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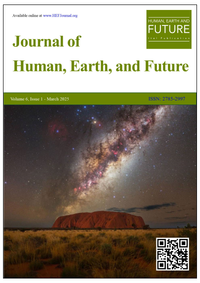

Managing Disposable Face Mask Waste as Circular Economy Products through Life Cycle Assessment

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Abstract

The COVID-19 pandemic has resulted in a surge of disposable facemask waste, posing significant health and environmental risks. This study aims to recycle disposable facemask waste into reusable materials using Post-Consumer Recycled Plastic (PCR) within a Life Cycle Assessment (LCA) framework. The process involves sorting, collecting, and sterilizing the masks through the Advanced Oxidation Process (AOP). The sterilized material is then processed into PCR pellets, which can be used to produce polypropylene plastic flakes. The findings indicate that disposable facemask waste can be effectively sterilized using AOP (Advanced oxidation Process) and converted into PCR through extrusion. The Life Cycle Inventory Assessment (LCA) identified Human Non-Carcinogenic Toxicity (HNCT) as the most significant environmental impact, amounting to 65.04705 tons of 1,4-DCB. Additionally, PCR production emits 22.3297 tons of CO_2 equivalent, with an Eco-Efficiency assessment of 0.9906 tons of product per ton of raw material. This approach supports sustainable waste management practices and introduces a circular economy business model for repurposing disposable facemasks.

Keywords: Disposable Face Mask Waste (DFM); Life Cycle Assessment (LCA); Post-Consumer Recycled Plastic (PCR); Eco-Efficiency.

1. Introduction

The surge in the use of disposable face masks during the COVID-19 pandemic has significantly increased their production as infectious waste, along with higher energy and raw material consumption [1]. This increase is a contributing factor to greenhouse gas emissions [2]. In 2021, approximately 5.4 million tons of face masks were produced globally, most ending up in landfills or incinerated [3]. This disposal process poses severe ecological risks, including soil, water, and air pollution, impacting human health and leading to high management costs [4, 5]. Studies show that producing a disposable face mask emits 32.7 grams of CO_2 equivalent [2, 6]. Additionally, discarded masks contribute to microplastic pollution in ecosystems and the human food chain. They also act as vectors for the spread of pathogens, posing further health risks [7, 8]. These findings highlight the urgent need for sustainable solutions to address the environmental and health challenges associated with the increased use and improper disposal of disposable face masks.

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Most disposable face masks are made from polypropylene (PP) and polyethylene (PE) [9], which can be disassembled and recycled. They can undergo sterilization through the Advanced Oxidation Process (AOP) to transform infectious masks into non-infectious ones. AOP is an advanced treatment method that accelerates oxidation and decomposes both organic compounds that are resistant to conventional treatments. This process combines ozone, hydrogen peroxide, ultraviolet (UV) radiation, and photocatalysis to oxidize contaminants in water, air, and soil effectively. AOP has been widely applied for wastewater treatment, disinfection, color reduction, and odor removal [10]. Recent research has focused on repurposing the vast amounts of discarded masks worldwide through circular economy (CE) principles. Examples include using biodegradable natural materials for mask production and developing reusable masks [11]. Masks have also been incorporated into construction materials, such as asphalt, bricks, and paving blocks [12]. However, concerns remain about the release of microplastics from PP-based masks. One effective method to address this is converting used masks into Post-Consumer Recycled (PCR) plastic pellets using the extrusion process, which has a lower environmental impact than traditional disposal methods like incineration and landfilling [13]. Recycling disposable face masks into raw materials for other products through CE principles aligns with sustainable development goals (SDGs). This approach mitigates environmental impacts, supports waste reduction, and promotes a sustainable solution to the growing issue of mask disposal [14].

It is crucial to evaluate the health and environmental impacts of recycling disposable face masks into Post-Consumer Recycled Plastic (PCR plastic) products under Circular Economy (CE) principles. This process involves sterilization through the Advanced Oxidation Process (AOP) before recycling, which requires additional energy and operational steps. Therefore, conducting a Life Cycle Assessment (LCA) is necessary to systematically assess the impacts of every stage of the product's life cycle, from raw material acquisition to disposal [15]. Life Cycle Assessment is a tool for assessing products, processes of environmental impacts, and life cycle as a cradle to grave. It offers a comprehensive view of environmental impacts, considering all stages of a product's life cycle, including production, transportation, use, and end-of-life. LCA aids in informed decision-making, resource efficiency, regulatory compliance, consumer awareness, product design and innovation, benchmarking, and collaboration. It helps businesses identify stages with the highest environmental impact, enabling informed decisions to improve sustainability and reduce ecological footprints. LCA also promotes resource conservation, reducing waste, and cost savings. It also facilitates collaboration between stakeholders in supply chains, promoting shared sustainability goals. LCA is vital for advancing sustainability and promoting responsible consumption and production practices. This study aims to explore the management of infectious waste from face masks and transform them into circular economy products through the extrusion process, guided by LCA principles. The research provides empirical evidence that can inform policymaking by evaluating impacts across the entire life cycle.

Additionally, this study integrates Eco-Efficiency assessment, which analyzes LCA data to create indicators linking economic and environmental performance. This approach aligns with sustainable development goals, specifically SDG 12: Responsible Consumption and Production and SDG 13: Climate Action. It emphasizes sustainable solutions that promote efficient resource use and reduce environmental impacts, contributing to global efforts to mitigate climate change and ensure sustainable production practices. Moreover, the aims of the research are to evaluate the environmental impacts due to PCR production from disposable face mask waste and to conduct an LCA study for a new business for a green economy.

2. Material and Methods

This study collected data on producing PCR plastic Post-Consumer Recycled Plastic (PCR) from disposable face mask waste. The process includes sourcing raw materials through sorting and collection at designated points, sterilization via the Advanced Oxidation Process (AOP), transportation, PCR production, and product packaging. The study focuses on a densely populated community in a pollution control zone, Rayong, Thailand. While the community has effective solid waste management systems, it requires improved strategies for efficiently managing used face masks.

2.1. Management of Disposable Face Mask Waste Using the AOP Process

In this step, public awareness campaigns were conducted within the community to educate residents on the importance of separating and collecting disposable face masks waste. These collected masks were then delivered to municipal collection points for sterilization using the Advanced Oxidation Process (AOP) with a disposable face mask waste sterilization machine (Figure 1). Once sterilized, the masks were transported for further processing through the extrusion method (Figure 2).

