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Mathematical Model for Circular Economy Prospect Analysis: Processing Low-Value Plastic Waste into High-Value Products and Minimizing Environmental Impacts

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Abstract: *The prospects for a circular economy in the management of low-value plastic waste are highly promising, offering environmental solutions alongside substantial economic opportunities through innovative recycling into high-value products. Such an approach can transform challenges into economic opportunities, create employment, conserve natural resources, and reduce pollution through technological innovation. Mathematical modeling plays a crucial role by integrating data on costs, revenues, technologies, waste reduction, and environmental impacts, including emissions, thereby supporting strategic decision-making, scenario simulation, and investment justification to achieve economically viable and sustainable systems with minimal negative impacts. This study aims to analyze the prospects of a circular economy in processing low-value plastic waste into high-value products while minimizing environmental impacts using mathematical modeling approaches, including flow and mass balance models, economic models such as cost–benefit and profitability analysis, and environmental impact minimization models. The results provide quantitative estimates of material flows entering, being processed within, and exiting the plastic waste management system, measures of financial feasibility based on cost and revenue variables, and environmental impact metrics derived from life cycle assessment (LCA). Overall, this research contributes a robust quantitative framework for predicting the economic and environmental implications of circular plastic recycling and offers data-driven solutions to optimize waste-to-value processes while simultaneously reducing environmental pollution.*

Keywords: **Mathematical model, circular economy, plastic waste, cost–benefit analysis, life cycle assessment.**

1. INTRODUCTION

Plastic waste is a serious global environmental issue due to its highly persistent nature, requiring hundreds of years to decompose. It pollutes soil, freshwater, and marine environments, threatens ecosystems and human health through microplastic contamination, causes flooding by clogging waterways, and generates air pollution when burned. Indonesia is currently the world's second-largest contributor to marine plastic waste, with plastic waste generation continuing to increase annually [1]. Mitigation efforts include regulatory measures such as plastic bag bans, environmental awareness campaigns, the development of circular economy–based recycling systems, and innovations in waste management. Indonesia produces millions of tons of waste every day, with plastic accounting for approximately fourteen to seventeen percent of total waste. This corresponds to an estimated nine million tons of plastic waste per year, much of which is inadequately managed and ultimately released into the environment [2].

The environmental impacts of plastic waste are severe, encompassing soil, water, and air pollution; harm to wildlife through entanglement and ingestion; degradation of marine ecosystems such as coral reefs; and risks to human health as microplastics enter the food chain, potentially causing diseases including cancer and reproductive disorders. Plastic degradation is extremely slow, and open burning releases toxic dioxins that exacerbate pollution. In Indonesia, awareness of plastic waste mitigation remains relatively low, as reflected in improper disposal practices, limited understanding of long-term impacts, insufficient waste management infrastructure, and low levels of active public participation, despite general awareness of plastic-related environmental problems. Addressing these challenges requires a combination of government regulation, industrial innovation, and sustained public education starting from an early age, supported by multi-stakeholder collaboration [3].

From an economic perspective, plastic waste can be classified into high-, medium-, and low-value categories depending on plastic type (such as HDPE, LDPE, PP, and PET), material purity, and processing requirements. Clean rigid plastics such as HDPE and PET often have high recycling value, while soft plastics such as LDPE bags have moderate value and require advanced processing methods like pyrolysis. Mixed or multilayer packaging, such as sachets, is typically low-value and difficult to recycle; however, ongoing innovations aim to convert such materials into construction materials or creative products to enhance their economic value. The prospects of a circular economy for low-value plastic waste are highly promising but face significant challenges. The core objective is to transform “waste” into economically valuable raw materials—such as fuels, handicrafts, and recycled products through recycling, reuse, and refurbishment. This approach has the potential to reduce waste volumes by up to fifty percent and generate economic opportunities worth trillions of rupiah in Indonesia, although it requires substantial investment, public education, adequate collection infrastructure, shifts in societal behavior, and strong governmental support to overcome supply chain constraints [4].

Mathematical modeling for a circular economy that upgrades low-value plastic waste into high-value products involves the integration of material flow analysis, economic valuation (costs and revenues), and environmental impact assessment. Commonly applied approaches include optimization models (linear and non-linear), system dynamics, life cycle assessment (LCA), and economic input–output models to identify the most efficient recycling or upcycling pathways that maximize profit while minimizing waste. Key variables include collection costs, market prices of processed products, technological efficiency, and policy incentives. Mathematical models play a critical role in circular economy engineering, particularly in the design of machinery and systems for processing low-value plastic waste into high-value products, as they enable process optimization, efficiency prediction, return on investment (ROI) estimation, waste minimization, and material flow modeling. This ensures technological feasibility, economic viability, reduced environmental impacts, and value creation from previously non-valuable plastic waste [5].

