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Development and Evaluation of an Eco-Friendly Plastic Waste Melter Using an Air Cleaner Water Bath System

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ABSTRACT

Background: Inadequate management and open combustion of plastic waste emit hazardous substances like dioxins and furans, posing significant risks to both environmental quality and human health.

Aims: This study aimed to develop and evaluate an eco-friendly plastic waste melting device equipped with an *Air Cleaner Water Bath (ACWB)* system as an alternative solution for reducing dioxin emissions during the plastic melting process.

Materials & Methods: An experimental pre-post test-only group design was conducted at the Health Polytechnic of Jambi. Dioxin concentrations were measured before and after the application of the ACWB system during the melting of three plastic types: bags, cups, and bottles. Gas analysis was conducted utilizing High-Resolution Gas Chromatography coupled with High-Resolution Mass Spectrometry (HRGC–HRMS). Data were statistically tested using the Wilcoxon signed-rank test and one-way ANOVA.

Results: The ACWB system significantly reduced dioxin concentrations across all plastic types. Mean emissions decreased from 0.25 to 0.12 ng.nm^{-3} for plastic bags, 0.29 to 0.09 ng.nm^{-3} for plastic cups, and 0.25 to 0.12 ng.nm^{-3} for plastic bottles (all p = 0.001). Post-treatment dioxin levels were below the national emission threshold of 0.1 ng.nm^{-3}. Unlike conventional wet scrubbers and activated carbon filters, the ACWB operates using a simple water-lime mixture, offering cost efficiency, ease of use, and effective chemical neutralization without the need for complex circulation or frequent material replacement.

Conclusion: The modified plastic waste melter with ACWB is a promising alternative for reducing toxic emissions. It demonstrates effective and affordable dioxin control, with potential applications in safer, small-scale plastic waste processing.

Keywords: Air Pollutants; Dioxins; Equipment Design; Plastics; Water Pollutants; Waste Management.

CITATION LINKS

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Introduction

Plastic waste, especially plastic bags, has become one of the major sources of environmental pollution [1]. Plastic is a non-biodegradable material, taking between 100 and 500 years to decompose completely. Plastic waste can contaminate soil, water, oceans, and air, creating widespread environmental impacts [2]. Polyethylene terephthalate (PET) is one of the most widely used plastics, particularly in the production of disposable plastic bags.

Global plastic consumption continues to increase. In the United States, plastic usage reaches 38 million kilograms per day, with a relatively well-managed waste management system. In contrast, in Indonesia, of the 11 million kilograms of plastic consumed daily, around 9 million kilograms end up as unmanaged waste [3–5]. This condition makes Indonesia one of the world's most significant contributors to plastic waste [4,5].

Efforts to utilize PET plastic waste through melting technology have been widely studied. For instance, the utilization of PET in plastic pellets during the heating process shows a calorific value of 3,472 $J.kg^{-1}$ at temperatures ranging from 120°C to 180°C [6]. However, most existing plastic melting equipment lacks a smoke capture system, resulting in the release of harmful emissions, including dioxins, carbon monoxide, and microplastic particles [7]. These emissions not only pollute the air but also pose health risks to communities in the vicinity of the operational area.

Moreover, many communities in Indonesia continue to engage in the open burning of plastic waste as a common method of disposal. Although this method reduces waste volume, it produces hazardous substances, such as dioxins and furans, which are toxic and can cause respiratory problems and increase the risk of cancer [8,9]. The burning of plastic also contributes to carbon dioxide emissions, worsening air pollution and damaging the ozone layer [10,11]. Unfortunately, most previous studies on plastic melting technology have not adequately addressed sustainability and environmental safety aspects, especially regarding the control of harmful emissions generated during the melting process [12]. This study presents an innovative approach to plastic waste management by developing an environmentally friendly melting technology equipped with a smoke capture system. This innovation aims to provide a practical approach to addressing plastic waste challenges while promoting safer and more sustainable waste-handling practices that align with green development goals.

Materials & Methods

Study Design

The study employed an experimental approach using a pre-post test-only group design [13], which allowed for the assessment of dioxin (C4H4O2) concentrations generated during the plastic melting residue process.

