0.0358
Steam		
Output	kg	0.28251
Canned pineapple		
Solid waste	kg	0.5873
Wastewater	kg	1.53
	L	4.58

The mass balance calculation for producing one can of Z-variant pineapple with a net weight of 0.5873 kg (FU) required 1.97 kg of processed pineapple from the core farm. The energy needs for producing one can of pineapple (0.5873 kg) include 0.0001 kWh of electricity from the national grid (PLN) and 0.0358 kWh of electricity from a coal-fired power plant, along with 0.3924 kg of steam from cogeneration, with the use of biodiesel and LPG being minimal. The inventory of the mass balance of the production of Z-variant canned pineapple over one year (in 2022) shows significant fresh pineapple and energy requirements, highlighting the importance of energy from steam and electricity cogeneration in the production process (Fig. 3).

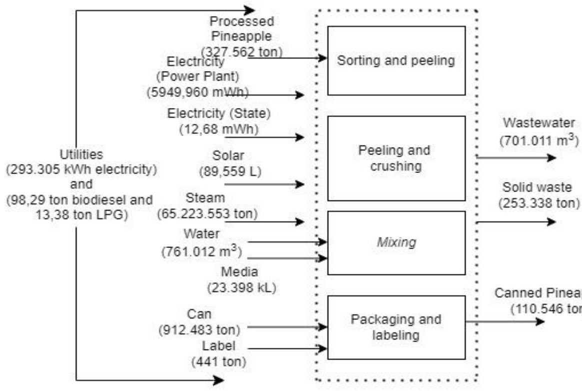


Fig. 3 Mass balance of canned pineapple production variant Z in 2022 (Developed by the authors)

The energy used in canned pineapple production comes from fuel, electricity, and steam. Fuels include biodiesel, with electricity sourced from both the national grid (PLN) and the factory's own power plant and steam generated by the power plant. The factory powers its machinery with self-generated electricity, ensuring self-sufficiency through its power plant. Internal electricity production is vital for optimizing the efficiency of pineapple processing plants because it is directly correlated with processing effectiveness.

Steam is a primary energy source in pineapple processing factories, where the produced steam power turbines at various stations to support production processes. Used steam from pineapple processing is collected back as condensate water and then returned to the boiler station as boiler feed water.

3.4. Impact Analysis

Environmental impact analysis identifies potential environmental impacts at each stage of the pineapple canning life cycle. This process is relatively efficient, adopting circular economy principles, and minimizes material and energy losses to the environment. The key environmental impacts are analyzed with a focus on significant potential effects. The waste generated during canning is primarily organics, including wastewater, solid waste, and air emissions. This study assumes that solid and wastewater are disposed of at their respective treatment stations.

The canned pineapple processing lifecycle, as illustrated, indicates that each processing step generates waste or byproducts. This waste can be recycled or reused, contributing to sustainable canned pineapple processing. Wastewater from the pineapple canning production station is channeled to a biogas plant to produce biogas fuel, which is used for electricity and steam generation. Other wastewater is directed to a wastewater treatment plant (WWTP).

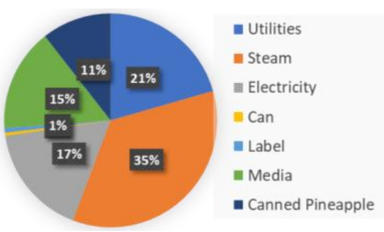
Throughout production, an increase in waste, including solid and wastewater, is documented in canned pineapple processing. Typically, pineapple pulp, filter cake, peels, and other solid wastes are recycled into other products like concentrate and juice for use in canned pineapple. Air emissions around the processing plants include flue gas or smoke from boiler chimneys and air around operating machinery at various plant stations. Emissions from this factory are minimally harmful because organic fuels.

The emission sources in pineapple processing plants include fuel usage in boilers, diesel burning/consumption, and the treatment of solid and wastewater. The produced emissions are related to greenhouse gas effects, especially CO_2, CH_4, and SO_2 emissions from plants. These emissions stem from fuel consumption in boilers, including coal-generated steam. The environmental impact values of the inputs used to produce one Z variant canned pineapple (0.5873 kg) are detailed in Table 2.