Numerous studies on circular economy engineering have been conducted, ranging from local implementation models such as integrated agriculture systems in East Kalimantan to household waste utilization through eco-enzyme production, as studied by Arenibafo [6], and broader applications of the Reduce, Reuse, Recycle (3R) principle and product redesign to maintain material value. These efforts emphasize technological innovation to create closed-loop systems that reduce waste and regenerate natural resources, as promoted by the Ellen MacArthur Foundation and analyzed in international scientific journals such as those indexed by ScienceDirect. Related studies include Mukhlis et al. [7], who initiated a local circular economy model through integrated agriculture in Karangwidoro Village during the COVID-19 pandemic; Fatonah et al. [8], who examined eco-enzyme production from household waste for public health benefits; Indiran et al. [9], who explored the role of circular economy, mindset, and education in sustainable economic development; Judijanto [10], who emphasized technological innovation in maximizing material potential within a circular economy; and Indra et al. [10], who focused on reducing plastic waste volumes while creating new economic value and conserving natural resources.

Based on this background, this study aims to analyze the economic potential of converting low-value plastic waste into high-value products using circular economy principles while minimizing negative environmental impacts through innovative recycling processes such as pyrolysis. These processes involve collection, sorting, shredding, and molding into functional products such as fuels or other value-added products to support local economic and ecological sustainability. The analysis of circular economy prospects for low-value plastic waste transformation employs mathematical models for cost–benefit optimization and life cycle assessment (LCA) for environmental impact evaluation. The findings indicate that transforming plastic waste into value-added products such as pyrolysis fuels, plastic pellets, or construction materials is highly advantageous from both economic and environmental perspectives.

2. PRELIMINARIES

2.1 Characteristics of Plastic Waste

According to Szostak et al. [12], the characteristics of plastic waste include its durability, light weight, chemical resistance, ease of molding, insulating properties, and difficulty to decompose (non-biodegradable), making it a serious environmental problem because it can persist for hundreds of years and break down into harmful microplastics. Plastics are made from synthetic polymers (such as PE, PP, PVC, and others) that can be formed into various products; however, many are designed for single use and contain potentially hazardous chemicals, such as PET, which can release antimony trioxide when exposed to heat. The physical and chemical properties of plastic waste include:

a) Durability and resistance to degradation: Difficult to decompose naturally, persisting in the environment for long periods, and breaking down through photodegradation (UV radiation) or biodegradation (microorganisms) into smaller particles (microplastics).
b) Lightweight and water-resistant: Low weight makes it easy to transport, and it is impermeable to water.
c) Insulating properties: Poor conductor of heat and electricity.
d) Ease of molding: Flexible and easily shaped into various products (bottles, bags, packaging).
e) Chemical resistance: Generally non-reactive and resistant to chemical substances.

Low-value plastic waste includes types of single-use plastics that are difficult to recycle and have low market demand due to high processing costs, such as flexible packaging (sachets, snack wrappers), used plastic bags, and small plastic cups (bottled drinking water containers) contaminated with food residues. These materials are often the largest contributors to environmental pollution. Nevertheless, such waste can potentially be processed into high-value products such as plastic asphalt, carts, or construction materials.

2.2 Circular Economy Model

Referring to Shien [13], the Circular Economy Model is a sustainable economic system that aims to eliminate waste and pollution by keeping products, components, and materials at their highest value for as long as possible, in contrast to the linear "take–make–dispose" economy. This is achieved through repair, reuse, refurbishment, and recycling, which extend product life cycles, optimize resource use, and create economic growth aligned with environmental sustainability. The prospects of the circular economy are very promising, offering green economic growth, the creation of new jobs (especially green jobs), and business innovation by transforming waste into valuable resources, encouraging cost efficiency, and reducing pressure on natural resources and greenhouse gas emissions, supported by national policies and technological advances, although its implementation in Indonesia still requires improvement. This represents a strategic shift from the linear “take–make–dispose” model toward a system that reuses, repairs, and recycles for long-term sustainability.