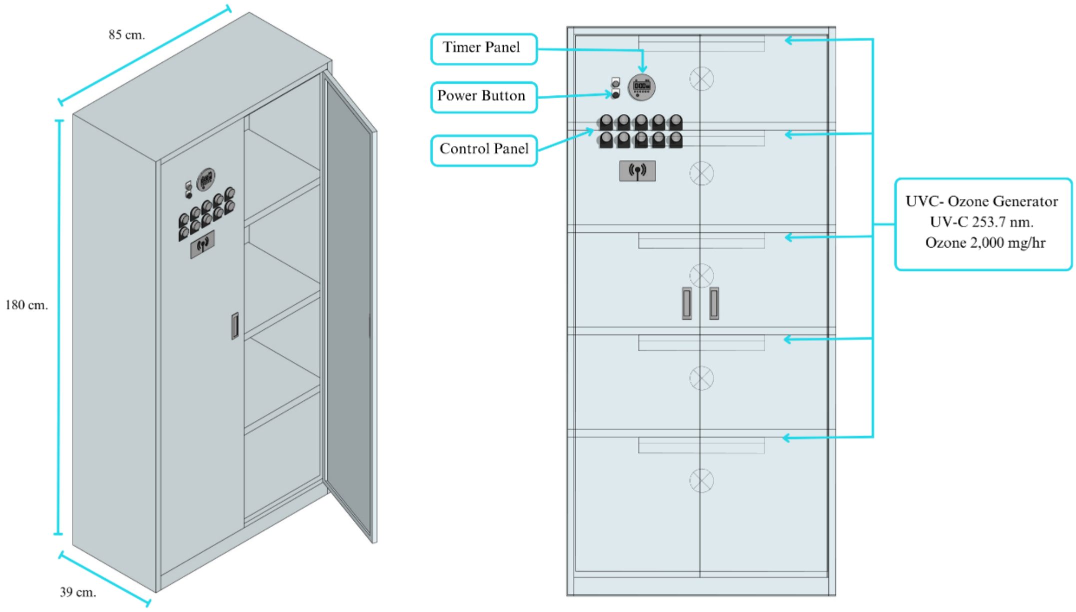

Figure 1. Disposable face mask waste sterilization machine using the AOP Process

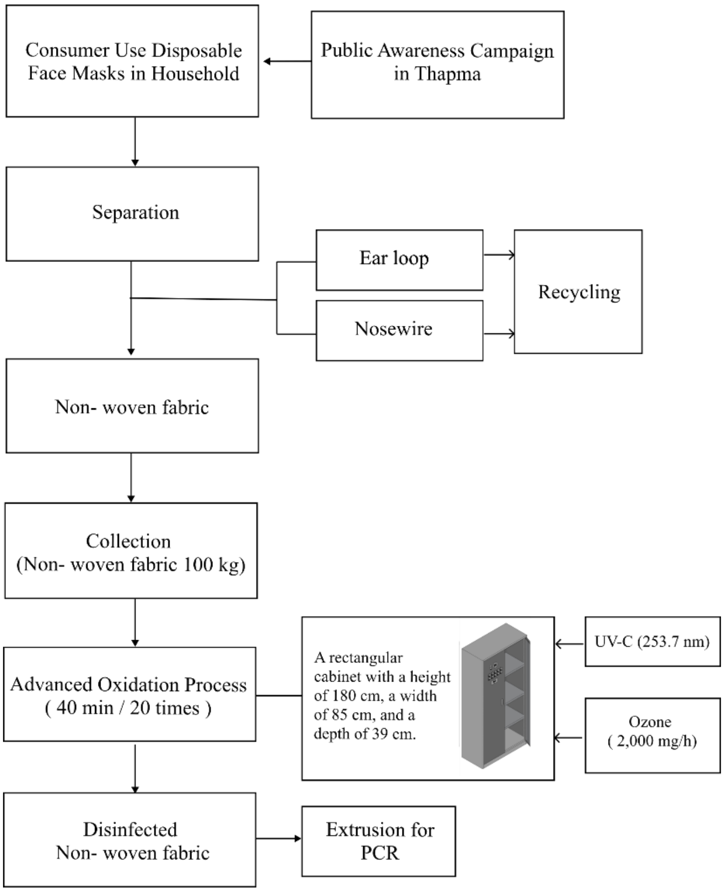

Figure 2. Management of disposable face mask waste in the community using the AOP

2.2. Extrusion Process

The Extrusion Process is a widely used manufacturing technique in the polymer industry [16]. In this process, raw materials are mixed in a 1:9 ratio, with 100 kg of nonwoven fabric from face masks and 900 kilograms of Polypropylene (PP) flakes. The mixture is then processed into plastic strands using an extruder at a temperature of 230°C for 30 minutes, with 500 kg processed per batch. After extrusion, the plastic strands are cooled in water for 30 minutes and then cut into pellets. These pellets are packaged into 1,000 kg bags. The production process includes air pollution treatment using a Wet Scrubber system and wastewater treatment using chemicals: 0.1920 kg of hydrogen peroxide and 0.1210 kg of acetic acid (Figure 3).