Sampling

This research was conducted at the workshop of the Environmental Health Department of the Health Polytechnic of the Jambi Ministry of Health. The research sample consisted of dioxin gas ($C_4H_4O_2$) captured from the residual melting of plastic bags, plastic cups, and plastic bottles. The sampling technique involved eight repetitions, examining dioxin concentrations as follows: Three types of plastic (plastic bags, plastic cups, plastic bottles) x eight repetitions (0.5 hours, 1 hour, 1.5 hours, 2 hours, 2.5 hours, 3 hours, 3.5 hours, 4 hours) = 24 samples before passing through the clean water bath. Three types of plastic (plastic bags, plastic cups, plastic bottles) x eight repetitions (0.5 hours, 1 hour, 1.5 hours, 2 hours, 2.5 hours, 3 hours, 3.5 hours, 4 hours) = 24 samples

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after passing through the clean water bath. In total, 48 inspections were conducted: 24 before and 24 after the clean water bath.

Device Description and Development

The plastic waste melting device used in this study was a modified version of an existing plastic melter, specifically adapted to be more environmentally friendly. The modification involved the addition of an *Air* Cleaner Water Bath (ACWB), which functions to filter gas emissions generated during the melting process. The device consists of a melting chamber, a gas flow control system, and an ACWB that captures and neutralizes harmful emissions. The water used in the ACWB was mixed with quicklime at a concentration of 10% by volume, and the total volume of water used was 5 liters. A schematic diagram of the modified device is shown in Figure 1.

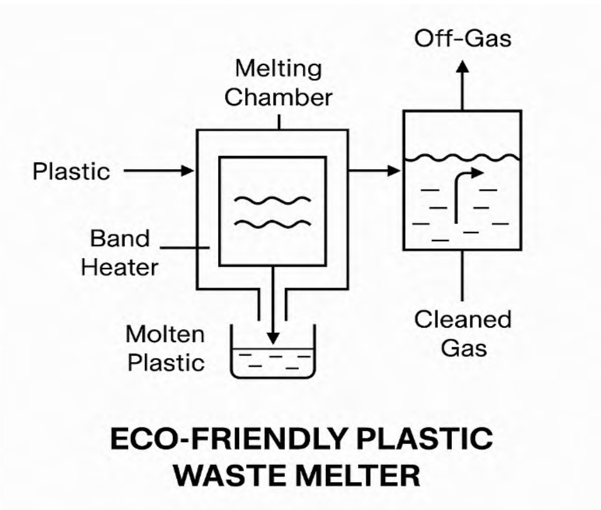

Figure 1) The air cleaner with a water bath system.

Measurement Method

Dioxin concentrations were analyzed using High-Resolution Gas Chromatography coupled with *High-Resolution Mass Spectrometry (HRGC–HRMS)*, specifically the Agilent 7890B GC system interfaced with a JEOL JMS-TQ4000GC HRMS detector. This instrument configuration was selected for its high resolution, sensitivity, and capability in trace-level quantification of dioxins. Before analysis, the system was calibrated using Certified Reference Materials (CRMs) by EPA Method 1613B for dioxin/furan analysis. Method validation included assessments of linearity (R^2 > 0.995), detection limits (LOD: 0.01 $ng.nm^{-3}$), quantification limits (LOQ: 0.03 $ng.nm^{-3}$), precision (CV < 10%), and accuracy (recovery rates between 85–115%).

Each analytical run included internal standards and quality control samples. Representative chromatograms and retention times for target dioxin congeners (e.g., 2,3,7,8-TCDD at ~21.4 minutes) were documented and are provided in the Supplementary Material (Table 1). These retention times were used to confirm peak identification in conjunction with mass spectral fragmentation patterns.

In Figure 2, two major peaks are observed at retention times of approximately 21.4 minutes and 25.7 minutes, indicating the presence of dioxin compounds. The peak intensities at both retention times show a significant reduction after treatment, reflecting the effectiveness of the ACWB system in reducing dioxin content in the products of the plastic melting process.

Data Collection

To understand the operation of the plastic melting tool, testing was conducted to gather data that would provide an overview of the tool's performance after modification. The

Table 1) Retention Times of Detected Dioxin Congeners in Plastic Bag Sample.