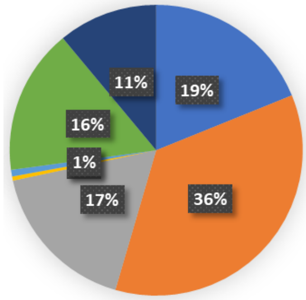
The main emission source in the canned pineapple production subsystem is steam input from cogeneration. The percentage of process input for each environmental impact is illustrated in Fig. 4.

Table 2 Impact values of input system for canned pineapple production variant Z (Developed by the authors)

Data	GWP (kg-CO_2eq)	Acidification (AP) (kg-SO_2eq)	Eutrophication (EP) (kg-PO_4^{3-}-eq)
Input			
Canned Pineapple	5.44E-03	2.88E-05	2.46E-05
Media	7.99E-03	4.23E-05	3.57E-05
Label	3.61E-04	1.93E-06	8.08E-07
Can	2.38E-04	1.23E-06	1.05E-06
Electricity	8.70E-03	4.49E-05	4.15E-05
Steam	1.81E-02	9.34E-05	8.63E-05
Utilities	1.06E-02	4.94E-05	1.07E-05
Output			
Canned Pineapple	5.44E-03	1.29E-06	2.46E-05
Solid Waste	3.01E-01	8.00E-04	1.40E-03
Wastewater	1.20E-03	4.00E-06	9.16E-05



(a)



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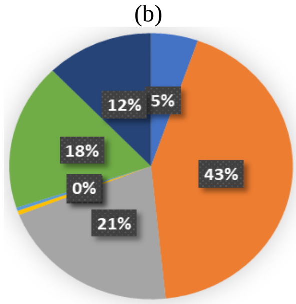

(c)

Fig. 4 Percentage of environmental impacts on canned pineapple production: (a) GWP, (b) AP, and (c) EP (Developed by the authors)

Table 2 illustrates the impact levels in numerical values, indicating the contribution of each element to the three environmental impact categories. The total environmental impact from all elements is the sum of values in each category, providing an overall view of the environmental impact of producing Z-type canned pineapple. This analysis is crucial to developing sustainable production practices and needs.

The three diagrams illustrate the contributions of different sources to various environmental impacts: Global Warming Potential (GWP) (Fig. 4a), acidification (AP) (Fig. 4b), and eutrophication (EP) (Fig. 4c). Steam is identified as the primary contributor to GWP, accounting for 35.21%, followed by utilities (20.62%) and electricity (16.93% (Fig. 4a). The emissions of greenhouse gases include different gases such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other hydrocarbons, measured in CO_2-equivalents. Regarding acidification (Fig. 4b), steam contribution stands at 35.65%, utilities at 18.85%, and electricity at 17.14%. Acidifying gases, including sulfur oxides (SOx) and nitrogen oxides (NOx), can react with water, oxygen, and ozone in the atmosphere, leading to the formation of acid rain. Acid rain adversely affects soil and vegetation, both directly and through soil oxidation processes [11]. In Fig. 4c, utilities contribute only 5.3% toward eutrophication, but steam’s impact is significantly larger at 43%. Steam generated from coal-fired power plants has the highest impact on all three environmental factors. High energy consumption is a major environmental impact factor, which is in agreement with [12], studying the life cycle assessment of fishery product processing. The multidimensional impacts of eutrophication on water quality, ecosystems, human health, and economic activities have been increasingly acknowledged [13].

3.5. Interpretation of LCA Results

The interpretation of the results of the LCA is the last step of the LCA analysis. This phase is designed to identify the most significant sources of emissions (hotspots) and propose remedial actions to mitigate the environmental impact of canned pineapple production. Although the demand for steam in the production of canned pineapple is relatively low, the company's production process, which utilizes coal, results in considerable emissions during the lifecycle of the Z variant of canned pineapple. The normalized outcomes for three environmental impacts (GWP, AP, and EP) related to the Z variant of canned pineapple are illustrated in Fig. 5.