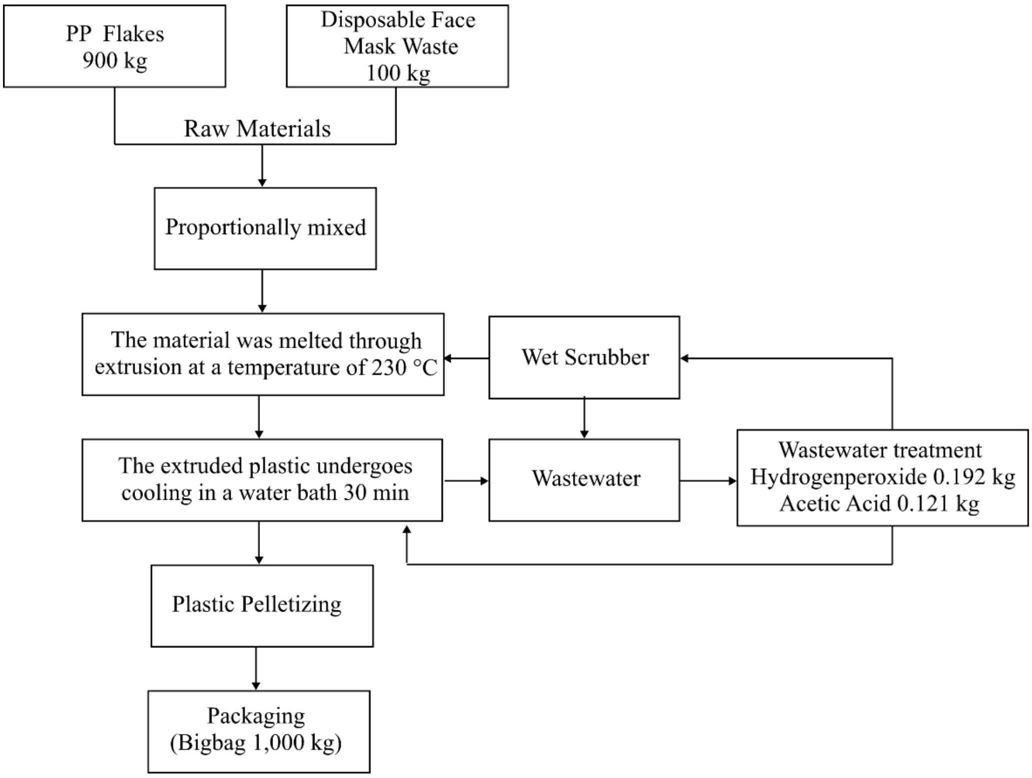

Figure 3. Extrusion Process of PCR

2.3. Life Cycle Assessment (LCA)

LCA consists of four stages: (i) goal and scope, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and (iv) interpretation of results [17] (Figure 4). LCA is a tool used to analyze and assess the environmental impacts of products and processes throughout their entire life cycle (Curran, 2016). It is a comprehensive and standardized method that is widely used and trusted to support decision-making in environmental management and sustainable development [18]. LCA is also part of the ISO 14000 (14040) standards [19].

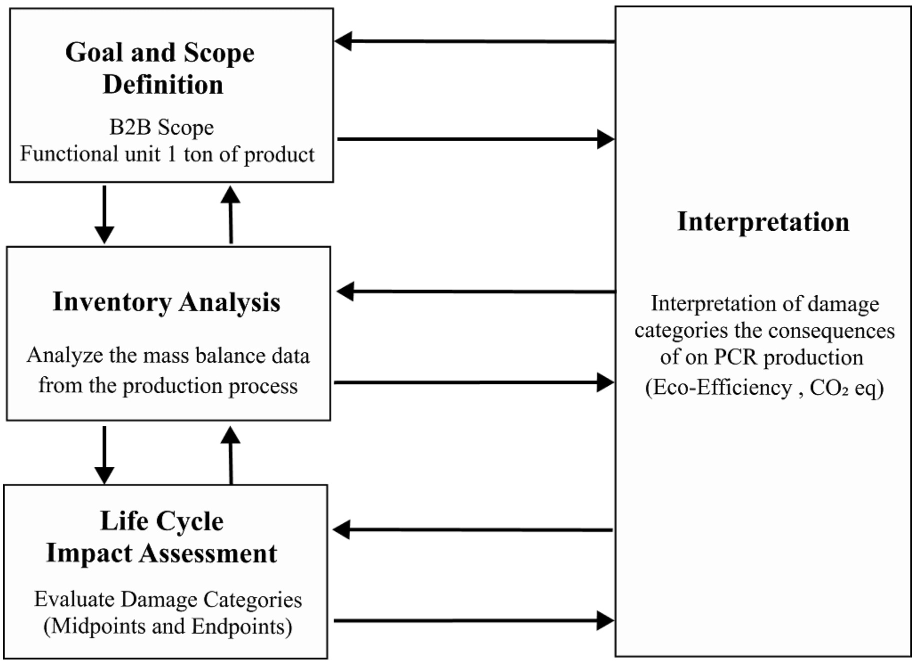

Figure 4. Study on Life Cycle Impact Assessment of PCR Products Made from Disposable face mask waste

- *Goal and Scope*

The first step in the LCA assessment is to define the goals and objectives of the evaluation. This includes determining the scope of the system assessment, which involves identifying the circular economy product system made from used disposable face mask waste to be analyzed, as well as specifying the environmental impacts to be assessed [20] ISO 14041 standards.

- *Life Cycle Inventory (LCI)*

Environmental inventory accounting is a process that involves Material Flow Analysis (MFA), which systematically analyzes the direction and quantity of target materials within a defined area and timeframe, based on the Mass balance Principle. The data for each process includes the flow of materials and resources at different stages, such as raw material acquisition, Transportation, product manufacturing, usage, disposal, recycling, and reuse, using standard units for measuring materials [21]. It also includes the allocation of environmental impacts that occur within the product system. This step is crucial for understanding resource usage and the environmental burdens associated with each stage [22].

- *Life Cycle Impact Assessment (LCIA)*

Environmental impact assessment throughout the life cycle of a product involves calculating the environmental impacts using data on the inputs and outputs of all related processes, from raw material acquisition, production processes, product distribution, usage, and end-of-life waste management, including Transportation. The energy usage data in the PCR production process is measured in terms of the function unit (FU), which is defined as 1 ton of production. The environmental impact analysis of the PCR product life cycle is evaluated through damage categories, focusing on stages like the PCR production process using the Extrusion Method. This includes classifying and quantifying impacts on various environmental indicators, such as global warming potential [23]. The selection of impact categories involves integrating midpoint impact assessment and endpoint impact evaluation. This study uses the ReCiPe 2016 method to assess impacts at two levels: midpoint indicators and endpoint indicators, as this method provides a comprehensive evaluation of health, ecosystem, climate change, and resource use impacts. It allows for flexible impact categorization and can be applied to national and regional data. The results are processed using the open-source software OpenLCA Version 2.0, developed by Green Delta which is widely used environmental impact assessment research [24].

- *Interpretation*

Interpretation is the process of combining t inventory analysis and impact assessment to draw conclusions and recommendations that align with the study's goals, objectives, and scope accurately and thoroughly [25]. A systematic environmental impact analysis will lead to the identification of ways to identify maximum efficiency and effectiveness.

2.4. Eco-Efficiency

Eco-efficiency is a concept that promotes sustainable development by focusing on the efficient use of natural resources, reducing environmental impacts, and enhancing economic competitiveness as a new business model for circular economy products [26]. The Eco-efficiency assessment approach has been established as an international standard within the environmental management standards series Life cycle assessment (LCA) process based standard on the ISO 14044 standard. The phases of Eco-efficiency assessment consist of five steps (as shown in Figure 5.):

- Goal and Scope Definition of Eco-efficiency (including defining the scope of the assessment, interpretation, study, and identifying study limitations);
- Environmental Assessment;
- Product System Value Assessment;
- Quantification of Eco-efficiency;
- Interpretation of Results.