Congener	Approximate Retention Time (min)	Intensity (Before ACWB)	Intensity (After ACWB)
2,3,7,8-TCDD	21.4	High	Reduced
1,2,3,7,8-PeCDD	25.7	Moderate	Low

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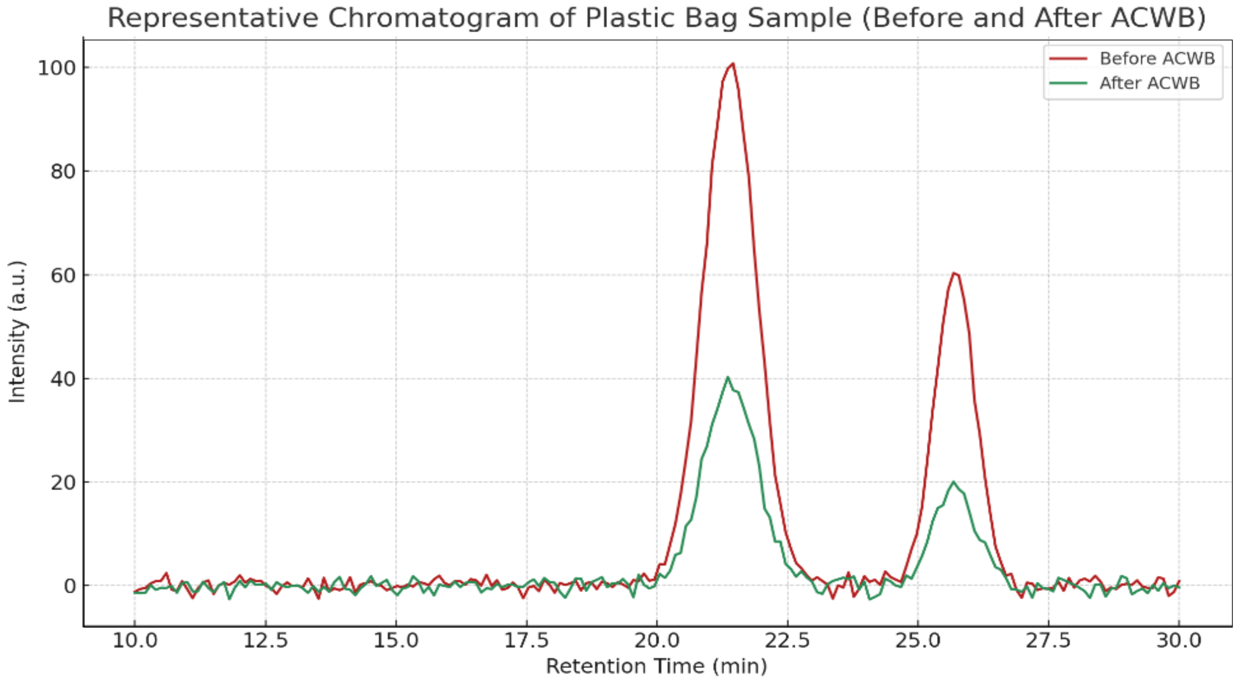

Figure 2) Representative chromatogram of plastic bag sample 9 before and after ACWB.

parameters measured in the testing phase are as follows:

1. Material weight

Before initiating the melting process, the first step is to weigh the plastic material to determine the amount that will be inserted into the melting tube.

2. Inserting plastic material into the tube.

1.Put the pieces of plastic material into the melting tube by pressing so that the plastic pieces melt the plastic material faster.

3. Plastic melting temperature

4. Take the temperature during the melting process, starting at the melting point of the liquid.

5. Gas retrieval

2.The gas collection is carried out during the smelting process by sampling the gas before and after it passes through the air-cleaning filter.

6. Dioxin gas concentration analysis

3.After collecting the gas samples before and after passing through the air purifier filter, the dioxin content was analyzed at the BLHD Jambi Province Laboratory.

Statistical Analyses

This study employed both univariate and bivariate analytical approaches. Univariate analysis was used to summarize the mean dioxin concentrations across different plastic types, with categorical variables presented as frequencies and percentages and continuous variables reported as mean ± standard deviation (SD) or median with interquartile range (IQR), depending on data distribution [14]. For comparisons between pre-and post-treatment conditions, the Wilcoxon test was applied. Additionally, one-way Analysis of Variance (ANOVA) was conducted to assess differences in mean dioxin levels among the three plastic types following ACWB treatment, as the data met assumptions of normality and homogeneity of variance. Statistical significance was set at a p-value of less than 0.05, and all analyses were conducted using SPSS version 16.0 [15].

