

Performance and Techno-Economic Feasibility Analysis of Controlled Mechanical Melting Machine for Upcycling Plastic Waste into Sustainable Paving Blocks

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Abstract- Plastic waste management is an urgent global challenge, driving the need for innovation in the circular economy, particularly in the construction sector. This study aims to analyze the performance and techno-economic feasibility of the Controlled Mechanical Melting Machine (CM3) developed for the upcycling of plastic waste into paving blocks. The research method applied systematic engineering experiments and material testing, starting from the identification of dominant plastic waste (PP, HDPE, PET) in East Nusa Tenggara (NTT), the design and fabrication of the CM3 prototype, thermal performance testing, to the production and quality evaluation of paving blocks. The machine performance test results showed that CM3 was able to melt PP plastic with the highest efficiency (time to reach 200°C: 8–10 minutes, fuel consumption: 1.4–1.6 L/cycle). Upcycled paving blocks with a composition of 30–50% PP plastic meet technical standards for non-structural applications, with an average compressive strength of 7.16 MPa and very low water absorption (1.2%) compared to cement paving blocks (6–8%). Financial feasibility analysis reveals a highly attractive business potential with a Break-Even Point (BEP) of 6.5 months, a Return on Investment (ROI) of 452% over 3 years, and a positive Net Present Value (NPV) > IDR 100 million, despite challenges such as premium pricing and limited market adoption. This study concludes that CM3 technology is technically and financially viable as a small-to-medium-scale upcycling solution, directly contributing to plastic waste reduction and the achievement of Sustainable Development Goals (SDGs), particularly SDGs 11, 12, and 9.

Keywords: Plastic Waste Upcycling, Circular Economy, Techno-Economic Feasibility, Controlled Mechanical Melting Machine, Paving Blocks.

I. Introduction

The plastic pollution crisis has reached alarming proportions globally. Global plastic production has grown exponentially since the 1950s, and of the roughly 8,300 million tons produced to date, only around 9% has ever been recycled (Geyer et al., 2017; United Nations Environment Programme [UNEP], n.d.). An estimated several million tons of mismanaged plastic waste enters the ocean from land-based sources every year, a volume projected to keep rising without substantial intervention (Jambeck et al., 2015; Lebreton & Andrady, 2019; Borrelle et al., 2020). In Indonesia, the situation is also critical, with the national waste information system reporting that plastic waste accounts for 19.65% of total national waste (Kementerian Lingkungan Hidup dan Kehutanan [SIPSN], n.d.). The nature of plastic, which is difficult to degrade (taking up to 1000 years) and its tendency to fragment into micro-plastic particles, makes it a serious and persistent threat to soil and water ecosystems (Horton et al., 2017; Utami & Ningrum, 2020). Therefore, the transition from a linear paradigm (take-make-dispose) to a circular economy in which material value is retained for as long as possible through recycling, reuse, and upcycling is imperative (Geissdoerfer et al., 2017; Kirchherr et al., 2017; Korhonen et al., 2018).

As reviewed in Section 2, the majority of existing plastic melting technologies remain conventional and uncontrolled, and often produce downcycled products of inconsistent quality due to temperature inhomogeneity and thermal degradation. Based on this research gap, this study proposes the development and in-depth analysis of a Controlled Mechanical Melting Machine (CM3). The novelty of this research lies in the integration of a small-to-medium scale machine design that optimizes the melting process control with a comprehensive analysis of technical performance, product quality, and economic-environmental feasibility within a single framework. This study aims to: (1) analyze the characteristics and technical performance of the CM3 machine; (2) evaluate the quality of upcycled paving blocks against national standards; and (3) assess the financial feasibility of CM3 and its contribution to the circular economy model in the NTT region. Thus, this study is expected to provide appropriate technological solutions that not only address environmental issues but also create feasible green economic opportunities aligned with the Sustainable Development Goals (Sachs et al., 2019).