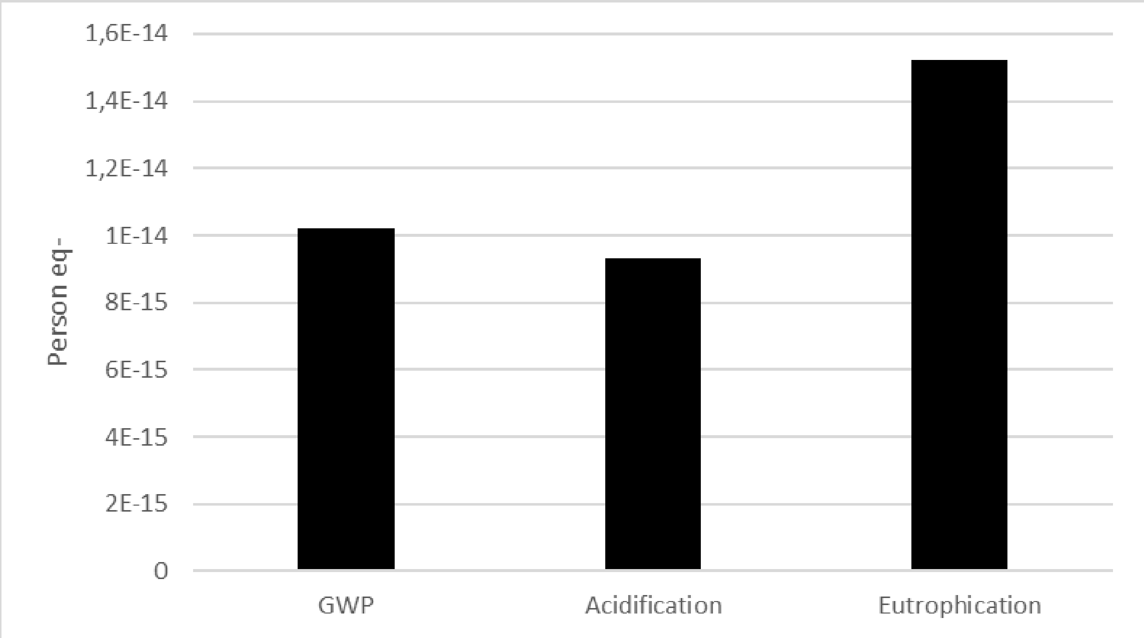

Fig. 5 Normalized environmental impact of the canned pineapple variant Z (Developed by the authors)

The methodology employed in this study adheres to the ISO 14040 standard framework, ensuring that the calculation and comparison of environmental impacts are performed consistently and reliably, thus enhancing the validity of the findings compared with previous studies. A more detailed interpretation is presented in Fig. 5. The scientific notation values on the y-axis of the graph represent normalized impact indices, providing a clearer perspective on the magnitude of the environmental impacts caused by the production of canned pineapple. The chart in Figure 5 compares the normalization of three environmental impacts: GWP, AP, and EP, where the scientifically notated values on the y-axis denote the normalized impact indices. The results reveal that the impacts of GWP and acidification are comparatively low, suggesting that the environmental effects of producing the Z-type canned pineapple are less significant in these areas than in eutrophication. The analysis examines the specific canned pineapple production process and its environmental impacts at every stage, from raw material preparation to packaging. Earlier research [14] has detailed how processing stages and energy consumption contribute specifically to generated emissions.

Eutrophication was identified as having significantly high values, highlighting its comparatively greater environmental impact than GWP and AP. This indicates that within the framework of normalized environmental impacts, an increased focus on environmental impact mitigation is necessary. Such assessments are critical for prioritizing actions within environmental policies and impact reduction initiatives. The results suggest that substituting coal for renewable energy sources should be a key strategy for mitigating environmental impacts. Not only would this approach help in lowering GWP emissions, but it would also address acidification and eutrophication. As demonstrated in [15], the effectiveness of renewable energy implements in similar sectors, reinforcing the argument that such strategies are beneficial for the sustainability production process. A comparison of the current environmental impact conditions with benchmarks is presented in Table 3, as well as a comparison of environmental impacts before and after the implementation of improvement scenarios.

Table 3 Comparison of the impacts of GWP, AP, and EP between existing conditions and other references (FU at 0.5873 kg/can) (Developed by the authors)

Condition	EF (MJ)	GWP ($kgCO_2$ eq)	Acidification ($kgSO_2$ eq)	Eutrophication ($kgPO_4^{-3}$ eq)
Existing (2022)	7.00	0.04	2.12E-04	1.62E-04
[16]	5.92	0.34	2.90E-04	6.61E-05
[9]	10.22	0.38	9.96E-03	7.69E-03

Table 3 presents four critical environmental impact parameters for various entities. These include the energy factor (EF), indicating the energy consumption of each entity in megajoules (MJ); global warming potential (GWP), indicating the entity's contribution to global warming in kilograms of CO_2 equivalent; acidification, assessing environmental acidity levels in kilograms of SO_2 equivalent; and eutrophication, reflecting the entity's impact on nutrient levels in the environment in kilograms of PO_4 equivalent. A comparison between different entities, such as the examined company, and studies [9, 16] offers detailed insights into the environmental performance of each subject.