The main equation used to calculate eco-efficiency is shown in the Equation 1.

$$\text{Eco Efficiency} = \frac{\text{Product system value}}{\text{Environmental impact of a product system}} \tag{1}$$

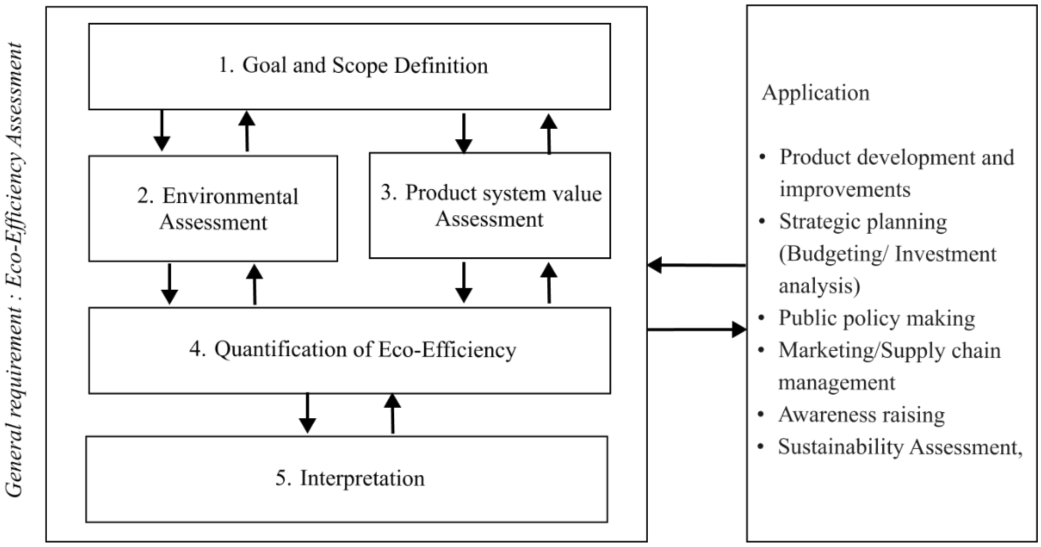

Figure 5. Eco-efficiency based on ISO 14045

3. Results and Discussion

3.1. Management of Disposable Face Mask Waste with AOP Method

The community has cooperated in the sorting and collection of used face mask parts, which are then delivered to the collecting by the local municipality. The collected masks undergo a sterilization process using the AOP (Advanced Oxidation Process) method, specifically UV-Ozone, which is an effective disinfection method capable of killing various pathogens including bacteria, viruses, fungi, and protozoa. Additionally, it is an environmentally friendly method that does not leave harmful residues [27]. The UVC wavelength of 280 nm is most effective at eliminating the 2019 coronavirus, and an ozone concentration of 20 ppm for 40 minutes can disinfect disposable face masks waste contaminated with the influenza A virus. Ozone is highly effective against various microorganisms, including viruses and bacteria, and can significantly reduce viral activity [28]. In this research, the sterilization process uses UVC radiation at a wavelength of 253.7 nm and ozone at 2,000 mg/h for 40 minutes in a face mask sterilizer, patented under number 2103003631 on December 13, 2021. This sterilizer can process up to 5 kg of face masks per cycle. A study on the sterilization effectiveness of this device found that it effectively eliminated *Staphylococcus aureus* at a concentration of 106 CFU/ml on face masks within 30 minutes [29]. The principle of combining ozone and ultraviolet light (O_3 /UV) in removing organic pollutants involves a photochemical oxidation process that occurs under visible or ultraviolet light. The process begins with the photolysis of ozone, followed by a reaction between oxygen atoms (O·) and water to form hydroxyl radicals. The O_3 /UV process has developed rapidly due to its mild reaction conditions (ambient temperature and pressure) and high oxidative power. The direct production of hydroxyl radicals proceeds as follows:

$$O_3 + UV \rightarrow O\cdot + O_2 \quad O\cdot + H_2O \rightarrow 2OH\cdot \quad 2O\cdot + H_2 \rightarrow OH\cdot + OH\cdot \quad 2OH\cdot \rightarrow H_2O_2$$

Ozone disinfection is a method with high potential for effectively destroying pathogens, using only 0.1 kWh of electrical energy per cycle. This method is more cost-effective compared to others, such as microwave disinfection, which requires high temperatures ranging from 177°C to 540°C and consumes a significant amount of electrical power [30], or using a low-heat autoclave, which operates at temperatures between 95°C and 180°C and has high system investment costs [31]. The AOP method combines the disinfecting properties of UV light with the oxidizing ability of ozone, making it ideal for disinfecting surfaces and medical equipment [32].

3.2. Life Cycle Analysis (LCA)

- *Goal and Scope*

The scope of the LCA is defined by using data on resource use, energy, and the release of various waste forms, covering all stages throughout the life cycle of the waste product, specifically disposable face mask. The scope is set for a B2B (Business-to-Business) evaluation, covering everything from the acquisition of raw materials to the production process. The processes evaluated include the management of collected used face mask waste in the area, followed by disinfection using AOP, and recycling into plastic pellets via the Extrusion process (Figure 6). This study defines the functional unit as 1,000 kg of PCR, and data is collected for 1 year (from January 1, 2023, to December 31, 2023).

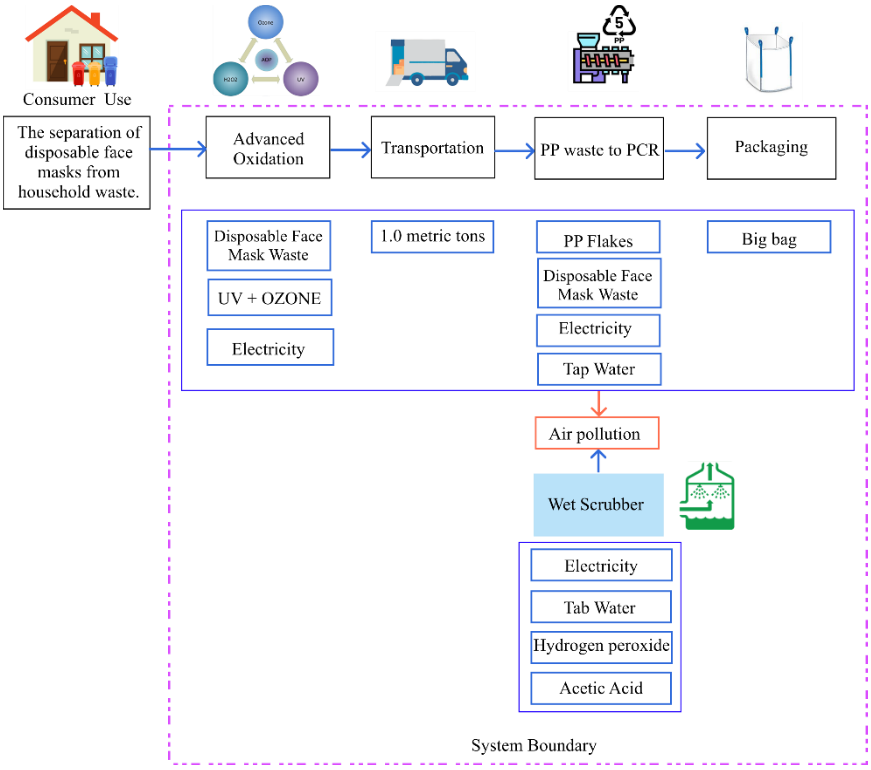

Figure 6. The scope of the study is the LCA of disposable face mask waste management