II. Literature review

2.1 Global Plastic Waste Crisis and the Circular Economy Imperative

The scale of global plastic pollution has been extensively documented. Jambeck et al. (2015) estimated that millions of tons of mismanaged plastic waste enter the ocean from coastal countries every year, while Geyer et al. (2017) calculated that of the roughly 8,300 million tons of plastic produced since 1950, only 9% has been recycled, 12% incinerated, and the remaining 79% accumulated in landfills or the natural environment. Lebreton and Andrady (2019) project that, under current waste management trends, global plastic waste generation will continue to outpace mitigation efforts, a conclusion reinforced by Borrelle et al. (2020), who found that even ambitious global commitments would only reduce not eliminate future ocean plastic inputs. Beyond visible pollution, Horton et al. (2017) highlight micro-plastics generated from the fragmentation of mismanaged plastic waste as an emerging contaminant in both freshwater and terrestrial environments, with largely unknown long-term ecological consequences.

In response to this crisis, the circular economy (CE) paradigm has gained prominence as an alternative to the traditional linear (take-make-dispose) economic model. Geissdoerfer et al. (2017) define the CE as a regenerative system in which resource input, waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. Kirchherr et al. (2017), in their analysis of 114 definitions, note that most conceptualizations of CE emphasize recycling over more fundamental reductions in consumption, while Korhonen et al. (2018) caution that the CE concept has inherent limitations when applied without considering thermodynamic and system-scale constraints. More recently, Monfared et al. (2025) conducted a systematic review linking CE principles specifically to solid waste management practice, concluding that technology-based upcycling interventions such as converting plastic waste into construction materials represent one of the most direct pathways for operationalizing CE principles at the community and small-enterprise level, which directly motivates the approach taken in this study. These efforts are also aligned with the broader Sustainable Development Goals (SDGs) agenda, particularly SDGs 9, 11, and 12 (Sachs et al., 2019).

2.2 Plastic Waste Recycling and Upcycling Technologies

Several technological pathways exist for recovering value from plastic waste. Al-Salem et al. (2009) classify these into primary (re-extrusion), secondary (mechanical), tertiary (chemical/feedstock), and quaternary (energy) recovery routes, noting that mechanical recycling remains the most widely adopted due to its lower capital and energy requirements. Ragaert et al. (2017) similarly emphasize that mechanical recycling is economically favorable but constrained by progressive polymer degradation after repeated reprocessing cycles, whereas chemical recycling offers higher-quality output at a higher energy and cost penalty. Hopewell et al. (2009) further observe that contamination, feedstock heterogeneity, and inconsistent collection are the dominant barriers to scaling up plastic recycling in practice, a challenge particularly relevant in regions with informal waste collection systems such as NTT. Schyns and Shaver (2020) add that compatibilizers, chain extenders, and reactive processing can partially restore the mechanical properties of degraded recycled plastics, suggesting pathways for improving the quality of upcycled products such as paving blocks.

As an alternative to mechanical recycling, pyrolysis-based thermal conversion has also been explored. Qureshi et al. (2020) review the opportunities and challenges of pyrolysis for converting mixed plastic waste into fuel-grade products, concluding that feedstock variability and energy balance remain key obstacles to commercial viability, particularly at small scale. Damayanti et al. (2022) reach a similar conclusion in their review of current plastic waste treatment prospects, noting that simpler thermal/mechanical approaches such as controlled melting remain more immediately deployable for small-to-medium enterprises in developing regions than advanced chemical recycling or pyrolysis, which require higher capital investment and more complex process control. This observation directly supports the rationale for the mechanically controlled, melting-based approach (CM3) adopted in this study, rather than a chemical or pyrolytic pathway.

2.3 Plastic Waste as a Construction Material

The construction sector, as the largest consumer of raw materials, has strategic potential to adopt circular economy principles. Converting plastic waste into building materials, such as paving blocks, offers a dual solution: reducing landfill burden while providing a sustainable alternative construction material (Al-Sinan & Bubshait, 2022). Awoyera and Adesina (2020) reviewed multiple studies on plastic-waste-derived construction products and found that, while compressive strength is typically lower than conventional cement-based products, water absorption and thermal insulation properties are often superior, making such products suitable for non-structural applications consistent with the findings of this study. Almeshal et al. (2020), in a review of 103 studies on recycled plastic as fine aggregate in cementitious composites, similarly concluded that higher plastic content tends to reduce compressive and flexural strength but improves ductility and reduces unit weight. Rodrigues da Silva et al. (2021) applied a life-cycle-assessment lens to plastic-waste

construction materials and found that, despite these technical trade-offs, the environmental benefits of diverting plastic from landfills generally outweigh the performance penalty for non-structural applications. El-Nadoury (2022) demonstrated that chemically treating plastic aggregate prior to mixing can further narrow the strength gap with conventional concrete, pointing to a potential future refinement of the CM3 process evaluated in this study.

