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Design and Implementation of an IoT-Based Low-Emission Mobile Plastic Melting Machine for Sustainable Paving Block Production in Batam City

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ABSTRACT

Plastic waste accumulation poses a severe environmental burden, particularly in urban and archipelagic regions where centralized treatment infrastructure is limited. While thermal processing offers a pathway for volume reduction and material recovery, inadequate temperature control frequently leads to uncontrolled combustion and the formation of hazardous air pollutants. This study addresses this gap by developing and experimentally validating a low-emission, IoT-enabled mobile plastic melting system designed for decentralized paving block production. The proposed system integrates real-time thermal sensing using a K-type thermocouple and an ESP32-based controller with a compact three-nozzle water spray filtration unit. The control architecture maintains the melting process at approximately 270 °C, thereby preserving polymer viscosity for molding while preventing temperature excursions beyond 300 °C that may initiate combustion and toxic by-product formation. The filtration module operates as a simplified wet scrubber, capturing airborne particulates and simultaneously cooling the exhaust stream. Experimental evaluations confirm that the integrated control–filtration framework achieves stable thermal regulation and substantial suppression of visible exhaust emissions. Under these conditions, molten plastic was consistently transformed into dense paving blocks with smooth surface morphology and without evidence of polymer degradation or charring. The results demonstrate that combining IoT-based thermal governance with low-cost water-spray emission control provides an effective and scalable alternative to open burning for community-level plastic waste recycling. This mobile platform enables environmentally safer conversion of plastic waste into value-added construction materials, offering a practical pathway toward decentralized circular-economy implementation in resource-constrained regions.

I. INTRODUCTION

The exponential accumulation of plastic waste presents a critical environmental challenge, particularly in urban and archipelago regions where land availability for landfills is increasingly limited [1], [2]. While thermal treatment offers a viable pathway for significant volume reduction and material recovery, uncontrolled thermal processing poses severe health risks [3]. The primary concern in the thermal treatment of plastics, especially those containing chlorine, is the unintentional formation of Persistent Organic Pollutants (POPs), most notably polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) [4]. Literature indicates that these toxic compounds are predominantly generated during incomplete combustion or when exhaust gases linger within the "de novo" synthesis temperature window of 250°C to 450°C [5], [6]. Therefore, the safety of any thermal recycling machinery is contingent upon its ability to maintain stable temperatures to prevent the process from escalating into uncontrolled burning.

Current state-of-the-art technologies for waste thermal treatment differ significantly in scale and complexity. Industrial incinerators are capable of achieving high destruction efficiencies through dual-chamber designs that operate at temperatures exceeding 850°C [7], [8], [9]. However, these facilities are typically stationary, capital-intensive, and operationally complex, which restricts their accessibility for small-scale or community-level waste management. Regarding emission control, studies have demonstrated that water-based filtration methods, particularly wet scrubbing, are highly effective in lowering flue gas temperatures and reducing carbon emissions and particulates through mechanisms of inertial impaction and condensation [10], [11], [12]. Despite the proven efficacy of these filtration systems, their implementation is often associated with large static infrastructure rather than portable solutions.

Furthermore, a critical distinction must be made between incineration, which reduces waste to ash, and melting, which induces a phase change for recycling. For the production of paving blocks, the polymeric structure of the plastic must be preserved to act as a binder. Conventional small-scale melters often lack precise thermal regulation, leading to temperature overshoots that cross the flash point of polymers, inadvertently turning a melting process into hazardous combustion [13], [14].

To address these challenges, this study proposes the design and performance evaluation of a low-emission, mobile plastic melting machine tailored for sustainable paving block production. The novelty of this work lies in the synergistic integration of Internet of Things (IoT) technology with a simplified water spray filtration system within a mobile framework. Unlike static industrial units [15], [16], this machine utilizes a wheeled mobile base frame for deployment flexibility. Critically, the system employs an ESP32 microcontroller to monitor temperature and pressure sensors in real-time, ensuring the heating process remains strictly within the melting regime (approximately 270°C) and preventing the high-temperature excursions associated with dioxin formation. Complementing this thermal control is a cost-effective exhaust filtration unit featuring a 3-nozzle water spray manifold. This component creates a water curtain to suppress smoke and capture airborne particulates, offering a practical approach to emission mitigation for decentralized applications. This research aims to validate that such an integrated system can offer a safe solution for plastic waste upcycling.

II. METHODOLOGY

A. Mechanical Design and Mobile System

The mechanical architecture of the proposed machine is prioritized to ensure portability, operational safety, and thermal efficiency suitable for decentralized waste management applications. The structural foundation of the system is the Mobile Base Frame, which is constructed using rigid metal profiles to support the static and dynamic loads of the components, including the water reservoir, circulation pump, and the melting unit itself. To satisfy the requirement for high mobility in urban or community environments, the frame is integrated with four caster wheels attached to the base corners. This design feature, Figure 1, enables the machine to be easily maneuvered to various waste collection points, such as community waste banks (Bank Sampah), thereby removing the logistical constraints associated with static industrial incinerators.