The current conditions show a higher EF than the two other entities analyzed, yet they have lower environmental impacts related to GWP, acidification, and eutrophication. The research [16] indicated a higher GWP level, whereas findings of [9] exhibited significantly higher rates of AP and EP than the other entities. This analysis is crucial for comprehending the environmental impacts associated with the activities of these entities and plays a vital role in guiding decision-making processes aimed at mitigating such impacts. Strategies for reducing energy consumption include enhancing energy efficiency or producing energy from the waste materials generated [17].

The company studied, despite having a higher EF, demonstrated better performance in terms of GWP, AP, and EP compared to other studies. This indicates higher efficiency in energy use and environmental impact management. It is worth noting that a high EF value may indicate a higher energy consumption per unit of production, which poses the potential for further optimization. Lu et al. [18] emphasize the importance of integrating energy efficiency strategies and renewable energy sources to enhance environmental performance.

A comparative analysis of the existing conditions with other studies provides valuable insights into the effectiveness of implemented measures. A related company has adopted a circular production approach that uses generated waste, a strategy [19] that not only reduces environmental impact but also enhances operational sustainability. This research indicates that by embracing the principles of circular economy, especially waste management and energy efficiency. Canned pineapple processing can significantly reduce the negative environmental impacts. This approach, which involves waste reduction, reuse, recycling, and energy optimization, is crucial in environmental impact mitigation efforts and fostering more sustainable operations.

The use of Solar Photovoltaics (SPV) is one of the primary recommendations for replacing coal in the company’s steam power plants. Solar PVs offer substantial environmental benefits, particularly in terms of reducing greenhouse gas emissions. Unlike coal, which is a major source of CO_2 and other pollutants, solar PV systems generate electricity without direct emissions. This makes them crucial to combat climate change and reduce air pollution. For example, a previous study highlighted that replacing coal with solar PVs could significantly decrease CO_2 emissions and improve public health by reducing air pollution-related illnesses [20]. Implementing SPV technology not only reduces dependence on fossil fuels but also offers a significant reduction in greenhouse gas emissions, contributing to a decrease in GWP. Additionally, SPV has the potential to reduce AP and EP, providing a clean and sustainable solution to the company's energy needs.

The second scenario involves replacing existing sub-bituminous coal with anthracite coal because of its higher carbon content and greater heat generation per unit weight than other types of coal. Anthracite coal, which has a higher carbon content, emits approximately 98.3 kg CO_2 per GJ, which is slightly higher than sub-bituminous coal (96.1 kg CO_2 per GJ, but it produces fewer SO_2 and particulate emissions, making it a more efficient fuel source [21]. These characteristics also result in anthracite emitting less pollution when burned, such as sulfur dioxide and solid particles, contributing to a reduction in the negative impacts on air quality and associated health risks. Moreover, due to its high efficiency, anthracite has a smaller carbon footprint per unit of energy produced, indicating that its use can be a more environmentally friendly option than other types of coal in terms of greenhouse gas emissions.

Furthermore, replacing coal with Liquid Natural Gas (LNG) offers significant reductions in emissions. Replacing coal with Liquefied Natural Gas (LNG) can reduce CO_2 emissions by approximately 50% in electricity generation because LNG has lower carbon content and higher combustion efficiency [22]. LNG, which burns cleaner than coal, can drastically reduce the impacts of AP and EP, in addition to reducing greenhouse gas emissions. Implementing LNG as a substitute fuel in Steam Power Plants marks a significant step toward more environmentally friendly operations and reducing the overall environmental impact. A part of coal usage, the canned pineapple production process generates solid and liquid waste, both of which contribute to environmental pollution. This provides a holistic view of the environmental performance of various entities and serves as a crucial basis for sustainable decision-making to reduce negative environmental impacts.