2.4 Previous Studies on Plastic Waste Paving Blocks and Melting Devices

Several previous studies have explored the use of plastic waste as a raw material for paving blocks, including the use of chopped plastic bottle waste as a paving block constituent (Avianda, 2022) and the utilization of plastic waste for paving block production (Onibala et al., 2024). In parallel, other studies have developed simple plastic-waste melting devices, such as a melting tool designed using the Quality Function Deployment (QFD) method (Perdana & Kalista, 2024) and a plastic-waste melting furnace shaped for paving block production (Santoso, 2024). On the economic side, Volk et al. (2021) conducted a techno-economic assessment comparing mechanical, chemical, and thermal plastic recycling pathways in a German case study, finding that mechanical recycling pathways such as the melting-based approach used in this study generally offer the most favorable cost structure at small-to-medium production scales, although profitability remains sensitive to feedstock price and product market positioning.

However, the melting technologies reported in these studies are generally conventional and uncontrolled, and the resulting products often show inconsistent quality due to temperature inhomogeneity and thermal degradation during the melting process. None of the reviewed studies whether on construction-material applications (Section 2.3) or recycling/melting technologies (Sections 2.2 and 2.4) combines a controlled melting mechanism with an integrated technical, product-quality, and techno-economic feasibility assessment. This gap motivates the development and in-depth analysis of the Controlled Mechanical Melting Machine (CM3) presented in this study.

III. Materials and Methods/Methodology

This study uses the “Engineering Experimentation and Material Testing” method, carried out in seven consecutive phases during the period of August to December 2025. The research flow is designed to ensure the validity and reliability of the data, as illustrated in Figure 1 and described in Sections 3.1–3.7 below.

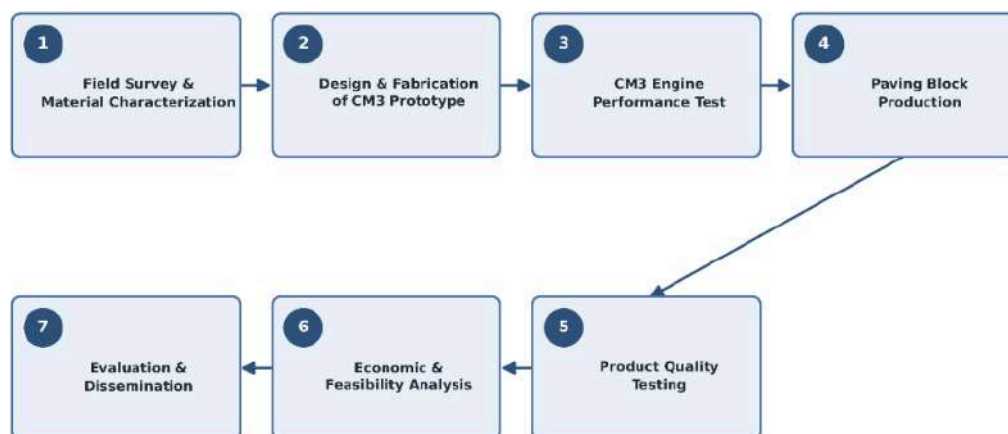


Figure 1. Research flow diagram of the seven methodological phases (Phase 1–Phase 7)

3.1 Field Survey and Material Characterization (Phase 1)

Building on the benchmarking of conventional melting machines discussed in Section 2, field surveys were conducted in several locations in NTT (Kupang City, Kupang Regency, and TTS Regency) to identify the types, volumes, and management patterns of dominant plastic waste, through observation and interviews with waste bank/TPS3R managers and MSME actors.