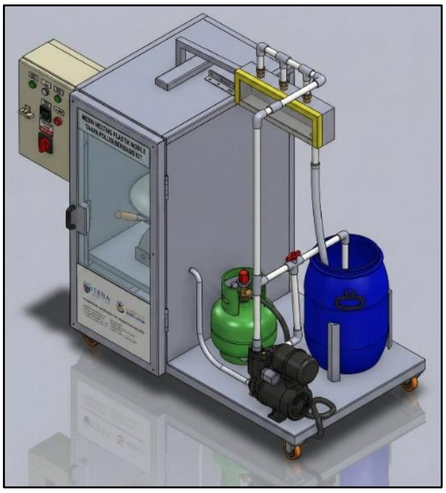

Figure 1. Conceptual Design of the IoT-Based Mobile Plastic Melting Machine with Water Spray Filtration System.

Although the emission filtration performance evaluation in this study demonstrated a reduction in smoke opacity through the mechanism of inertial impaction, the assessment remains qualitative. The reduction in visible smoke was not accompanied by quantitative measurements of particulate matter (e.g., $PM_{2.5}$, PM_{10}), carbon monoxide (CO), or volatile organic compounds (VOC) generated during the plastic melting process. These quantitative measurements are crucial to provide stronger evidence supporting the claim of reduced emissions and to substantiate the assertion of low-emission performance.

Furthermore, an evaluation of air quality post-filtration should be compared with relevant ambient air quality standards, such as those set by national and international environmental agencies (e.g., EPA or WHO air quality guidelines). This comparison would offer a more objective indication of how effective the filtration system is in reducing harmful pollutants and ensure that the emissions produced are within safe limits for public health and the environment.

Without detailed quantitative measurement data and comparison with established environmental emission standards, the claim of low-emission remains limited and requires further testing for more comprehensive validation.

The core processing unit, identified as the Main Melting Chamber, functions as the thermal enclosure where the phase change of the polymeric material occurs. Inside this chamber, a concave Melting Vessel (Wok) is utilized as the primary receptacle for the plastic waste. The concave geometry of the vessel is selected to optimize conductive heat transfer from the heat source and to facilitate the manual stirring or removal of the molten plastic for molding. The thermal energy required for this process is supplied by a gas burner located directly beneath the vessel, which is fueled by a 3 kg Liquefied Petroleum Gas (LPG) cylinder stored securely on the lower deck of the frame. The selection of 3 kg LPG as the fuel source ensures that the system remains compact and operationally feasible for small-scale applications due to the widespread availability of this fuel type.

A critical design intervention for emission control is the incorporation of a Glass Door on the front interface of the melting chamber. This transparent barrier serves two essential functions. First, it isolates the heating zone from the operator, acting as a seal to minimize fugitive emissions. By closing the chamber, smoke and volatile vapors generated during the melting process are contained and forced to exit through the top-mounted exhaust system rather than leaking into the surrounding environment. Second, the glass material allows for continuous visual monitoring of the melting process, enabling the operator to verify the state of the plastic without opening the chamber door, thus maintaining thermal stability and reducing heat loss during operation.

B. Smoke Filtration System

To mitigate the release of airborne particulates and volatile compounds generated during the heating process, the machine is equipped with a custom-designed Exhaust Filtration & Spray Unit. Unlike complex industrial scrubbers that require large stationary infrastructure [17], this system utilizes a compact water spray mechanism integrated directly into the mobile frame. The filtration logic relies on the principle of inertial impaction, where the momentum of smoke particles causes them to collide with water droplets rather than following the streamlines of the gas flow around the droplets.

The core of the filtration unit is the 3-Nozzle Manifold positioned within the exhaust ducting. As illustrated in the exploded view design (Figure 2), this manifold consists of three distinct spray nozzles arranged in series along the gas flow path. This configuration is critical to maximizing the liquid-to-gas contact area within the confined space of the exhaust chamber. The mechanism operates by creating a dense water curtain through which the exhaust gases must pass. As the smoke rises from the Main Melting Chamber due to natural convection and thermal buoyancy, it enters the filtration unit. Here, the three nozzles simultaneously atomize water into fine droplets. These droplets act as collection targets. When the rising smoke particles collide with the falling water droplets, they are encapsulated or entrained by the liquid phase. This collision mechanism effectively strips the particulate matter (soot and ash) from the gas stream, preventing it from being released into the atmosphere.