The circular economy strongly fosters the creative economy by transforming waste into valuable resources, stimulating innovation in new products and services (such as recycling waste into pillows or fertilizer), creating sustainable business models, encouraging cross-sector collaboration, and opening new business opportunities for MSMEs, especially in creative industries such as culinary and handicrafts, by utilizing creativity to redesign environmentally friendly products and packaging, generating new economic value while preserving nature. How the circular economy drives the creative economy includes:

a) Product innovation from waste: Transforming residual materials (plastic, organic waste) into new value-added products (pillows, compost, handicrafts), which requires creative ideas.
b) New business models: The emergence of platforms and businesses focused on repair, rental, or recycling (such as Back-source) creates new creative sectors.
c) Increased value added: Through creative design and marketing, recycled products can gain higher attractiveness and better prices.
d) Empowerment of MSMEs and communities: Providing opportunities for MSMEs and local communities to create unique products from local materials, increasing their income.
e) Cross-sector collaboration: Bringing together designers, creative industry actors, environmental experts, and communities for innovative solutions, for example collaboration between ITS visual communication design students and waste processors.
f) Focus on sustainable design: Encouraging designers to create products that are durable, easy to repair, and easy to recycle (3R/5R principles).

The circular economy opens many new job opportunities by shifting linear consumption patterns toward models that retain product and resource value, creating jobs in sectors such as sustainable design, repair, recycling, circular logistics, and waste management, and encouraging social innovation that requires more local and skilled labor than traditional automated industries, with the potential to create millions of new jobs in Indonesia. Types of jobs created include:

a) Sustainable product design: Designing products to be durable, repairable, and recyclable.
b) Repair and maintenance: Jobs focused on repairing products instead of discarding them (repair, refurbishment).
c) Material collection and sorting: Collecting and sorting waste materials for reprocessing.
d) Circular manufacturing: Reprocessing recycled materials into new products.
e) Logistics and digital technology: Tracking secondary raw material supply chains and managing circular systems.
f) Social innovation: Community-based movements to reduce waste and promote household efficiency, creating local jobs.

The prospects of the circular economy for transforming low-value plastic into high-value products are highly promising and transformative, offering environmental solutions as well as new economic opportunities through innovation, smart design, and advanced recycling, which can reduce waste, create valuable resources, and drive green economic growth in Indonesia, although it requires appropriate investment and policies [14].

2.3 Environmental Sustainability

Environmental sustainability refers to the responsible management of natural resources to prevent degradation, achieved through energy-efficient lifestyles, waste reduction based on the 3R principles of reduce, reuse, and recycle, the use of environmentally friendly transportation, and active participation in reforestation and waste management initiatives. The environment is essential for the survival of all living beings, as humans, animals, and plants cannot exist without it. However, environmental degradation continues to occur, largely as a result of irresponsible human activities. A sustainable and healthy environment is one that meets present needs without compromising the ability of future generations to meet their own needs. It is characterized by clean air, clear water, and minimal pollution and is supported by the consistent application of 3R practices, energy and water conservation, the use of green transportation, and effective waste management systems, all of which aim to maintain ecological balance and human quality of life [15].

The relationship between the circular economy and the environment is very close, as the circular economy offers a fundamental solution to environmental crises such as climate change, pollution, and biodiversity loss. It replaces the “take–make–dispose” model with closed-loop systems that minimize waste, maximize resource efficiency, and protect ecosystems through the principles of reduce, reuse, and recycle, as well as durable product design. This approach reduces the extraction of natural resources, lowers carbon emissions, enhances ecological resilience, and creates new sustainable economic opportunities. Although the primary objective of the circular economy is environmental improvement, its implementation may still pose certain environmental challenges, such as potential pollution from inefficient recycling processes, energy demands for circular infrastructure, and logistical complexities in material management. Nevertheless, overall impacts are substantially more positive than those of linear economic models, as circular systems promote efficient resource use, reduce landfill waste, and support environmental regeneration [16].

2.4 Mathematical Models for the Circular Economy and Environmental Impacts

Referring to Sessa et al. [17], mathematical models for a circular economy that converts low-value plastic waste into high-value products involve material flow modeling (mass balance), cost–benefit analysis, efficiency assessment, and environmental impact evaluation (such as carbon emission reduction). These models incorporate variables such as raw material prices (waste), processing costs (pyrolysis or extrusion), final product prices (fuel or other uses), and waste volumes.