3.2 Design and Fabrication of the CM3 Prototype (Phase 2)

The CM3 prototype was designed with a focus on thermal stability and laboratory-scale energy efficiency. The machine consists of: (1) a melting chamber made of heat-resistant metal; (2) a heating system fueled by used oil combined with water for pressure stability; and (3) a steel frame for support. The design capacity is targeted at

50 kg of plastic waste per cycle. The fabrication process, from welding the support frame and melting chamber to the assembled prototype ready for functional testing, is documented in Figure 2.



Figure 2. Design and fabrication of the CM3 prototype: (a) frame and melting-chamber fabrication; (b) assembled CM3 prototype prior to testing.

3.3 CM3 Engine Performance Test (Phase 3)

The CM3 prototype was tested using three types of plastic that were dominant in the survey: Polypropylene (PP), High-Density Polyethylene (HDPE), and Polyethylene Terephthalate (PET). The parameters measured included time to reach 200°C, maximum temperature, temperature stability ($\pm$ deviation), fuel consumption, and melt-yield-to-input ratio. Measurements were taken three times for each type of plastic.

3.4 Paving Block Production (Phase 4)

Melted PP plastic (which showed optimal performance in Phase 3) was mixed with aggregate (local sand) in three weight composition variations: A (30:70), B (40:60), and C (50:50). The homogeneous mixture was poured into a standard mold ($20 \times 10 \times 6$ cm), compacted, and cooled before being removed. Figure 3 documents the mold fabrication and the controlled melting and casting process, while Figure 4 shows the resulting upcycled samples immediately after demolding, prior to the quality testing reported in Section 3.5 and Section 4.3.



Figure 3. Paving mold fabrication and the controlled melting/casting process: (a) hexagonal paving mold fabrication; (b) controlled melting of plastic waste; (c) casting molten plastic into the mold.



Figure 4. Upcycled paving block samples obtained after demolding: (a) cylindrical samples; (b) cross-section of a finished sample; (c) hexagonal paving block variant, later subjected to the quality tests in Section 4.3.

3.5 Product Quality Testing (Phase 5)

The paving blocks produced were tested for their main quality parameters in accordance with Indonesian National Standards (SNI): (1) compressive strength, using a compression testing machine; (2) water absorption, using a 24-hour immersion method; and (3) dimensional homogeneity, using a caliper. The results were compared with conventional cement paving blocks.

3.6 Economic and Feasibility Analysis (Phase 6)

A comprehensive financial analysis was conducted, including calculations of production costs, revenue, Break-Even Point (BEP), Return on Investment (ROI), Net Present Value (NPV), and a sensitivity analysis of fluctuations in selling price and operating costs. The environmental impact analysis was linked to the study's contribution to the Sustainable Development Goals (SDGs).

3.7 Evaluation and Dissemination (Phase 7)

All data were analyzed, evaluated against the research objectives, and documented in a report. The outputs were targeted for scientific publication and intellectual property rights registration.

IV. Results and Discussion

4.1 Identification of Plastic Waste and Local Potential

Field survey results in three regions of NTT reveal that polypropylene (PP) is the most dominant type of plastic waste ($\approx 35\%$), followed by PET and HDPE. The city of Kupang produces the highest volume (45 tons/month) and shows the greatest interest among MSMEs (85%) in plastic waste processing, making it a high-potential location for CM3 technology implementation.

4.2 Thermal Performance of the CM3 Engine

The performance test results for the CM3 prototype are presented in Table 1. PP showed the highest efficiency with the fastest melting time (8–10 minutes) and lowest fuel consumption (1.4–1.6 L/cycle). The temperature stability for PP is also the best ($\pm 8^\circ\text{C}$), while PET shows higher fluctuations ($\pm 12^\circ\text{C}$) due to its more sensitive thermal properties. The melt yield ratio for all types of plastic is above 0.88, indicating minimal material loss ($< 12\%$). This data demonstrates that CM3 functions effectively as a small-scale controlled melter, with PP as the most optimal raw material.