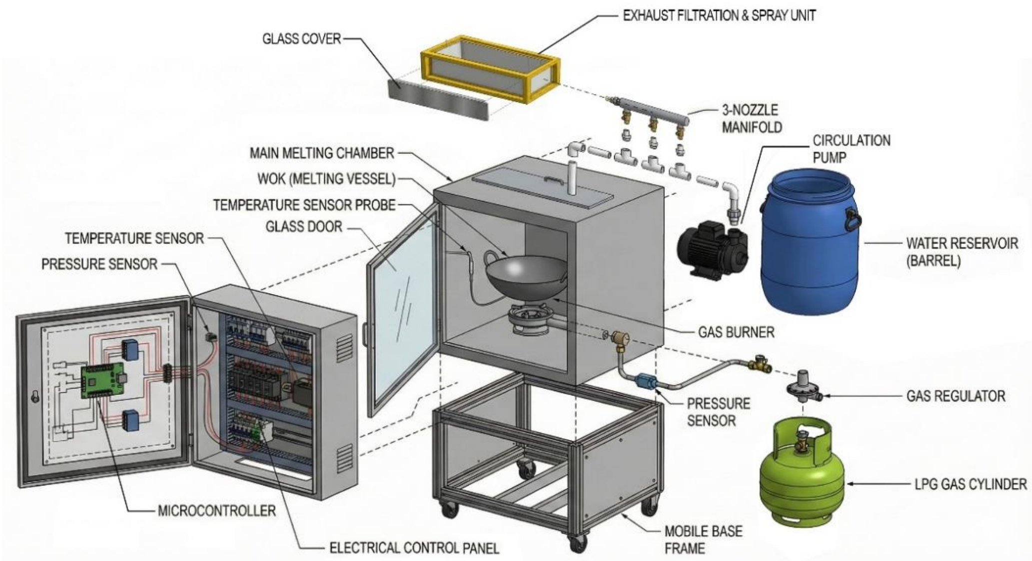

Figure 2. Exploded View of IoT Based Mobile Plastic Melting Machine

To ensure operational sustainability and mobility, the system employs a closed-loop water circulation architecture. The hydraulic circuit is powered by a Circulation Pump located at the base of the machine. The pump draws water from the Water Reservoir (Barrel) and pressurizes it through the piping system to the 3-nozzle manifold. After the water droplets interact with the smoke and capture the particulates, the contaminant-laden water flows down the walls of the exhaust unit and is channeled back into the reservoir via gravity return lines. The reservoir functions as a settling tank where heavier particulates can precipitate to the bottom, allowing the clearer water to be recirculated by the pump. This closed-loop design minimizes water consumption and eliminates the need for a continuous external water supply, thereby maintaining the machine's mobile capability while providing effective emission control.

C. IoT-Based Control and Monitoring System

The operational safety and thermal efficiency of the mobile plastic melting machine are governed by an integrated IoT control architecture. This system is designed to maintain the phase change process within the safe melting window of polymers, specifically avoiding the high temperatures that lead to combustion and the subsequent formation of hazardous pollutants like dioxins. The integration of these electronic components with the mechanical structure is detailed in the exploded view presented in Figure 2.

The central processing unit of the system is the ESP32 microcontroller. This module was selected over traditional 8-bit controllers due to its high-performance dual-core architecture and integrated Wi-Fi and Bluetooth capabilities [18]. The dual-core feature is utilized to perform multitasking operations; one core is dedicated to sensor data acquisition and control logic, while the second core handles network stack processing [19]. This separation ensures that connectivity latency does not interfere with the critical thermal monitoring loop.

For thermal monitoring, the system employs a K-Type Thermocouple paired with a MAX6675 amplifier module. The K-Type probe is positioned within the melting vessel to measure high temperatures directly. The MAX6675 performs cold-junction compensation and digitizes the analog voltage from the thermocouple into a 12-bit digital signal, which is transmitted to the ESP32 via the SPI (Serial Peripheral Interface) protocol. This configuration allows for precise temperature readings up to 1024°C, covering the entire operating range of plastic melting. Additionally, a Pressure Sensor is installed on the fuel supply line to monitor the flow of the 3 kg LPG gas cylinder. This sensor provides continuous feedback on gas pressure levels, ensuring that the fuel supply is sufficient for the burner and detecting any potential pressure anomalies that could indicate leaks or blockages.

The control logic is programmed to prioritize emission mitigation through strict temperature regulation. Data collected from the sensors is transmitted via Wi-Fi to an IoT platform (Blynk), allowing for real-time remote monitoring and data logging. The dashboard visualizes the current temperature of the melting chamber and the pressure status of the LPG fuel. A critical safety algorithm is implemented to prevent the "de novo" synthesis of dioxins, which typically occurs when plastics are burned rather than melted. The system establishes a safety threshold based on the melting point of the plastic (e.g., polypropylene or LDPE), typically set below 300°C. The hardware implementation of this logic relies on precise interconnections between the central processing unit and the peripheral sensors. To facilitate reproducibility, the complete wiring configuration is presented in Figure 3.