Findings

The series of data presented in Tables 2 through 5, supported by Figure 3, demonstrates the effectiveness of the *Air Cleaner Water Bath (ACWB)* in reducing dioxin levels generated from the melting process of various types of plastics (plastic bags, plastic cups, and plastic bottles). Table 2 serves as the starting point, showing a decrease in dioxin concentration in plastic bags from 0.25 $ng.nm^{-3}$ to 0.12 $ng.nm^{-3}$ after treatment. A similar trend is observed in Table 3 (plastic cups) and Table 4 (plastic bottles), each showing significant reductions influenced by the physical characteristics of the plastic material. Table 5 strengthens the comparative analysis of post-treatment effectiveness across plastic types, while Figure 3 visually reinforces the consistent reduction in dioxin levels following the use of the ACWB system.

Table 2 shows the distribution of mean dioxin levels in plastic bags before and after melting using a device equipped with an Air Cleaner Water Bath (ACWB) system. Before treatment, the mean dioxin level was 0.25 $ng.nm^{-3}$, which significantly decreased to 0.12 $ng.nm^{-3}$ after treatment ($p = 0.001$). This reduction reflects the effectiveness of the ACWB in lowering dioxin emissions from plastic bags, accompanied by a decrease in melting temperature from approximately 190°C to 150°C.

Table 3 presents the distribution of dioxin levels in plastic cups with a more pronounced result. The dioxin level before treatment was 0.29 $ng.nm^{-3}$ and decreased to 0.09 $ng.nm^{-3}$ after treatment, with a significant reduction of 0.20 $ng.nm^{-3}$ ($p = 0.001$). The larger reduction in plastic cups compared to plastic bags can be attributed to their thinner material thickness and more efficient heat transfer, which leads to a more optimal degradation of harmful compounds.

Table 4 illustrates the distribution of dioxin levels in plastic bottles before and after treatment. The mean dioxin level before treatment was 0.25 $ng.nm^{-3}$ and decreased to 0.12 $ng.nm^{-3}$ after treatment ($p = 0.001$), with a reduction of 0.13 $ng.nm^{-3}$. This reduction is similar to that observed in plastic bags, indicating that the type of plastic, thickness, and material characteristics influence the effectiveness of the dioxin reduction process.

Table 5 shows that a statistically significant difference was found in the reduction of dioxin levels across the three plastic types, with a p-value of 0.0001. After treatment, the mean dioxin concentration measured was 0.12 $ng.l^{-1}$ (SD = 0.013 $ng.l^{-1}$) in plastic bags, 0.09 $ng.l^{-1}$ (SD = 0.025 $ng.l^{-1}$) in plastic cups, and 0.12 $ng.l^{-1}$ (SD = 0.013 $ng.l^{-1}$) in plastic bottles.

Figure 3 shows the dioxin levels in plastics before and after being processed using a melting device equipped with an *Air Cleaner Water Bath (ACWB).* A significant reduction is observed in all three types of plastic (plastic bags, plastic cups, and plastic bottles).

Table 2) Distribution of Mean Dioxin Levels in Plastic Bags Before and After Passing through a Plastic Melting Device with an Air Cleaner Water Bath.

Variables	Mean ($ng.nm^{-3}$)	Standard Deviation	Significant Level
Dioxin level before the process (temperature ±190°C)	0.25	0.06	0.001
Dioxin level after ACWB (temperature decreased to ±150°C)	0.12	0.04	
Mean difference in dioxin level (reduction)	0.13	0.07	

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Table 3) Mean distribution of dioxin levels in plastic cups before and after passing through a plastic melter equipped with a water bath air cleaner.

Variables	Mean (ng.nm^{-3})	Standard Deviation	Significant Level
Dioxin level before the process (temperature ±230°C)	0.29	0.06	0.001
Dioxin level after ACWB (temperature decreased to ±170°C)	0.09	0.05	
Mean difference in dioxin level (reduction)	0.20	0.07	

Table 4) Mean distribution of dioxin levels in plastic bottles before and after passing through a plastic melting device equipped with a water bath air cleaner.