The mathematical model for calculating the quantity of material entering, being processed within, and exiting the circular economy system is formulated using Equation (1):

$$M_{input} = M_{collected} + M_{aditif}, \quad (1)$$

where M_{input} represents the amount of plastic waste entering the circular economy process as input material, $M_{collected}$ collected denotes the amount of plastic waste for sorting, and M_{aditif} denotes the amount of plastic waste that cannot be utilized in the circular economy process. The mathematical model for calculating the production process is expressed using Equation (2):

$$M_{output} = M_{final\_product} + M_{residu} \quad (2)$$

Furthermore, mathematical models for cost–benefit and profitability analysis are developed using the following equations. To calculate revenue from the sale of final products, Equation (3) is used:

$$TR_{\text{sales}} = P_{\text{sell}} \times M_{\text{final\_product}}, \quad (3)$$

Where TR_{sales} represents total revenue from final product sales, P_{sell} denotes the unit selling price of the final product, and $M_{\text{final\_product}}$ represents the quantity of final products sold. Next, the operational cost of the circular economy process is calculated using Equation (4):

$$TC_{operational} = C_{mat\_unit} \times M_{input} + C_{\text{processing}} \times M_{input} + C_{labor\_others}, \quad (4)$$

Where TC_{op_unit} denotes the total operational cost of the circular economy process, C_{mat_unit} represents the material cost per unit, $C_{\text{processing}}$ represents the processing cost of circular economy activities, and C_{labor_others} represents labor costs, including other additional costs. Profit can then be calculated using Equation (5):

$$TP_{profit} = TR_{sales} - TC_{operational} - C_{investment}, \quad (5)$$

Where TP_{profit} represents total profit and $C_{investment}$ represents the initial investment cost of circular economy activities. Finally, the Cost–Benefit Ratio (BCR) is calculated using Equation (6):

$$BCR = \frac{TP_{profit}}{TC_{operasional}}, \quad (6)$$

where a BCR value greater than 1 indicates that the project is feasible, a value less than 1 indicates infeasibility, and a value equal to 1 requires further consideration because revenue equals cost [18]. Mathematical modeling for minimizing environmental impacts is conducted using Life Cycle Assessment (LCA) metrics or emission calculations, as expressed in Equation (7):

$$\Delta E_{emisi} = E_{\text{new\_prod\_process}} + E_{\text{old\_stockpiles}} \quad (7)$$

Minimizing the environmental impacts of a circular economy is critically important because it shifts the system from a linear model (take–use–dispose) to a closed-loop cycle that reduces waste sent to landfills, conserves natural resources, lowers greenhouse gas emissions, and protects biodiversity by keeping materials within the production cycle. This approach supports the creation of more sustainable systems and green economic growth while reducing pollution and dependence on the extraction of new natural resources [19–20].

3. MATERIALS AND METHODS

3.1 Materials

To analyze the prospects of a circular economy for processing low-value plastic waste into high-value products, the primary materials include case studies of recycling communities or companies, data on the volume and types of plastic waste, processing technologies such as pyrolysis and mechanical recycling, market analysis of final products, policy and regulatory frameworks, and analytical methodologies including Life Cycle Assessment (LCA) and economic analysis to measure environmental and economic impacts.

1) Waste Data and Analysis: Specific data on plastic types (PET, HDPE, LDPE, etc.) and the quantity of low-value plastic waste in the study area, including waste

characteristics, composition analysis, contamination levels, and potential processing difficulties.

2) Technology and Processes: Shredders, washing units, and extruders to produce plastic pellets; chemical recycling technologies such as pyrolysis; thermal processes that convert plastics into multifunctional boards; and product innovation involving the design of high-value final products such as construction materials, furniture, and creative products.
3) Economic and Market Aspects: Cost analysis covering collection, sorting, processing, and marketing stages; value-added analysis comparing material value before and after processing; and market analysis assessing demand for recycled products such as handicrafts and secondary raw materials.
4) Circular Economy and Environmental Framework: Application of the 3R principles (Reduce, Reuse, Recycle) as the basic framework for circularity, relevant policies and regulations including government rules and incentives at national and local levels, and case studies of circular economy actors (for example, Recycle Goods) to understand business models and operational challenges.

3.2 Methods

To analyze the prospects of a circular economy for converting low-value plastic waste into high-value products while minimizing environmental impacts, this study applies Life Cycle Assessment (LCA) to evaluate environmental impacts, Cost–Benefit Analysis (CBA) to assess economic feasibility, SWOT analysis for strategic evaluation, and approaches such as Design for Recycling (DfR) and upcycling. These methods are supported by case studies and mathematical modeling to validate technologies such as pyrolysis or chemical recycling for converting plastic waste into high-value fuels or chemical products, while considering policy contexts and stakeholder engagement.