This study identified that coal usage in the canned pineapple production process significantly contributes to high environmental impacts, particularly in terms of GWP, AP, and EP. A comparison of the environmental impacts between the existing conditions and after implementing the improvement scenarios is presented in Table 4. Scenario 1, which utilizes SVP, demonstrated a significant reduction in 71.78% GWP, 67.94% AP, and 93.34% EP. Scenario 2, employing anthracite coal, results in a reduction of 75.29% GWP and 73.48% AP but an increase in 93.34% EP.

Replacing coal with renewable energy sources such as solar photovoltaics or biomass can significantly reduce GWP emissions [23]. Scenario 3, using LNG, indicates a reduction of 16.79% in AP and 94.49% in EP but an increase of 46.69% in GWP. LNG produced from the purification of natural gases showed the higher emission factor of GWP impact. This finding illustrates how the selection or use of various energy sources can affect the environmental impacts of GWP, AP, and EP.

Table 4 Comparison of the impacts of GWP, acidification, and eutrophication between existing conditions and improved canned pineapple production scenarios (Developed by the authors)

Condition	GWP ($kgCO_2$ eq)	GWP Reduction (%)	Acidification (AP) ($kgSO_2$ eq)	AP Reduction (%)	Eutrophication (EP) ($kgPO_4^{-3}$ eq)	EP Reduction (%)
Existing	5.14E-02	-	2.62E-04	-	2.01E-04	-
Scenario 1 (SPV)	1.45E-02	71.78	8.50E-05	67.94	1.36E-05	93.34
Scenario 2 (anthracite coal)	1.27E-02	75.29	6.94E-05	73.48	3.78E-04	+ 88.06
Scenario 3 (LNG)	7.54E-02	+ 46.69	4.36E-05	16.79	1.11E-05	94.49

The analysis of wastewater and solid waste emissions based on data from the SimaPro database (Table 5) shows that the number of emissions from a related company's waste does not create significant emission hotspots; thus, it is important to explore alternatives in waste utilization. The utilization of wastewater or solid waste can improve the reduction efficiency of GWP, AP, and EP in canned pineapple production. One of the proposed improvement scenarios is to convert waste into juice. A comparison between the emissions from unused waste and those after use is presented in Table 5.

Table 5 presents a comparison between the current waste condition and the scenario of waste use in juice production. The process of preparing concentrated juice from pineapple waste involves several key steps. First, pineapple peels, cores, and other waste materials are collected and thoroughly washed. The cleaned waste is crushed to extract juice, which is filtered to remove any residual residue. This juice is evaporated to remove excess water and achieve the desired concentration, followed by pasteurization to ensure safety and extend the shelf life. Finally, the concentrated juice is packaged in sterilized containers, labeled, and stored appropriately until distribution. This method not only reduces food waste but also adds economic value by using by-products efficiently. Significantly, GWP experienced a drastic decrease from 0.301 $kgCO_2$ eq to 0.00328 $kgCO_2$ eq, representing a reduction of 98.91%. This indicates significant progress toward reducing waste contributions to climate change. Additionally, the AP impact, which measures the potential increase in environmental acidity, also decreased from 0.00084 $kgSO_2$ eq to 0.0000212 $kgSO_2$-eq, marking a reduction of approximately 97.53%.

Table 5 Comparison of the impacts of GWP, AP, and EP on existing waste conditions and the scenarios of solid or liquid waste use (Developed by the authors)

Condition	**GWP ($kgCO_2$eq)**	**GWP reduction (%)**	**Acidification (AP) ($kgSO_2$ eq)**	**AP reduction (%)**	**Eutrophication (EP) ($kgPO_4^{-3}$ eq)**	**EP reduction (%)**
Existing solid waste use	3.01E-01	-	8E-04	-	1.40E-03	-
Solid waste use to Juice production	3.28E-03	98.91	2.12E-05	97.53	4.02E-05	97.13
Existing wastewater utilization	1.20E-03	-	4E-5	-	9.16E-05	-
Wastewater use as biogas fuel	3.49E-04	70.92	1.55E-06	96.12	4.49E-06	95.1

Finally, EP, which is the accumulation of excess nutrients in water bodies that can lead to uncontrolled algae growth, also decreased from 0.00140 $kgPO_4^{-3}$-eq to 0.000042 $kgPO_4^{-3}$-eq, representing approximately 97.13%. These changes demonstrate the effectiveness of waste use scenarios in reducing the negative impacts of canned pineapple production on the environment.