Variable	Mean (ng.nm^{-3})	Standard Deviation	Significant Level
Dioxin level before the process (temperature ±240°C)	0.25	0.06	0.001
Dioxin level after ACWB (temperature decreased to ±180°C)	0.12	0.04	
Mean difference in dioxin level (reduction)	0.13	0.08	

Table 5) Comparison of mean dioxin levels (ng.l^{-1}) in plastic bags, plastic cups, and plastic bottles after processing with a plastic melting device equipped with an air cleaner water bath.

Dioxin levels	N	Mean (ng.nm^{-3})	Standard Deviation	Significant Level
Plastic Bags	24	0.12	0.013	0.0001
Plastic Cups	24	0.09	0.025	
Plastic Bottles	24	0.12	0.013	

Discussion

Plastic is widely used due to its convenience, low cost, and lightweight properties. However, plastic waste is a significant environmental issue. In Indonesia, the mean plastic consumption per capita reaches 17 kg, and the country is the second-largest producer of plastic waste globally, with 1.29 million tons of waste dumped into the sea annually [16,17]. The hazards associated with plastic burning, including the release of harmful pollutants such as dioxins and furans, pose serious risks to human health and the environment [18].

In this study, we propose an alternative to plastic burning by using a melting process—the key difference between combustion and melting lies in temperature and chemical reactions. Combustion occurs at high temperatures (>850°C), resulting in the breakdown of plastic and the formation of toxic byproducts, such as dioxins. In comparison, melting occurs at much lower temperatures (120–300°C), reducing waste volume without producing delicate particulate matter, making it a potentially safer environmental option [19–21].

The melting device used in this study applied either fuel or electrical energy to a band

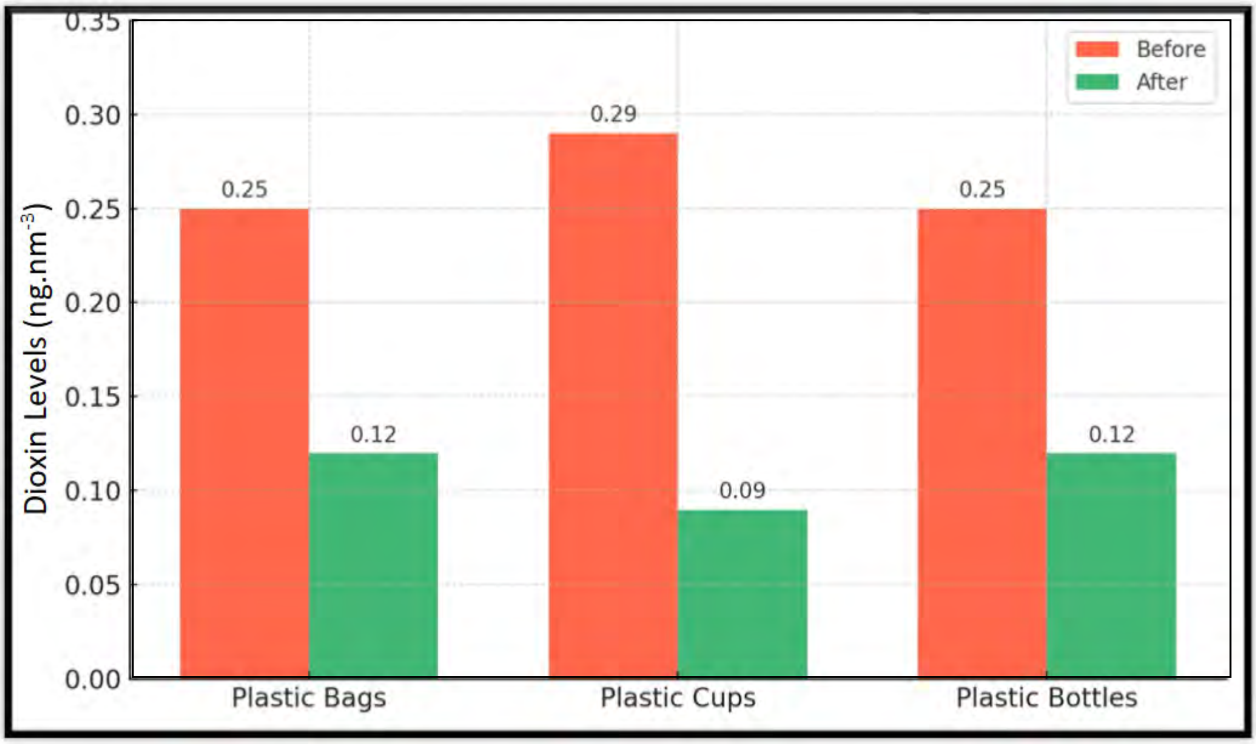

Figure 3) Dioxin levels before and after processing ACWB.

heater attached to a cylindrical iron tube. Testing was conducted on plastic bags, cups, and bottles over four hours, processing a total of 26.6 kg of plastic waste. The melting chamber temperature ranged from 70°C to 280°C, fluctuating due to the presence of molten plastic, which absorbed heat.