1) Strategic and Potential Analysis
    a. SWOT Analysis (Strengths, Weaknesses, Opportunities, Threats): Identification of internal strengths such as technological innovation, weaknesses such as production scale limitations, opportunities including market demand, and threats related to raw material prices and regulatory constraints.
    b. Case Studies and Modeling: Analysis of recycling industry case studies (for example, Recycle Goods) to understand practical implementation, challenges, and solutions, combined with mathematical modeling for process optimization.
2) Economic Analysis
    a. Cost–Benefit Analysis (CBA): Comparison of operational costs, including collection, machinery, and labor, with revenues from high-value products such as fuels, monomers, and functional products, as well as external benefits such as pollution reduction and job creation.
    b. Business Model Analysis: Use of frameworks such as the Business Model Canvas to map value propositions, customer segments, and revenue streams within the circular economy ecosystem.
3) Technology and Design Approaches
    a. Upcycling and Chemical Recycling (Pyrolysis, Depolymerization): Application of advanced methods to convert low-value plastics, such as mixed plastics, into high-value products including fuels or monomers for new plastics, rather than downcycling.
    b. Design for Recycling (DfR): Analysis of product design to ensure materials are easier to recycle from the early stages of the product life cycle.
4) Policy and Social Aspects
    a. Policy and Regulatory Analysis: Examination of government policies that support circular economy implementation, such as tax incentives, as well as policies that may hinder it, including licensing requirements and standards.

b. Stakeholder Engagement: Mapping the roles of government, industry, communities, and non-governmental organizations within the circular economy ecosystem to ensure long-term sustainability.

5) Environmental Impact Analysis
Assessment of environmental impacts from cradle to grave, or cradle to cradle within a circular system, including carbon dioxide emissions, energy consumption, and waste generated from collection, sorting, processing (for example, pyrolysis), and final products, compared with virgin plastic production.

By integrating these methods, the analysis comprehensively evaluates the feasibility and impacts of a circular economy for processing low-value plastic waste, thereby encouraging innovation toward sustainability.

4. RESULTS AND DISCUSSION

4.1 SWOT Analysis

SWOT analysis is essential for identifying the circular economy potential of processing low-value plastic waste into high-value products while minimizing environmental impacts. This analysis highlights strengths such as waste reduction and resource conservation, weaknesses related to technology and infrastructure, opportunities for product innovation and job creation, and threats associated with regulatory barriers or unsupportive consumer behavior. Together, these factors inform strategies for sustainable and economically viable waste management.

1) Strengths
Reduction of landfill waste volumes and environmental pollution in soil and water; decreased dependence on virgin raw materials derived from fossil fuels; creation of economic value by converting plastic waste into high-value inputs for new products; and job creation in collection, sorting, and processing sectors.
2) Weaknesses
High initial investment requirements for advanced recycling facilities; significant operational costs associated with sorting and processing; and quality challenges, as low-value plastics are often mixed and difficult to process into high-quality products.
3) Opportunities
Product innovation through the development of creative and functional products such as multifunctional boards; supportive regulations and tax incentives for circular economy initiatives; growing market demand for sustainable products; and cross-sector collaboration among communities, government, and the private sector.
4) Threats
Fluctuations in virgin plastic prices that may reduce the competitiveness of recycled products; limited consumer awareness regarding waste sorting and support for recycled products; and inadequate regulations due to weak policy enforcement.

SWOT analysis is important because it provides a strategic roadmap for transforming low-value plastic waste into economic assets, addressing challenges through innovation, and minimizing environmental impacts, thereby supporting the transition from a linear "take–make–dispose" model to a sustainable circular system.

4.2 Economic Analysis

Economic analysis of circular economy activities aims to assess financial feasibility and impacts by examining costs, revenues, and profits from the perspectives of individuals, firms, and initial investment requirements. In this study, the economic analysis is conducted based on material flow analysis (mass balance) and cost–benefit analysis, as described in Section 2.4.