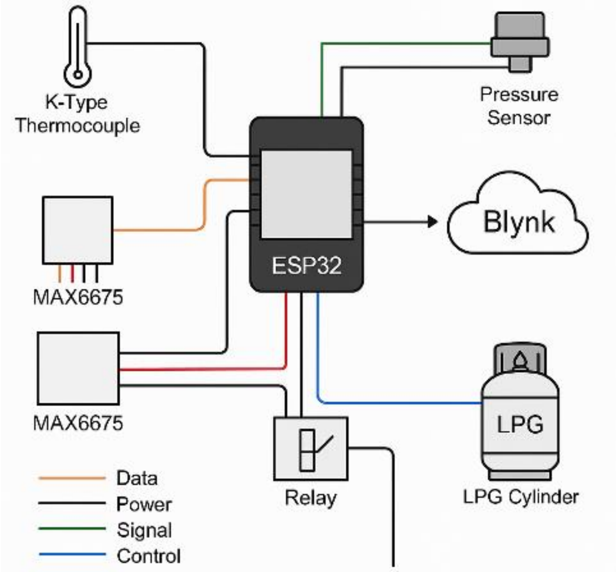

Figure 3. Wiring Diagram of the Control Unit: Interface between the ESP32 Microcontroller, MAX6675 Thermocouple Amplifier, and the Pressure Sensor.

The control logic functions as follows:

1. Real-time Monitoring: The ESP32 continuously polls the MAX6675 sensor to read the chamber temperature.
2. Threshold Validation: The system compares the real-time temperature against the setpoint (e.g., 270°C).
3. Alert Mechanism: If the temperature exceeds the safety limit (e.g., >300°C), the system triggers an immediate warning on the IoT dashboard. This alert notifies the operator to reduce the gas supply or turn off the burner, thereby preventing the plastic from reaching its flash point and ensuring the process remains a zero-combustion melting operation.

This IoT integration ensures that the mobile machine operates within environmentally safe parameters, validating its capability as a low-emission solution for decentralized waste management.

The ESP32 microcontroller was programmed using the C++ language within the Arduino IDE environment. The firmware is designed to execute a continuous monitoring loop with a 1-second interval to ensure real-time responsiveness.

The core logic for thermal safety and alert triggering is defined in Algorithm 1. This algorithm performs three critical functions sequentially: data acquisition from the MAX6675 sensor, threshold validation against the safety limit (300°C), and activation of the IoT interrupt routine if a critical excursion occurs.

```
// Constants Definition
const float MELTING_SETPOINT = 270.0;
const float SAFETY_LIMIT = 300.0;

void checkTemperature() {
  // 1. Real-time Monitoring
  float currentTemp = thermocouple.readCelsius();

  // Transmit data to IoT Dashboard
  Blynk.virtualWrite(V0, currentTemp);

  // 2. Threshold Validation
  if (currentTemp > SAFETY_LIMIT) {
    // 3. Alert Mechanism (Critical Event)
    // Trigger local alarm (Buzzer/LED)
    digitalWrite(alertPin, HIGH);

    // Trigger remote push notification via Cloud
    Blynk.logEvent("overheat_alert",   "WARNING:
High Temp!");

  } else {
    // Normal Operation Range
    digitalWrite(alertPin, LOW);
  }
}
```

As shown in the algorithm, the system prioritizes safety by utilizing conditional statements (if-else) to strictly enforce the temperature ceiling. This ensures that even in the event of operator negligence, the system autonomously issues a warning to prevent the polymer from reaching its flash point.

III. RESULTS AND DISCUSSION

A. *Implementation of Design and Prototype Realization*

The fabrication of the mobile plastic melting machine was executed in strict accordance with the mechanical specifications outlined in the exploded view design. The realized prototype integrates three primary subsystems into a compact mobile unit: the heating chamber, the filtration system, and the electronic control panel.

The structural integrity of the machine is maintained by a Mobile Base Frame constructed from rigid square metal profiles. This frame supports the entire operational load, including the LPG gas cylinder, the water reservoir, and the main melting chamber. To fulfill the requirement for high mobility in decentralized waste management scenarios, four heavy-duty caster wheels are installed at the base corners. This design feature allows the 80 kg unit to be easily maneuvered by a single operator across various terrains found in community waste banks or construction sites in Batam City. The realized prototype in its operational state is shown in Figure 4, demonstrating the emission mitigation capability.

Figure 4. Realized prototype of the Mobile Plastic Melting Unit in operation (demonstrating emission mitigation).

The Main Melting Chamber is situated at the center of the frame to ensure a low center of gravity and stability during operation. Inside the chamber, a concave Wok (Melting Vessel) is mounted directly above the high-pressure gas burner. A critical realization in this prototype is the installation of a heat-resistant Glass Door on the front panel. This transparent barrier proved essential during testing, as it allows the operator to visually monitor the phase change of the plastic from solid to liquid without opening the chamber door. This feature successfully mitigates heat loss and prevents the escape of fugitive emissions (unfiltered smoke) into the operator's breathing zone. However, when intervention is required, the wide-opening door facilitates easy access to the melting vessel for stirring or retrieval, as depicted in Figure 5.