- *Life Cycle Inventory (LCI)*

The structure of disposable face masks is divided into three parts: a 3-layer nonwoven fabric (PP), a nose strip, and ear loops. Disposable face masks are made from polypropylene (PP), with the nose strip consisting of a 0.5 mm diameter aluminum wire coated in white plastic. The ear loops are made from spandex fabric. In the impact calculation process, only the 3-layer nonwoven fabric portion is considered after separating the nose strip and ear loops. The collected PP nonwoven fabric material is processed through the AOP and transported to a PCR manufacturing plant, where it is mixed with PP flakes, plastic scraps, and processed in a plastic extrusion machine (Waste Plastic Recycling). The extrusion temperature for PP ranges from 166 to 168°C [33] to produce plastic pellets, which are then bagged for sale. A Petty Patent for recycled polypropylene plastic pellets containing disposable face masks as part of the mixture was granted with patent number 2403001648 on June 5, 2024. The data for compiling the material flow accounting includes inputs, such as raw materials, energy, and utilities, and outputs, such as water pollution, air pollution, and waste. The researcher conducted fieldwork and gathered data from the plastic recycling plant, covering raw material acquisition, plastic pellet production processes, transportation, and product storage (Appendix). This data was used to create a Product Systems Model Graph in Open LCA 2.0 software for calculating the environmental impact, as the ReCipe 2016 method is shown in Figure 7.

- *Life Cycle Impact Assessment (LCIA) and Interpretation of Results*

1) The Results of the Environmental Impact Assessment at the Mid-Point Category.

The environmental impacts resulting from the comparative life cycle of PCR at the midpoint level for expression as percentages of total impact in each category in one Functional Unit (FU) are shown in Figure 8. The chart helps to evaluate and compare the relative effect between the different types of PCR from disposable mask waste. It is the highest greenhouse gas was from human non-cancer toxicity (HNCT), measured at 65.0471 tons of 1,4-DCB, which poses a significant health risk to humans, especially vulnerable populations. Research indicates that exposure to contaminated food and water sources increases health risks, particularly affecting the central nervous and endocrine systems [34]. The second-highest impact was from marine toxicity (MET), measured at 40.6915 tons of 1,4-DCB. This pollution includes various toxins, such as heavy metals, plastics, chemicals produced by humans, oils, municipal and industrial waste, pesticides, fertilizers, pharmaceutical chemicals, agricultural runoff, and wastewater, with over 80% originating from land-based sources. These pollutants pose significant risks to marine life and human health [35]. The third-highest impact was from global warming potential (GW), measured at 22.3297 tons of CO_2 eq. Global warming has widespread effects on ecosystems, human health, and the economy, disrupting sustainable development [36]. The fourth-highest impact was on soil toxicity (TE), measured at 13.9061 tons of 1,4-DCB. Toxic properties can be passed along the food chain [37]. The fifth-highest impact was fossil resource scarcity (FRS), measured at 6.6301 tons of oil eq. Fossil resource scarcity significantly impacts environmental sustainability, economic stability, and energy use patterns. As demand for fossil fuels rises due to population growth and economic expansion, increased resource use leads to higher greenhouse gas emissions and environmental degradation [38].