As an illustration, suppose that based on data from a circular economy process that converts plastic waste into multipurpose boards, it is obtained that the amount of waste material collected is $M_{collected}$ = 100,000 kg/month, and catalytic additives or chemical substances are M_{aditif} =1%×100,000 kg/month = 1,000 kg/month. Therefore, referring to equation (1), the amount of plastic waste input is:

$$M_{input} = 100{,}000 \text{ kg/month} + 1{,}000 \text{ kg/month} = 101{,}000 \text{ kg/month}$$

It is also known that the conversion efficiency is 80%, with the final product produced (in the form of recycled plastic boards) amounting to $M_{final\_product}$ = 95,000 kg/month, and residue in the form of ash and other materials amounting to M_{residu} = 19,000 kg/month. Thus, referring to equation (2), the resulting material output is:

$$M_{output} = 95{,}000 \text{ kg/month} + 19{,}000 \text{ kg/month} = 114{,}000 \text{ kg/month}$$

If the price of plastic waste is C_{mat_unit} = IDR 500/kg, the cost of the circular economy process is $C_{\text{processing}}$ = IDR 2,000/kg, other costs are IDR 1,500,000/month, and the selling price of plastic boards is P_{sell} = IDR 10,000/kg. Referring to equation (3), the total revenue is obtained as:

$$TR_{\text{sales}} = \text{IDR } 10{,}000 \times 95{,}000 = \text{IDR } 950{,}000{,}000 \text{ /month}$$

Referring to equation (4), the total operational cost of the circular economy activity is:

$$TC_{operational} = \text{IDR } 500 \times 101{,}000 + \text{IDR } 2{,}000 \times 101{,}000 + \text{IDR } 1{,}500{,}000 = \text{IDR } 1{,}010{,}000{,}000$$
$$= \text{IDR } 254{,}000{,}000 \text{ /month.}$$

Therefore, the circular economy activity generates a monthly profit that can be calculated by referring to equation (5):

$$TP_{profit} = \text{IDR } 950{,}000{,}000 \text{ /month} - \text{IDR } 254{,}000{,}000 \text{ /month} = \text{IDR } 696{,}000{,}000$$

Finally, the Cost Benefit Ratio (BCR) analysis, calculated using equation (6), yields:

$$CR = \frac{\text{IDR } 696{,}000{,}000}{\text{IDR } 254{,}000{,}000} = 2.74$$

Since the resulting BCR is greater than 1, the project is considered highly feasible for further development and wider implementation.

4.3 Applying the Technology and Design Approach

The technology and design approach to transforming low-value plastic waste into high-value products, in this case multipurpose boards, focuses on recycling innovations such as the ecobrick method, which compacts plastic into multipurpose boards, as well as integration with other materials (e.g., steel) to create competitive composites that combine functional aspects (boards) with aesthetic value and circular economy principles.

The technological approach includes: Ecobricks, namely compacting non-organic plastic waste into plastic bottles until they are highly dense for use as non-structural building materials (furniture, gardens, partitions). Chemical recycling (pyrolysis), which involves heating plastics without oxygen to break them down into oil, gas, or other chemical substances that can then be processed into raw materials for composite boards. Molding/extrusion (mechanical recycling), which melts plastics, mixes them with additives or other materials (e.g., wood powder, sawdust), and then molds them into board shapes. Composite technology, which mixes recycled plastic flakes (HDPE, LDPE, etc.) with natural fibers (bamboo, rice husks) to increase strength and reduce dependence on new materials.

The design approach includes: Sustainable product design, which creates boards that not only function as building materials but also have aesthetic value, modular design, and are easy to assemble and disassemble (circular economy principles). Modular and functional design, which produces boards with standard sizes that can be combined for various uses, from furniture (tables, chairs) to architectural elements (floors, walls). Aesthetics and texture, which utilize the natural colors of plastic or add pigments and special textures so that the boards have an attractive appearance, rather than merely being perceived as “recycled plastic.” Participatory design, which involves communities in the design and production process (e.g., ecobrick making in schools) to increase ownership and environmental awareness.

Examples of products and designs include plastic waste processed into multipurpose boards in the form of board sheets, as shown in Figure 1.

Figure 1. Multipurpose Board Sheets

Plastic–steel composite boards combine the strength of steel with the load-bearing durability of recycled plastic for decking boards or outdoor furniture, such as garden tables and chairs, as shown in Figure 2.

Figure 2. Garden Table–Chair Set

Ecobrick furniture includes tables, benches, or partition walls made from arranged and bound ecobrick bottles, as shown in Figure 3.

Figure 3. Tables and Partition Walls

Recycled sandwich boards consist of a core layer of recycled plastic with outer layers of other materials for strength and aesthetics, such as recycled plastic boards for building roofs, as shown in Figure 4.

Figure 4. Recycled Plastic Boards for Building Roofs

4.4 Policy and Social Aspects

Processing low-value plastic waste into multipurpose boards within a circular economy framework involves policy aspects (supportive regulations, EPR, incentives) and socio-economic aspects (job creation, local economic improvement, environmental awareness, and community empowerment through schemes such as waste banks). Together, these aspects reduce waste, conserve natural resources, and encourage innovation and green economic growth in Indonesia, in line with sustainable development goals.