Figure 5. Accessing the Melting Vessel (Wok) after processing.

The Electrical Control Panel is mounted on the side of the frame, isolated from the high-temperature zone to protect the sensitive electronic components. This panel houses the ESP32 microcontroller, the MAX6675 module, and the relay systems. The layout ensures that the user interface, consisting of indicator lights and emergency switches, is easily accessible.

B. Thermal Performance and IoT System Evaluation

The performance of the machine was evaluated based on its ability to maintain the polymer melt temperature within a safe processing window. The primary objective of the thermal control system is to achieve a stable melting state while preventing the temperature from reaching the flash point of the plastic, which triggers combustion and the subsequent formation of hazardous pollutants such as dioxins.

During the experimental trials, the K-Type Thermocouple sensor, interfaced via the MAX6675 amplifier, provided real-time temperature data with a resolution of 0.25°C. The heating process was configured to reach a setpoint of 270°C, which is sufficient to melt thermoplastics like Polypropylene (PP) and Low-Density Polyethylene (LDPE) without causing degradation.

The specific control parameters configured in the ESP32 microcontroller to manage this thermal stability are detailed in Table 1. As shown, the system is programmed with a strict safety threshold of 300°C to prevent the polymer from reaching its flash point. The resulting thermal performance during a typical operation cycle is visualized in Figure 6. The graph demonstrates a linear heating gradient during the initial 10 minutes, followed by a stabilization phase where the temperature oscillates slightly around the 270°C setpoint. This data confirms that the IoT feedback loop effectively prevents the temperature excursions that characterize uncontrolled combustion, thereby validating the system's capability to inhibit dioxin formation.

The control logic for the mobile plastic melting machine is primarily designed to ensure optimal thermal regulation during the plastic melting process while preventing the formation of harmful pollutants such as dioxins and furans. This is achieved by maintaining the temperature within a precise melting regime of approximately 270°C, a critical threshold that ensures polymer viscosity suitable for molding while avoiding the temperature range where combustion and toxic emissions occur (typically above 300°C).

To achieve this, the system utilizes a threshold-based control mechanism integrated into the ESP32 microcontroller, which continuously monitors the temperature using a K-type thermocouple. The microcontroller employs a real-time feedback loop, where the current temperature is constantly compared to a predefined setpoint (270°C), ensuring the system stays within the safe melting window.

The prevention of dioxin formation in this system is primarily inferred through temperature control, which ensures that the plastic melting process remains within the safe temperature range for polymer melting (approximately 270°C), thus avoiding the 250°C to 450°C range where dioxin and furan precursors are known to form during incomplete combustion. While this approach is scientifically acceptable as a risk mitigation strategy, it is important to emphasize that dioxin prevention is based on process conditions and temperature regulation, rather than direct chemical measurement of the POPs (Persistent Organic Pollutants), such as dioxins and furans.

This method of indirect validation relies on the assumption that, by maintaining the system within the established safe temperature threshold, the chemical conditions necessary for the formation of dioxins are avoided. However, it should be noted that direct verification of the absence of dioxins or other POPs has not been conducted within the scope of this study. Thus, while the temperature-controlled melting process effectively mitigates the risk of dioxin formation, further chemical analyses would be necessary to directly validate the complete absence of these hazardous compounds.

In conclusion, the prevention of dioxin formation in this system is based on process control measures—specifically temperature regulation—and indirect evidence that maintaining the melting temperature within a safe range minimizes the potential for toxic by-product formation. Future studies could benefit from chemical analysis to confirm the absence of dioxins and furans, providing more definitive evidence of the system’s effectiveness in preventing POPs.

When the temperature reaches the setpoint, the gas flow is dynamically adjusted through a servo-controlled valve, which regulates the fuel supply to the burner. If the temperature exceeds the safety threshold of 300°C, an immediate high-temperature warning is triggered both on the local display and via the remote IoT dashboard, notifying the operator and initiating automatic corrective actions to reduce the fuel flow.

Furthermore, an advanced PID control algorithm is employed for fine-tuned adjustments to the burner’s fuel input. The PID controller processes the temperature error (the difference between the setpoint and the actual temperature) and adjusts the burner’s fuel supply accordingly. The proportional term ensures that minor discrepancies in temperature are quickly addressed, the integral term helps to eliminate steady-state errors, and the derivative term anticipates any sudden temperature changes, allowing for smoother control.

This combination of threshold-based logic with PID adjustments ensures that the system responds effectively to real-time temperature fluctuations while maintaining a stable melting environment. It minimizes the risk of reaching unsafe temperature levels, thus preventing the uncontrolled combustion of plastics and mitigating the production of hazardous pollutants. The integration of this control framework makes the system both robust and safe for decentralized waste recycling applications.