Biogas is one of the most promising solutions for addressing liquid waste issues. The biogas production process likely involves waste collection, pre-treatment, anaerobic digestion, biogas capture, and use. During anaerobic digestion, organic waste undergoes biochemical reactions in sealed tanks, producing biogas primarily composed of methane. The biogas is then captured, purified if necessary, and used for various purposes, such as electricity generation and heating. However, emissions can occur due to methane leakage and incomplete combustion during biogas production and usage. To mitigate these emissions, the company should focus on minimizing methane leakage through proper maintenance and optimizing combustion processes to maximize efficiency and reduce pollutants. Comprising a mixture of methane (CH_4) and carbon dioxide (CO_2), biogas is produced via anaerobic digestion, the decomposition of organic matter in the absence of oxygen. This process not only reduces the volume of waste that needs to be disposed of but also converts it into a valuable energy source. Through the implementation of anaerobic digestion technology, liquid waste resulting from processing industries, such as canned pineapple, can be converted into biogas. This approach has been successfully implemented by a related company that adopts a circular system model [24]. The following subsection compares untreated liquid waste conditions to biogas processing conditions.

Table 5 presents a comparison of the environmental impacts between untreated wastewater and biogas fuel. In terms of GWP, there was a reduction from 1.20E03 kg of CO_2 equivalent ($kgCO_2$ eq) to 3.49E-04 $kgCO_2$ eq, marking a reduction of 70.92%. Meanwhile, the acidification potential (AP) shows a more significant decrease from 4E-05 $kgSO_2$ eq to only 1.55E-06 $kgSO_2$ eq, indicating a reduction of 96.12%. Finally, in the context of eutrophication potential (EP), the value derived from untreated liquid waste is 9.16E-05 $kgPO_4^{-3}$-eq, which decreases to 4.49E-06 $kgPO_4^{-3}$-eq after liquid waste utilization, with a reduction percentage reaching 95.1%. These results confirm that the transformation of liquid waste into biogas not only reduces the negative environmental impacts but also demonstrates the potential of waste as a valuable resource.

In this study, the benefits are significant in the context of the circular economy, especially the pineapple industry. Through this approach, companies can improve waste utilization efficiency, save material and energy, and reduce operational costs, thereby increasing profit margins. The circular economy concept, which emphasizes the principles of reduction, reuse, and recycling, is highly relevant in agribusiness industries like pineapple. These practices not only benefit the economy but also provide significant environmental benefits. Pineapple industry tree diagram is shown in Figure 6, and circular processes in a company are shown in Figure 7.

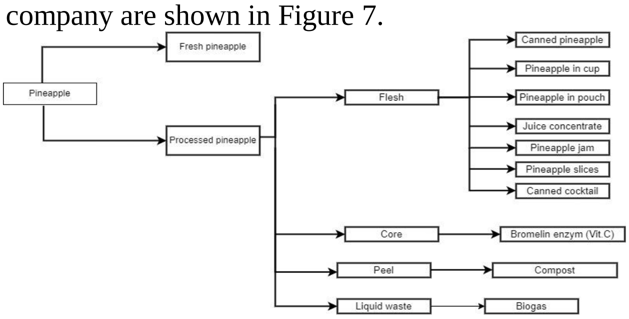

Fig. 6 Industrial pineapple tree and waste utilization (Developed by the authors)

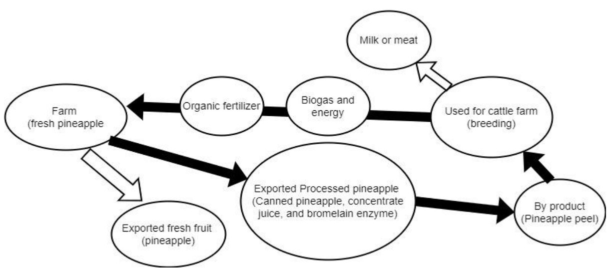

Fig. 7 Circular process in the canned pineapple industry (Developed by the authors)

Figures 6 and 7 show that, in the downstream sector of pineapple processing, the use of solid and liquid waste has great potential. Given the wide variety of pineapple-derived products available, farmers and industries have many options to engage in pineapple-based production efforts and take advantage of opportunities to expand their presence in the global market. Implementing a circular economy [25] can reduce environmental impacts and increase business sustainability.