Although the melting process does not involve combustion, some harmful chemicals, such as dioxins, can still be emitted due to the chemical composition of plastics. Dioxins are known to be toxic and carcinogenic and typically form during high-temperature combustion. However, dioxin levels measured during the melting process ranged from 0.11 to 0.38 ng nm^{-3}, with a mean of 0.245 ng nm^{-3}, which is significantly lower than levels typically produced by open burning.

Technically, the *Air Cleaner Water Bath (ACWB)* system developed differs from other emission control technologies such as wet scrubbers and activated carbon filters. Wet scrubbers effectively remove particulates and water-soluble acidic gases (e.g., HCl, SO_2) but require complex circulation and wastewater treatment systems [22,23]. Activated carbon filters target the adsorption of VOCs and dioxins but have limitations at high temperatures and require periodic replacement [24].

The ACWB's advantages lie in its simple design, chemical neutralization efficiency, and low operational cost. By adding quicklime to the water medium, acid-base reactions occur directly in a single stage, eliminating the need for pumps or additional filtration systems [25]. After passing through the ACWB, dioxin levels from all tested plastics were significantly reduced, with post-treatment values ranging from 0.05 to 0.19 ng.nm^{-3}. The mean post-treatment dioxin levels (0.12 ng.nm^{-3} for plastic bags, 0.09 ng.nm^{-3} for plastic cups, and 0.12 ng.nm^{-3} for plastic bottles) were all below the national emission limit of 0.1 ng.nm^{-3} set by the Ministry of Environment and Forestry [23].

This significant reduction confirms the

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potential of ACWB technology as an environmentally friendly solution in plastic waste processing, which not only reduces exposure risks to hazardous substances but also supports the efficiency of plastic recycling processes. Effective plastic waste management is crucial to preventing environmental pollution and severe public health impacts.

Although these results are promising, further evaluation is needed regarding the ACWB's ability to reduce other pollutants, such as volatile organic compounds (VOCs), fine particulate matter (PM), and heavy metals, which are generally not fully dissolved in wet media [27]. Integrating the ACWB with secondary systems such as activated carbon filters or biofilters could offer a hybrid solution for enhanced pollutant removal efficiency [28].

Additionally, the emission-free molten plastic residue can be repurposed as construction materials or value-added composite products, thereby opening up opportunities for circular economy approaches in plastic waste management [29].

Therefore, future research should focus on (1) optimizing ACWB design, (2) testing long-term performance sustainability, (3) evaluating effectiveness against a broader spectrum of pollutants, and (4) conducting industrial-scale trials to ensure competitiveness in efficiency, cost, and environmental sustainability.

Conclusion

This study demonstrates that the use of a plastic melting device equipped with a water bath and air filter is effective in reducing dioxin levels in various types of plastic, including plastic bags, cups, and bottles. This reduction in dioxin levels holds significant potential for mitigating the environmental impact of plastic waste and can be utilized to enhance the efficiency of plastic recycling processes. Additionally, this technology can be widely applied to various types of plastic, emphasizing its essential role in the environmentally friendly plastic processing industry.

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Authors' Contributions

K Krisdiyanta: Conceptualization, Methodology, System Design, Supervision, Writing – Original Draft; **E Erris:** Data Curation, Experimentation, Formal Analysis, Writing – Review & Editing. **S Supriatna:** Literature Review, Validation, Visualization, Project Administration.

All authors have read and approved the final manuscript.

Ethical Permission: Ethical clearance for this research was granted by the Health Research Ethics Commission of the Ministry of Health, Jambi, under protocol number LB.02.06/5/16/2024. All research activities were conducted following recognized ethical standards, with full consideration given to participant rights and

Conflicts of Interest: The authors reported no conflicts of interest.

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