Policy aspects include: Government regulation and support, where central government policies through the 3R (Reduce, Reuse, Recycle) program and the implementation of Extended Producer Responsibility (EPR) are key to integrating plastics into the circular economy cycle rather than ending up in landfills. Incentives and cooperation, where governments need to provide incentives for recycling innovation and encourage partnerships between industry (such as plastic asphalt or biofuel programs) and communities to manage waste effectively. Standard development, which involves establishing quality standards for recycled products such as plastic boards to increase market value and consumer trust.

Socio-economic aspects include: Job creation and economic growth by activating the waste collection, sorting, and processing sectors and creating new markets for recycled products, thereby increasing community income and local economic growth. Community empowerment and awareness through initiatives such as waste banks that turn waste into savings, educate residents to sort waste at the source, and raise collective awareness of waste management. Innovation and value addition by transforming plastic waste previously considered worthless into construction materials (multipurpose boards) with high economic value, minimizing the negative impacts of waste on the environment (marine and terrestrial), and conserving natural resources. SDGs harmonization supports the achievement of the Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 14/15 (Life Below Water/Life on Land), by creating an economic model that decouples growth from natural resource consumption.

Implementation (Multipurpose Boards) includes models aligned with innovations such as Waste Banks and “Bank Receh” schemes that convert plastic waste into boards or other materials, integrating economic aspects (savings) with environmental education simultaneously. The goal is to create a strong circular plastic value chain in which plastic waste is no longer an environmental problem but a valuable resource in the production of new materials, such as building boards or road construction materials.

4.5 Environmental Impact Analysis

Processing low-value plastic waste into multipurpose boards within a circular economy framework provides significant positive impacts, such as reducing waste accumulation in landfills and conserving natural resources by reducing the need for new raw materials, while also creating economic value from waste. However, challenges include process energy consumption, potential greenhouse gas (GHG) emissions if not well managed, and ensuring sustainability and production scale so that plastic impacts are truly reduced on a massive level, in line with the principles of reduce, reuse, and recycle to minimize environmental damage.

Positive impacts include: Waste reduction by diverting plastics from landfills and the environment, reducing soil, water, and marine pollution, as well as adverse effects on wildlife. Resource conservation by reducing dependence on virgin plastic raw materials, saving valuable natural resources, and lowering exploitation. Economic value creation by transforming waste into valuable products (multipurpose boards), creating new jobs in the processing sector, and stimulating green economic growth. Climate change mitigation by reducing GHG emissions from waste that decomposes in landfills or is openly burned.

Challenges and potential negative impacts include: Energy and chemical consumption, where recycling processes (shredding, molding) require energy and possibly chemicals that, if inefficient, may cause environmental impacts. Emissions from transportation and production, as waste transport and board production require energy that may generate emissions if non-renewable energy sources are used. Residual waste, where not all plastics can be processed into boards (e.g., due to contamination), leaving residual waste that still needs to be managed and may again become an environmental problem. Mathematical modeling for environmental impact minimization analysis is conducted using equation (7).

As an illustration, based on information during the recycling process to produce plastic board products, the process generates 1.2 kg C_2e per kg of product, while the production of new plastic generates 3.0 kg CO_2e per kg of product. Plastic waste stockpiling before processing generates 0.5 kg CO_2e per kg of product (methane). Therefore, if the collected amount =100,000 kg/month is processed, it will result in new process emissions of:

$E_{\text{new\_prod\_process}}$ = 3.0 kg CO_2e/kg × 100,000 kg/month = 300,000 kg CO_2e/kg/month.

If $M_{collected}$=100,000 =100,000 kg/month is not processed (stockpiled), it will generate stockpiling emissions of:

$E_{\text{old\_stockpiles}}$= 0.5 kg CO_2e/kg × 100,000 kg/month = 50,000 kg CO_2e kg/month.

This process represents an effective circular economy model for addressing plastic waste problems by transforming them into valuable resources, in line with sustainability objectives. However, its effectiveness depends on energy efficiency, residual waste management, and the scale of implementation to ensure that it delivers significant and overall positive environmental impacts.