Furthermore, it is important to conduct an in-depth study of the ‘cradle to grave’ scope of the pineapple industry, tailored to the existing conditions of the company. A case study [26] in the coconut industry demonstrated that integrating plantation and processing activities into one entity can reduce environmental impacts, such as GWP, AP, and EP, while also achieving more sustainable operations compared to separate operations. A similar approach can be applied in the pineapple industry, where integration between plantation and processing can enhance sustainability.

In line with the focus on sustainability, it's imperative to address the issue of waste management within the pineapple industry. By implementing effective waste management strategies, such as composting or bioconversion, pineapple processing facilities can minimize the environmental footprint associated with by-product disposal. Using innovative technologies for waste valorization can mitigate environmental pollution and generate value-added pineapple industry. Moreover, collaborations with local communities and governmental agencies can facilitate the development of integrated waste management systems tailored to the specific needs and resources of the region. By prioritizing waste reduction and resource optimization, the pineapple industry can further enhance its contribution to a circular economy paradigm by fostering environmental stewardship and economic prosperity [27].

In the canned pineapple industry, the use of more sustainable raw materials, waste utilization, and processes can significantly reduce environmental impacts. Considering environmental impacts at every production stage can be a sustainable implementation strategy. The sustainable implementation of paper production using recycled fibers has a lower environmental impact than paper produced using virgin wood fiber [28].

Additionally, it has been demonstrated that fruit by-products contain valuable compounds like polyphenols with high antioxidant activity, which can be extracted using biotechnological methods for various industrial applications. Integrating the valorization of fruit by-products into a circular economy framework addresses environmental concerns while fostering economic growth and social responsibility [29]. This research emphasizes the importance of comprehensive environmental impact analysis, from raw materials to end products, which can be applied to research on canned pineapple to improve environmental sustainability.

4. Conclusion

This work uses input-output inventory data to analyze the environmental impacts of FU of 0.5873 kg/canned pineapple, focusing on gate-to-gate processes. The existing conditions for pineapple production indicate significant environmental impacts in the form of global warming potential (GWP), acidification (AP), and eutrophication (EP) at 5.14E-02 kg CO_2 eq, 2.62E-04 kg SO_2 eq, and 2.01E-04 kg PO^3_4 eq, respectively.

The main emissions come from thermal power plants using bituminous coal. Hence, proposed improvements by renewable energy sources such as solar photovoltaic (SPV) have achieved reductions of 71.78% GWP, 67.94% AP, and 93.24% EP. If sub-bituminous coal is substituted with anthracite, it can reduce 75.29% GWP and 73.48% AP and can increase 88.66% EP. Coal substitution to Liquefied Natural Gas (LNG) reduced 16.79% AP and 94.49% EP but increased 44.69% GWP.

One of the solid wastes of pineapple can be utilized in several by-products, such as juice production, significantly, and the environmental impacts decreased by 98.91% GWP, 97.53% AP, and 97.13% EP. If the wastewater was utilized as biogas, the environmental impacts significantly decreased by 70.92% GWP, 96.12% AP, and 95.1% EP. The substitution of renewable energy for SPVs and the use of liquid or solid waste can reduce the environmental impacts of GWP, AP, and EP in canned pineapple production. This highlights the significant potential of adopting sustainable technologies to mitigate the environmental impacts of the canned pineapple industry.

This study makes significant academic contributions by applying Life Cycle Assessment (LCA) to evaluate and reduce the environmental impacts of canned pineapple production. Unlike previous studies, the proposed method innovatively integrates renewable energy sources like solar photovoltaic (SPV) and waste utilization strategies, demonstrating substantial reductions in global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). These findings present a novel approach to sustainable pineapple production and provide a practical framework for implementing these solutions. This research fills a critical gap in the existing literature and supports global sustainability efforts by highlighting the benefits of sustainable technologies.

This study recommends the adoption of renewable energy sources and the use of waste by-products to reduce the environmental impact of canned pineapple production. This research highlights the significant potential of sustainable technologies to mitigate environmental impacts, emphasizing the need for industry-wide implementation. Future research should explore the scalability and economic feasibility of sustainable practices to enhance their adoption. By integrating innovative strategies, the canned pineapple industry can achieve substantial environmental benefits and contribute to global sustainability efforts.

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