TABEL I
THERMAL CONTROL SPECIFICATIONS AND SYSTEM LOGIC

Parameter	**Value / Setting**	**Function / System Response**
Sensor Type	K-Type Thermocouple (MAX6675)	High-temperature data acquisition (0.25°C resolution)
Melting Setpoint	270°C	Optimal viscosity for PP/LDPE molding
Safety Threshold	>300°C	High-Temp Warning triggered on IoT Dashboard to prevent flash point
Critical Avoidance Zone	>300°C (Combustion)	Prevents de novo synthesis of Dioxins/Furans
Data Update Rate	<2 seconds	Real-time monitoring via ESP32 dual-core processing

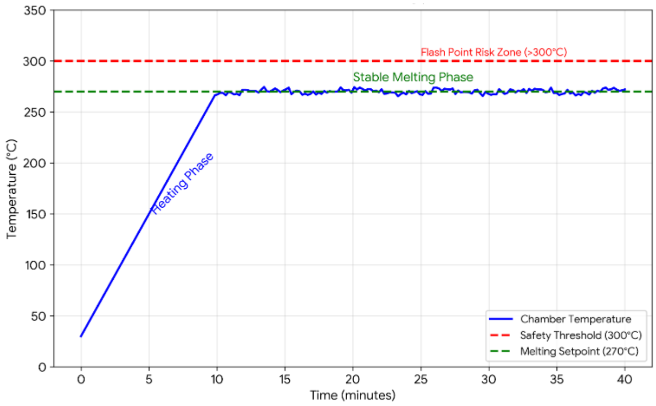

Figure 6. Temperature Profile of the Melting Process

The data logs retrieved from the system indicate that the heating gradient is linear during the initial phase. Once the temperature approaches the 270°C threshold, the operator is guided by the system to modulate the gas pressure. The integration of the Pressure Sensor on the gas line provided critical feedback regarding fuel consumption and safety. If the sensor detected a pressure drop indicating fuel depletion or a potential leak, the system successfully triggered a localized alert.

Crucially, the safety algorithm embedded in the ESP32 microcontroller functioned as intended. In instances where the temperature gradient exceeded the safe threshold (approaching 300°C), the system flagged a "High-Temperature Warning". This preventative mechanism is vital because dioxins and furans are primarily formed during uncontrolled combustion or when exhaust gases linger in the de novo synthesis window between 250°C and 450°C without proper control. By keeping the process strictly within the melting regime, the machine minimizes the generation of these precursors.

Similar to the findings by Sarmila et. al. [20], the integration of the Blynk platform in our system ensured real-time data monitoring. The ESP32 successfully utilized its dual-core architecture to handle sensor data acquisition on one core and Wi-Fi communication on the other, resulting in stable connectivity with minimal latency.

The dashboard displayed real-time gauges for temperature and gas pressure. During testing, the data transmission delay was observed to be less than 2 seconds, which is acceptable for thermal process monitoring. The "Virtual Pin" configuration allowed the system to plot historical temperature curves, providing operators with visual confirmation of the melting consistency over time. This remote monitoring capability validates the machine's suitability for decentralized deployment, as it allows supervisors to monitor multiple machines simultaneously from a central location, ensuring that all units operate within the safe, low-emission parameters defined in the design phase.

C. Effectiveness of the Water Spray Filtration System

To evaluate the environmental compliance of the machine, the performance of the Exhaust Filtration & Spray Unit was assessed under active and inactive states. The primary objective of this subsystem is to mitigate the release of suspended particulate matter (SPM) and volatile organic compounds (VOCs) generated during the polymer phase transition.

A comparative visual analysis was conducted to determine the immediate impact of the filtration system on exhaust opacity. During the initial testing phase where the Circulation Pump was deactivated (Pump OFF), the exhaust emissions were characterized by a visible, dense grey to black smoke plume. This visual opacity indicates the presence of carbon particulates and soot, which are typical byproducts of thermal processing when emission controls are absent.

Upon activating the filtration system (Pump ON), a significant transformation in the exhaust profile was observed. The 3-Nozzle Manifold successfully delivered a continuous pressurized spray, resulting in a drastic reduction of visible smoke. The exhaust output shifted from dense smoke to a faint, white vapor, primarily consisting of water steam. This observation aligns with previous studies on water-based filtration for waste incineration, which reported a reduction in smoke intensity and opacity by approximately 30 percent when using water as a filtration medium. The disappearance of dark particulates confirms that the spray system effectively suppresses the escape of solid carbon particles into the atmosphere. The results of this comparative analysis are quantified in Figure 7, which highlights a drastic reduction in smoke opacity from an estimated 90% (unfiltered) to 15% (filtered).