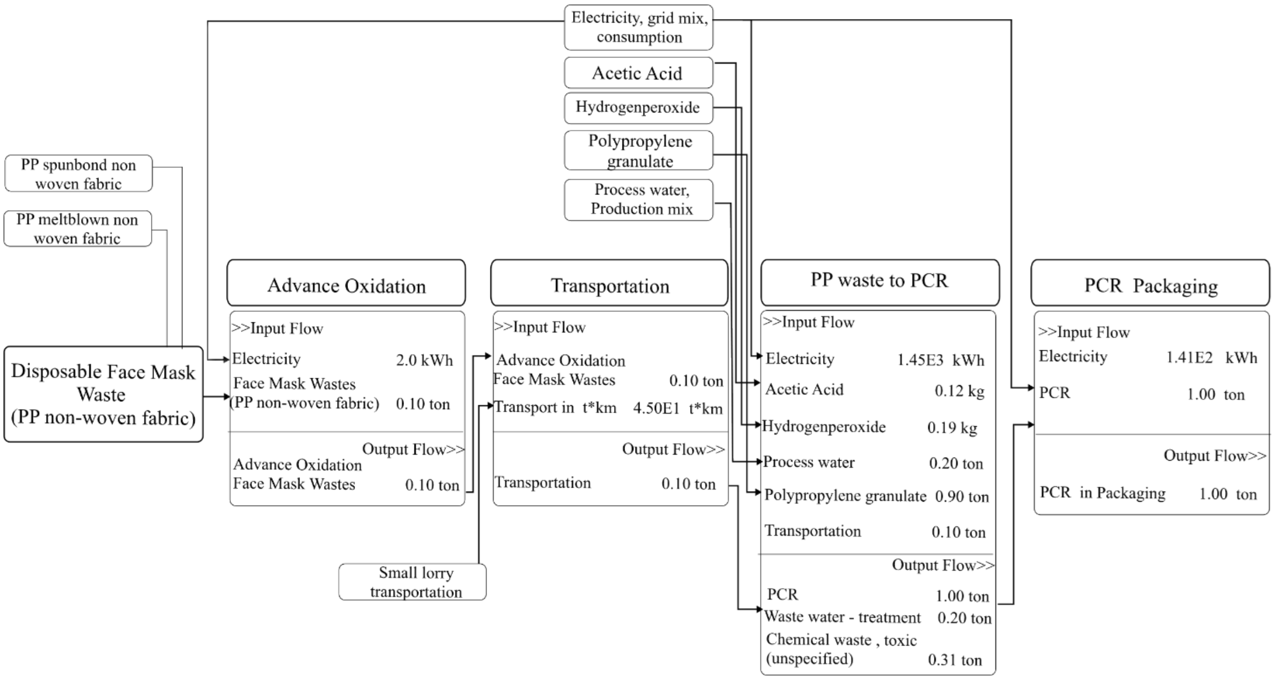

Figure 7. the Model graph of product systems PCR

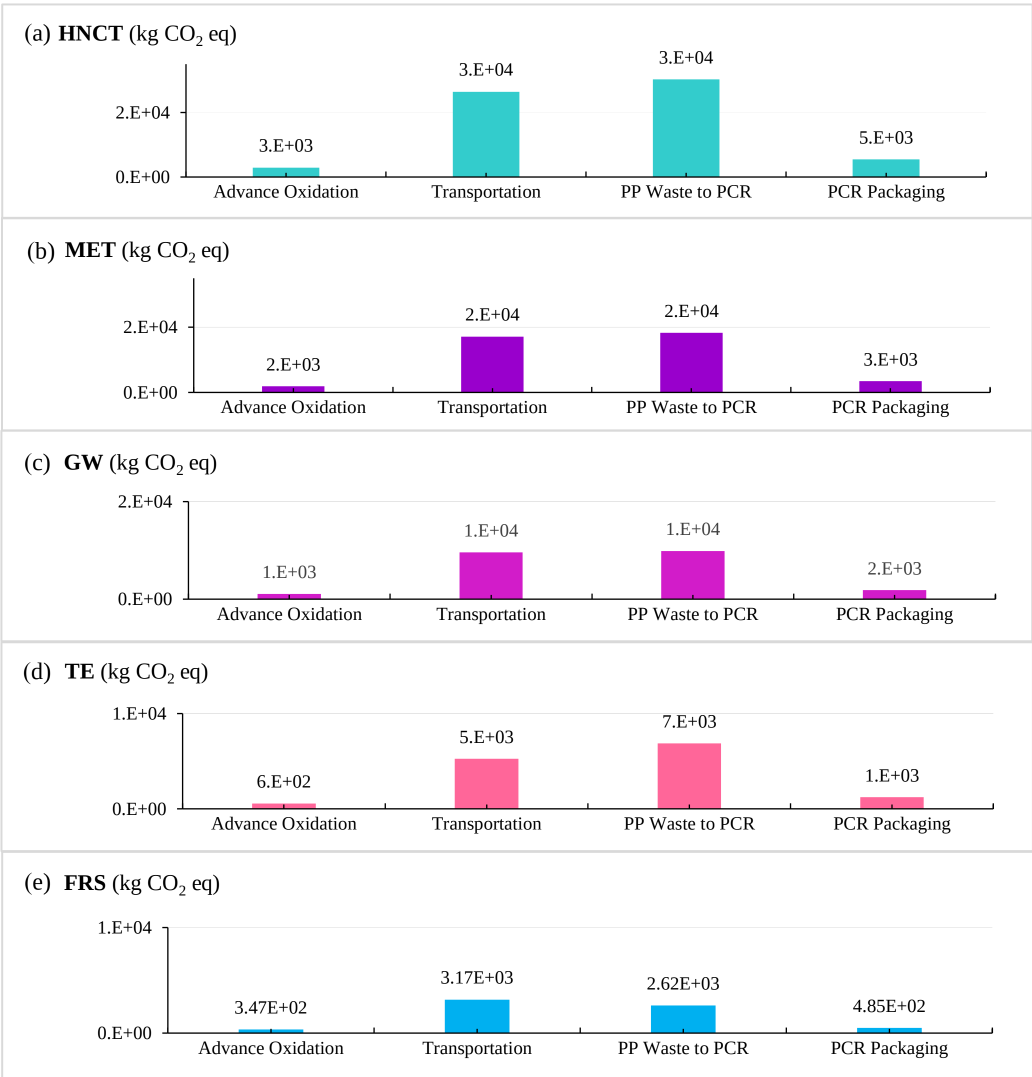

Figure 8. Flow model of life cycle assessment of greenhouse gas emissions from PCR production

The comparison of mid-point environmental impacts across the life cycle assessment of PCR reveals that the highest impact is from the PP Waste stage to the PCR process (45.5%) and Transportation (41.6%). The PCR packaging process has a total impact of 8.4%, while the advanced oxidation process has the lowest impact, contributing only 4.5%, as shown in Figure 9. The PCR processing and transportation had the highest environmental impact in fossil resource scarcity, electricity consumption, and global warming potential. This is mainly due to the excessive transportation fuel and the subsequent release of greenhouse gas.

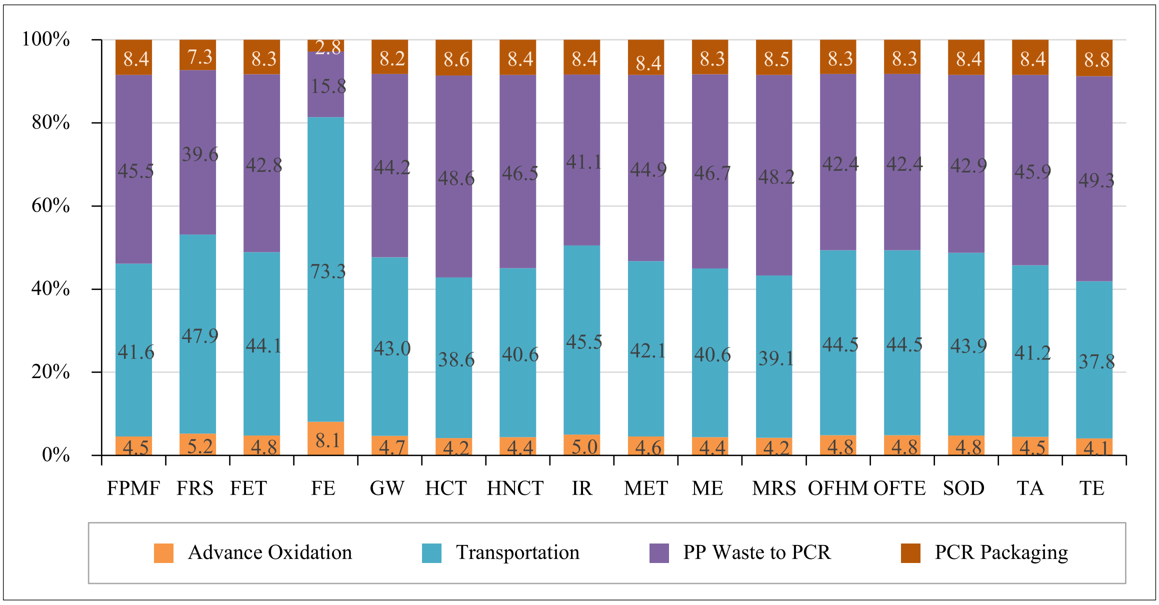

Figure 9. The comparison of mid-point environmental impacts across the life cycle of PCR

2) *The Results of the Environmental Impact Assessment at the Endpoint Category (Figure 10).*