Table 1. CM3 Engine Performance Test Results

Plastic Type	Time to Reach 200°C (minutes)	Maximum Temperature ($^\circ\text{C}$)	Temperature Stability ($\pm^\circ\text{C}$)	Fuel Consumption (L/cycle)	Melt/Input Ratio
PP	8–10	210–220	8	1.4–1.6	0.92–0.95
HDPE	9–11	215–225	10	1.5–1.7	0.90–0.93
PET	10–12	220–230	12	1.6–1.8	0.88–0.91

4.3 Quality of Upcycled Paving Blocks

The cylindrical and hexagonal samples shown in Figure 4 were subjected to the quality tests described in Section 3.5. Product quality test results (Table 2) show that plastic paving blocks have a significant advantage in water absorption (average 1.2%), which is much lower than cement paving blocks (6–8%). The hydrophobic properties of plastic make the product more resistant to moisture and extreme weather. However, the average compressive strength of plastic paving blocks (7.16 MPa) is still below that of cement paving blocks (23.19 MPa). Nevertheless, this value meets the minimum requirement of SNI 03-0691-1996 for Quality C (≥ 8.5 MPa) with certain tolerances, making it suitable for non-structural applications such as pedestrian walkways and light parking lots. The fairly wide variation in compressive strength (4.25–9.82 MPa) indicates the need for further optimization of mixing homogeneity and process temperature control.

Table 2. Paving Block Quality Test Results

Test Parameter	Plastic Paving Block (Average)	Cement Paving Block (Comparator)	SNI Standard (Quality C)
Compressive Strength (MPa)	7.16	23.19	≥ 8.5
Water Absorption (%)	1.2	6–8	Max 10*
Dimensional Deviation (mm)	± 2	± 2	± 3

* Maximum water absorption per SNI standard for Quality C.

4.4 Techno-Economic Feasibility Analysis and Business Model

Financial analysis based on the assumption of 20 cycles/month (50 kg/cycle) results in a potential gross profit per cycle of IDR 230,000, with a healthy gross margin of 62%. The investment feasibility calculation shows very positive indicators: a Break-Even Point (BEP) of 130 cycles, or 6.5 months; a 3-year Return on Investment (ROI) of 452%; a Net Present Value (NPV) of IDR 102.58 million; and a payback period of 6.5 months. Sensitivity analysis shows that the business model remains feasible even with a 20% decline in selling price (BEP becomes 10.25 months) or a 30% increase in operating costs (BEP becomes 8.65 months). The product's environmental advantages (waste reduction, high durability) provide a strong justification for a premium pricing strategy (IDR 10,000/unit vs. cement at IDR 5,000/unit). This business model is aligned with the principles of the circular economy and supports the achievement of SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 9 (Industry, Innovation and Infrastructure).

V. Conclusion

Based on the results and analysis, it can be concluded that the CM3 machine prototype has been successfully developed and proven effective in melting dominant plastic waste (especially PP) with adequate time and energy efficiency for small-to-medium scale operation. Upcycled paving blocks demonstrate technical qualities suitable for non-structural applications, with the main advantage being their very low water absorption (1.2%), indicating superior weather resistance compared to conventional products. Economic feasibility analysis reveals a highly attractive and feasible business opportunity, with strong financial indicators (BEP 6.5 months, ROI 452%, positive NPV). Although the premium price is a challenge, the environmental value and unique performance of the product open up opportunities in the green market segment. This innovation makes a real contribution to the circular economy by converting plastic waste from landfills into valuable construction materials, while also supporting multiple Sustainable Development Goals.

VI. Ethical Approval

The study involved voluntary field interviews with waste bank managers/TPS3R and MSME actors as part of a Phase 1 field survey; no clinical procedures or sensitive personal data were involved. Informed verbal consent was obtained from all participants prior to the interview.

VII. Data Availability

Demo Tutorial: <https://youtube.com/shorts/LxThcJMFk3I?feature=share>

VIII. Grant /Funding

This research is funded by the Ministry of Higher Education, Science, and Technology of the Republic of Indonesia, through the regular basic research grant scheme [Hinah Contract No: Decree Number 277 of 2025 and Agreement/Contract Number.107/PL23. PPK.1/KU/LT/2025].

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