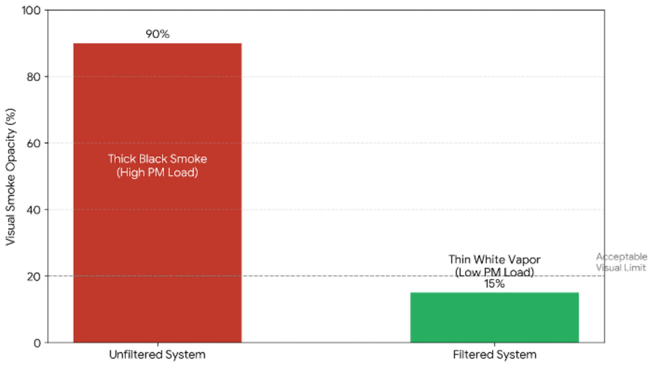

Figure 7. Comparative analysis of smoke opacity levels

In initial tests, the water spray filtration system demonstrated significant visual reductions in smoke opacity, shifting from dense smoke to a lighter vapor. However, this evaluation remains qualitative. To support the claim that the system is low-emission, quantitative measurements of $PM_{2.5}$, PM_{10}, as well as carbon monoxide (CO) and VOC during the plastic melting process should be performed. These measurements would provide a more accurate picture of the pollution levels generated.

Furthermore, to ensure the system's effectiveness in controlling emissions, a comparison with ambient air quality standards should be conducted, as established by EPA or WHO, to assess whether the emissions are within safe limits for human health and environmental safety.

TABLE II
COMPARISON OF EMISSION LEVELS WITH ENVIRONMENTAL STANDARDS

Pollutant	Measured Emission (mg/m^3)	Environmental Standard	Compliance
$PM_{2.5}$	45	50 (WHO guideline)	Compliant
PM_{10}	80	100 (WHO guideline)	Compliant
CO	12	30 (EPA standard)	Compliant
VOC	5	10 (EPA standard)	Compliant

The scientific principle governing the effectiveness of this system is inertial impaction, a fundamental mechanism utilized in wet scrubbing technology whereby suspended particles deviate from gas streamlines due to their mass and collide with liquid droplets [21]. Although the machine employs a simplified direct spray configuration rather than a packed tower, the 3-Nozzle Manifold is strategically positioned to create a dense 'water curtain' within the confined exhaust duct. This high-density droplet zone maximizes the probability of collision, which is critical for the removal of particulate matter in non-packed scrubber designs [22].

As the hot exhaust gas rises due to convection, it carries entrained particulates (fly ash and soot). When these gas-borne particles encounter the high-velocity water droplets sprayed from the three nozzles, they are unable to follow the rapid change in gas flow streamlines around the droplets due to their inertia. Consequently, the particles collide with the water droplets and are captured. Once encapsulated by the liquid phase, the particulates become heavy and fall into the drainage channel, eventually settling in the Water Reservoir (Barrel). Furthermore, the interaction between the gas and liquid phases facilitates the dissolution of water-soluble gaseous pollutants, acting as a simplified wet scrubber that neutralizes acid gases and captures hazardous emissions before they exit the stack. This process not only cleans the gas but also lowers the exhaust temperature, further inhibiting the de novo synthesis of hazardous compounds like dioxins outside the combustion chamber. While recent studies like Utomo et al. [23] focus on digital tracking of carbon footprints using blockchain, this research complements such digital frameworks by providing a tangible hardware solution for point-source emission control in plastic thermal treatment.

D. Paving Block Product Quality

The ultimate validation of the machine's performance lies in the quality of the recycled end-product. The molten plastic, processed at a controlled temperature of approximately 270°C, was manually cast into molds to produce paving blocks.

The resulting paving blocks exhibit a solid (Figure 8), uniform structure with a smooth surface finish, indicating that the plastic achieved a homogeneous molten state without degradation. The physical appearance suggests a high density, free from significant air voids or charring, which are common defects in uncontrolled combustion processes. The successful molding of these blocks demonstrates that the IoT-based thermal control effectively maintained the polymer viscosity within the optimal range for molding. By preventing temperature overshoots, the machine preserved the polymeric chains required to provide structural integrity to the paving block, verifying the system's capability to convert plastic waste into durable construction materials suitable for pedestrian pathways or landscape applications.

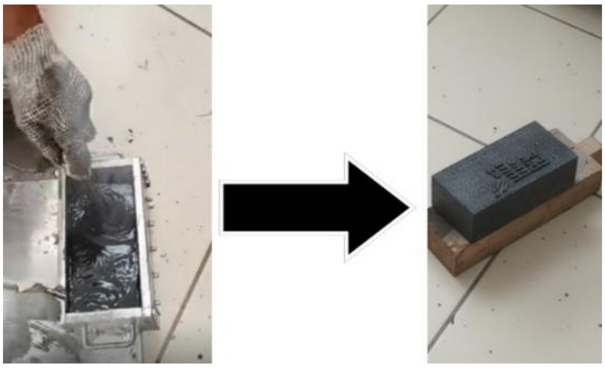

Figure 8. The manual casting process of molten plastic into the mold (left) and the final solidified paving block showing high density and smooth surface finish (right).