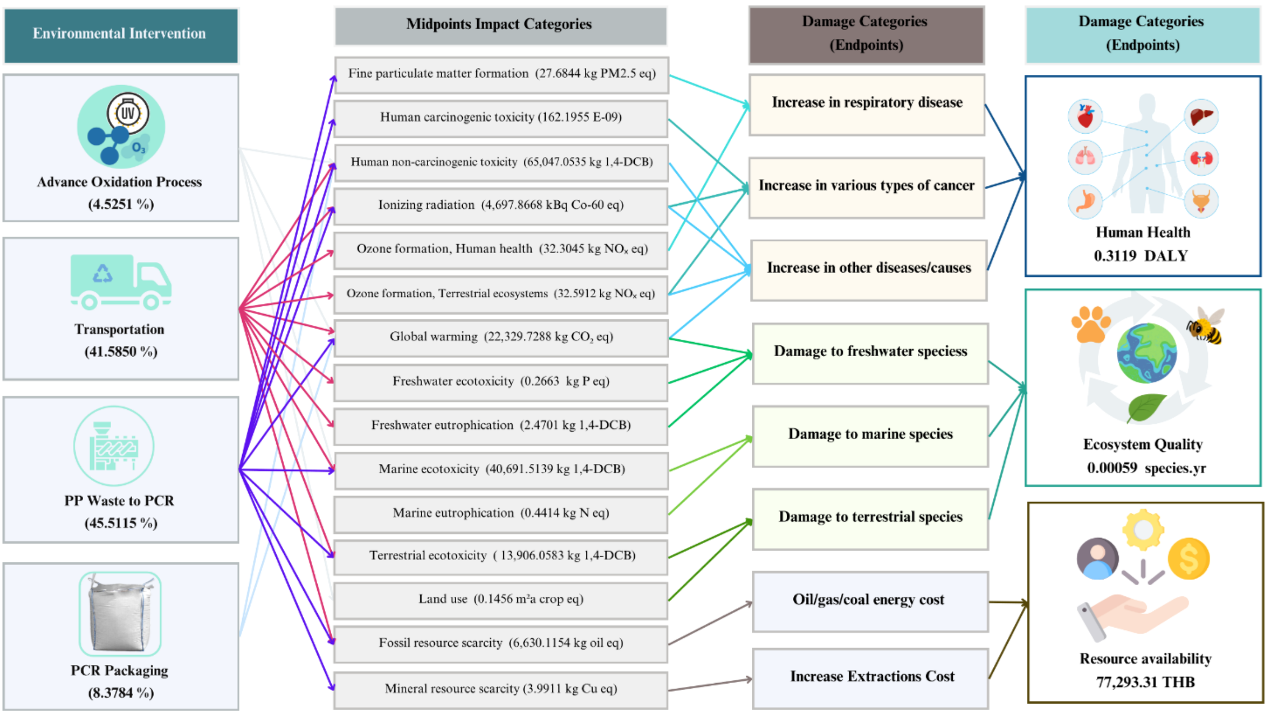

Figure 10. The relationship between the impacts occurring from the Midpoints and the Endpoint

- The total human health damage (Human Health) is equal to 0.3119 DALYs (Disability-Adjusted Life Years), meaning that humans lose 0.3119 years of healthy life due to diseases and injuries. Global warming has the highest impact on human health, accounting for 89.4623%. It is anticipated that global warming will lead to severe health issues, particularly among vulnerable groups, including heat-related illnesses and diseases spread by vector insects due to changes in the ecosystems of disease vectors [39]. The second most significant impact is from the formation of fine particulate matter (fine particulate matter formation), at 5.5716%. Research has shown that exposure to $PM_{2.5}$ is associated with the premature deaths of 135 million people worldwide from 1980 to 2020, which has worsened due to climate variability [40]. Long-term exposure to $PM_{2.5}$ can lead to chronic diseases [41]. The third-highest impact is from human non-carcinogenic toxicity (4.7457%), where toxins can interfere with enzyme function and damage DNA, leading to various health problems [42]. Understanding these impacts is crucial for developing strategies to mitigate these effects.

- The total ecosystem quality damage (Ecosystem Quality) measured at 0.00059 species per year, which means the loss of 0.00059 species per square meter over the span of one year. The LCA evaluation emphasizes the necessity of using indicators related to species richness to enhance relevance and ecological comparison ability [43]. The highest impact comes from global warming on terrestrial ecosystems, accounting for 95.0086%. This significantly stimulates greenhouse gas emissions from the soil, with notable increases in CO_2 and N_2O across different ecosystems [44], contributing to the intensification of climate change. The second most significant impact is terrestrial acidification, at 3.4395%. Acidification reduces the soil's ability to absorb phosphorus in plants [45]. The pH of the soil affects N_2O emissions, with moderate acidity promoting higher emissions [46-50]. The CE approach focuses on products and ecosystem services, striving to create a balance between human needs and ecosystem stability.
- The total impact of resource scarcity (Resource Availability) on the economy and society is valued at 77,293.31 THB. This result primarily stems from the indicator of fossil resource scarcity, which is a key raw material in plastic pellet production and transportation processes. Dependence on fossil fuels causes significant social impacts, including job creation and tax revenue, but also presents health risks and environmental degradation. Increased fossil fuel consumption correlates with higher greenhouse gas emissions, which intensify climate change. The scarcity of such fuels may lead to higher energy prices, affecting the product lifecycle and business viability, impacting GDP and household consumption, thus creating both economic and social consequences. Although fossil resources are essential for economic activities, their depletion poses severe risks to both the economy and the environment, making a shift to more sustainable alternatives necessary.

3.3. Eco-Efficiency

The scope of the eco-efficiency assessment is to evaluate the production cost of plastic pellets made from disposable face masks waste. This can be considered based on the production volume and the use of production factors for the year under study. Primary data was obtained from a PCR plastic pellet manufacturing industry in Chonburi province. The data covers production over one year (January 1, 2023–December 31, 2023). The production volume of PCR was 1,460.4970 tons, with a sales value of 30.6704 million THB (PCR price: 21,000 THB/ton). Raw material usage was 1,474.3950 tons, energy consumption was 1,767.0300 MW, water consumption was 1,091.1700 m^3, and waste generation (recyclable) was 104.6770 tons. The greenhouse gas (GHG) emissions from production over the year totaled 32,612.5019 tons CO_2 eq.

The assessment of the eco-economic efficiency of PCR production analyzes data regarding environmental impacts such as greenhouse gas emissions, energy consumption, raw material usage, and waste generation. The results are presented in Table 1.

Table 1. Eco-economic efficiency (production volume per production factor)

Production Volume	Unit	Eco-Efficiency
Raw material	ton product / ton	0.9906
Energy usage	ton product / MW	0.8265
Water consumption	ton product / m^3	1.3385
Waste generation	ton product / ton	13.9524
GHG emission	ton product/ ton CO_2 eq	0.0448

The eco-economic efficiency is analyzed based on the amount of product produced per quantity of production factors or resources used each year to demonstrate how efficient the system or production process is in utilizing resources. In 2023, the factory was able to produce 1,460.4970 tons of PCR. The results of the analysis are as follows:

- Raw Material Usage: The eco-economic efficiency of raw material usage in production is 0.9906 tons of product per ton of raw material. This means that for every 1 ton of raw material used, 0.9906 tons of product are produced, with a material loss of only 0.0094 tons (or 0.94%). In other words, to produce 1 ton of product, 1.0095 tons of raw material are required.
- Energy Usage: The eco-economic efficiency of energy usage is 0.8265 tons of product per MW of energy. This shows that 1 MW of energy can produce 0.8265 tons of product, or one ton of product; 1.2099 MW of energy is needed. This indicates that energy usage could be more efficient.