4.6 Discussion

The prospects of a circular economy for plastic waste processing are highly promising in addressing environmental crises and creating new economic value through recycling, reuse, and product innovation, although challenges related to infrastructure, regulation, and public awareness remain. Indonesia demonstrates governmental commitment and industrial support through policies such as the National Medium-Term Development Plan (RPJMN) and green economy campaigns, with major objectives of reducing waste sent to landfills and building new sustainable value chains that create jobs and reduce dependence on natural resources. The circular economy approach to processing plastic waste into multifunctional boards focuses on transforming waste into valuable products, closing material loops, reducing landfill use, and creating new economic opportunities; challenges lie in waste collection systems, sorting processes, and collaboration, while solutions include community education, recycling technologies, government incentives, and product design innovation, with significant potential to reduce plastic pollution and achieve the Sustainable Development Goals (SDGs). As the second-largest plastic waste producer in the world, Indonesia has substantial potential to adopt this circular economy approach, which aligns with SDG achievement and reduces the national burden of waste management.

The circular economy for processing plastic waste into multifunctional boards has strong potential to generate positive environmental impacts by reducing landfill waste, conserving natural resources, and fostering material innovation, as well as positive economic impacts such as job creation; however, implementation challenges and potential side effects such as emissions from recycling processes if not properly optimized must be addressed. Processing plastic waste into multifunctional boards within a circular economy framework can significantly reduce waste and natural resource use, but requires environmental impact analysis (LCA) to minimize risks such as toxic emissions, high energy consumption, and potential microplastic release from recycling processes, thereby ensuring that final products are truly environmentally friendly through product design, energy efficiency, and proper waste management in accordance with the 3R principles (Reduce, Reuse, Recycle). Overall, the circular economy approach to processing plastic waste into multifunctional boards is highly promising because it addresses environmental problems while creating economic value, generating employment, conserving resources, and aligning with sustainable development goals, making it a crucial solution that should be widely promoted.

Mathematical models for analyzing the circular economy of processing low-value plastic waste into high-value products directly support and contribute to several Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production), SDG 8 (Decent Work and Economic Growth), SDG 13 (Climate Action) through environmental impact minimization, and SDG 9 (Industry, Innovation, and

Infrastructure), as they create sustainable economic models, reduce waste, and drive industrial innovation. These models help realize longer product life cycles, reduce pollution, and create economic value from waste. Related SDGs include: SDG 12, focusing on waste reduction, recycling, and extending product life cycles through circular economy practices; SDG 8, creating new jobs in processing and recycling sectors and promoting sustainable green economic growth; SDG 13, reducing greenhouse gas emissions from conventional waste management (landfills) and improving resource efficiency; SDG 9, encouraging technological innovation in waste processing and developing circular economy infrastructure; and SDG 11, addressing urban waste challenges and creating cleaner environments. The role of mathematical models is to quantify these aspects, such as: (a) cost–benefit analysis to calculate investment versus economic returns from selling high-value products; (b) life cycle assessment (LCA) to evaluate total environmental impacts of recycling processes compared to conventional disposal; and (c) value-upgrading modeling to determine conversion ratios of low-value plastic waste into high-value products. Overall, these models serve as essential tools for implementing measurable circular economy principles to achieve global sustainable development goals.

5. CONCLUSION

The main conclusion of this study is that mathematical modeling successfully demonstrates that a circular economy approach to processing low-value plastic waste can serve as a sustainable solution, transforming waste into economically valuable products while reducing environmental impacts, although its implementation requires policy synergy, technological innovation, and community participation. The results show strong potential for creating new local economies, employment opportunities, and pollution reduction, provided that challenges such as land availability, capital, and technology can be addressed through multi-stakeholder collaboration. Key points of this study include: the potential of the circular economy, showing that recycling low-value plastics (such as packaging bottles) into high-value functional products (e.g., furniture and crafts) is economically feasible and profitable in line with circular economy principles; dual environmental benefits, reducing plastic waste pollution in land, water, and marine environments while decreasing dependence on virgin raw materials and emissions from primary plastic production; value creation, where plastic waste is no longer viewed as a burden but as a resource that can be processed into products with significant added economic value and job creation; the critical role of mathematical models in predicting financial feasibility, optimizing production processes (collection, sorting, processing), and minimizing environmental impacts at each stage as strategic decision-support tools; implementation challenges, including infrastructure limitations (land and machinery), capital constraints, and low public awareness that must be addressed through public–private partnerships and education programs; and the need for integrated solutions, as success depends on a holistic approach combining government regulation, recycling technology innovation, industrial support, and active participation from communities and consumers in reducing, reusing, and recycling. In summary, this model validates that the circular economy is an effective pathway for addressing plastic waste, transforming environmental problems into economic opportunities, while requiring systemic support to fully realize its potential.

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