- Water Consumption: The eco-economic efficiency of water usage is 1.3385 tons of product per m³ of water. This shows that one m³ of water can produce 1.3385 tons of product, or to produce 1 ton of product, 0.7471 m³ of water is required. This indicates that water usage is relatively efficient.
- Waste Generation: The eco-economic efficiency of waste generation is 13.9524 tons of product per ton of waste. This means that for every 1 ton of waste generated, approximately 13.9524 tons of product are produced. Therefore, to produce 1 ton of product, only 0.0717 tons of waste are generated. This shows that waste generation is relatively low, and the system is efficient.
- Greenhouse Gas Emission: The eco-economic efficiency of greenhouse gas emission is 0.0448 tons of product per ton of CO_2 eq. This means that for every 1 ton of CO_2 equivalent emitted, 0.0448 tons of product are produced. For a total production of 1,460.4970 tons of product, 32,600.3795 tons of CO_2 eq will be emitted.

The business model for recycling polypropylene plastic from disposable face mask waste aims to address the environmental issue of mask waste, which is hard to decompose and negatively impacts the environment. The model focuses on producing high-quality recycled plastic pellets that can be used in various industries, promoting a circular economy and reducing greenhouse gas emissions. This will allow green businesses to compete in the market sustainably.

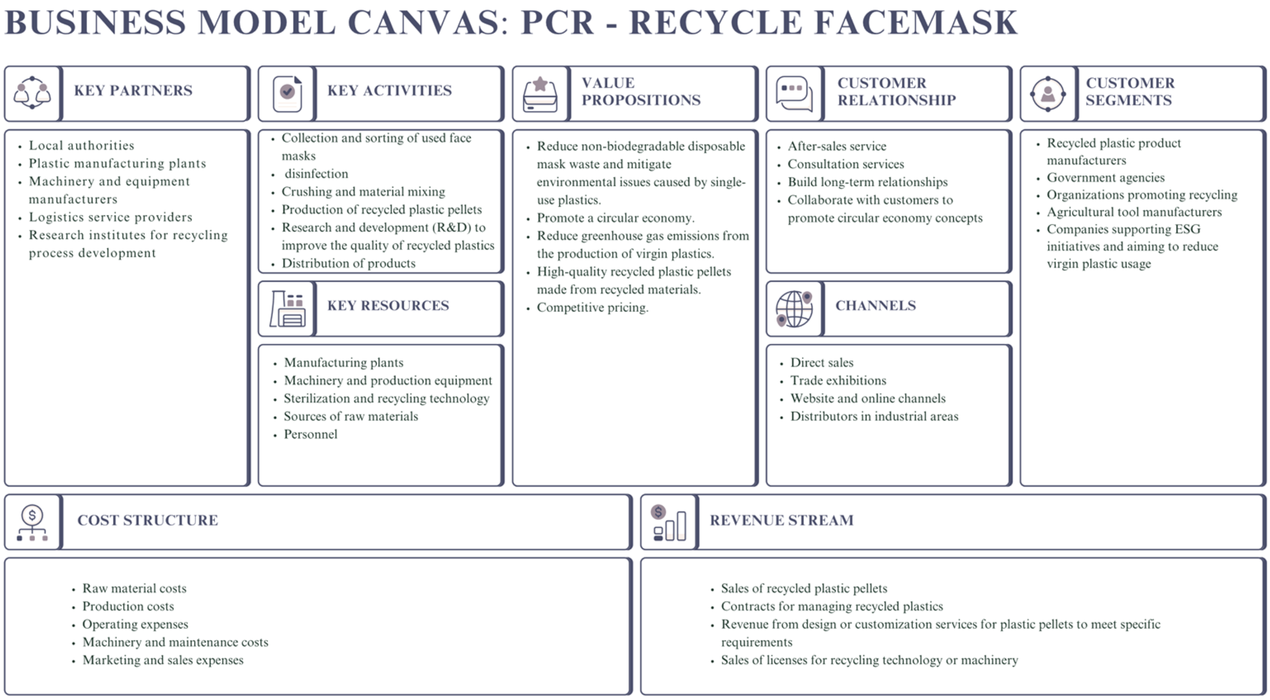

Figure 11. Green Business Model of Circular Economy Products (CEP)

4. Conclusion

Recycling Disposable face mask waste into post-consumer recycled (PCR) plastic pellets align with circular economy (CE) principles by reducing microplastic pollution, extending mask lifecycles, and decreasing reliance on virgin materials. This approach supports economic sustainability in line with SDG 12 by lowering production costs, creating jobs in the recycling sector, and promoting resource efficiency. Disinfecting masks through advanced oxidation processes (AOP) ensures worker safety and hygiene, enhancing social sustainability. Although the PCR production stage has the highest environmental impact, integrating renewable energy and clean technologies can reduce emissions and improve efficiency. Optimizing logistics by establishing collection points closer to production facilities, using clean energy for transportation, and defining efficient routes can further reduce CO_2 emissions, supporting SDG 13 and SDG 3. Life cycle assessments (LCA) and Eco-efficiency analyses provide reliable evaluations of environmental and economic impacts, though challenges in LCA standardization remain. This recycling model can be applied to other hazardous waste, offering policymakers a practical approach to mitigate environmental impacts while raising public awareness about sustainable practices. Extended Producer Responsibility (EPR) policies play a crucial role in CE, requiring producers to manage waste throughout the product lifecycle. Proper material separation, economic incentives for returning used packaging, and gradual implementation of realistic fees can enhance participation and minimize resistance from low-income households. In conclusion, recycling used face masks into PCR plastic pellets addresses environmental, social, and economic challenges. This model supports CE principles, aligns with SDGs, and provides a framework for sustainable waste management. By adopting renewable energy, clean technologies, and EPR strategies, industries and policymakers can reduce environmental impacts, promote sustainability, and drive systemic change.

5. Declarations

5.1. Author Contributions

Conceptualization, S.S., K.S., and D.B.; methodology, R.C. and K.S.; software, S.W.; validation, K.S., D.B., and T.K.; formal analysis, S.S. and K.S.; investigation, S.S.; resources, S.W.; data curation, S.W.; writing—original draft preparation, S.S.; writing—review and editing, K.S., R.C., and S.J.; visualization, K.S. and S.S.; supervision, K.S., R.C., and T.K.; project administration, K.S.; funding acquisition, K.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Acknowledgments

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5.5. Institutional Review Board Statement

Not applicable.

5.6. Informed Consent Statement

Not applicable.

5.7. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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