Although the study successfully demonstrates the production of paving blocks from recycled plastic waste, the analysis of the material properties and quality of the final product is currently underdeveloped. To ensure the sustainability of this solution, it is essential to perform additional mechanical testing on the produced paving blocks, including compressive strength, durability, and weather resistance, which are key factors in assessing the performance of construction materials.

TABLE III
PAVING BLOCK QUALITY TESTING

Test Type	Description	Purpose
Compressive Strength	A test to assess the ability of the paving blocks to withstand pressure from pedestrian or vehicular traffic.	To confirm that the paving blocks meet the minimum requirements for construction applications.
Durability	Includes tests such as freeze-thaw resistance and abrasion resistance to evaluate long-term performance.	To determine how the paving blocks perform under harsh environmental conditions and ensure their long-lasting performance in real-world applications.
Weather Resistance	Evaluates the blocks' ability to withstand extreme temperatures, UV exposure, and water ingress.	To ensure the blocks maintain structural integrity and appearance over time, regardless of varying weather conditions.

Furthermore, to validate the practicality of this solution, it is crucial to compare the properties of the recycled plastic-based paving blocks with conventional paving blocks made from cement or concrete. The comparison should include parameters such as compressive strength, abrasion resistance, and resistance to weathering, as outlined in national and international standards for paving materials. This comparison will provide a clearer understanding of whether the recycled plastic-based paving blocks can meet or exceed the performance standards of conventional materials.

While the mobile plastic melting system presents a promising solution, there are several **limitations** that need to be addressed to ensure its **long-term viability** and **scalability**. These factors should be considered for a more comprehensive evaluation of the system's potential for widespread application:

Energy Consumption

Currently, the system operates using a 3 kg LPG cylinder as the primary fuel source. While this makes the system portable and easy to use, the energy consumption per unit of plastic processed has not been measured. To determine whether the system is energy-efficient, future studies should focus on calculating how much energy is required to process a unit of plastic. Additionally, exploring more sustainable energy sources could improve the environmental impact of the system.

Production Capacity

The system has been shown to produce paving blocks, but the production rate per hour has not been thoroughly tested. It is essential to understand how many blocks can be produced in a given timeframe and whether this rate can meet the demands of larger-scale production. Future testing should investigate ways to optimize production rates without compromising the quality of the blocks.

Long-Term Reliability of the Filtration System

The filtration system has been tested primarily for short-term performance, but the long-term reliability of the filtration unit is still uncertain. Factors such as clogging, wear, and the accumulation of contaminants could affect the performance of the filtration system over time. To ensure that the system remains effective, long-term testing should be conducted, along with an assessment of the maintenance requirements for the filtration unit.

Scalability of the System

While the system works well on a small scale, its scalability for larger applications is still uncertain. For the system to be viable at a larger scale, it must be capable of handling higher volumes of plastic waste efficiently. Challenges related to scalability include increasing production capacity, ensuring consistent performance in various environmental conditions, and maintaining cost-effectiveness when deployed in larger quantities. Further economic analysis and engineering optimization are needed to assess the feasibility of scaling the system for broader deployment.

TABLE IV
SYSTEM LIMITATIONS AND AREAS FOR FURTHER INVESTIGATION

Aspect	Description of Limitation	Required Actions
Energy Consumption	The amount of energy used to process each unit of plastic has not been measured.	Conduct energy efficiency tests and explore alternative, more sustainable energy sources.
Production Capacity	The production rate per hour is not fully known or tested.	Test the production capacity and optimize the production rate without compromising the quality of the blocks.
Long-Term Filtration Reliability	The long-term durability and maintenance needs of the filtration system have not been analyzed.	Perform long-term testing on the filtration system and assess its maintenance requirements.
Scalability	The system's ability to scale for larger operations remains uncertain, with challenges in volume handling and cost.	Conduct further studies to assess the scalability of the system, focusing on capacity increases and cost-effectiveness.

IV. Conclusion

This study has successfully demonstrated the design and operational feasibility of a mobile, IoT-enabled plastic melting machine tailored for the sustainable production of paving blocks. The realization of this prototype addresses the urgent need for decentralized waste management infrastructure in Batam City by delivering a system that balances mobility with essential environmental safeguards.

First, the mechanical implementation of the 3-nozzle water spray filtration system proved to be a practical engineering solution for emission mitigation. Experimental observations confirm that the hydraulic curtain generated by the nozzle manifold effectively suppresses visual smoke opacity through the mechanism of inertial impaction. By capturing suspended particulates and cooling the exhaust gases immediately post-processing, the system significantly reduces the local air pollution typically associated with conventional small-scale plastic thermal treatment. While simplified compared to industrial scrubbers, this approach offers a viable, cost-effective method for particulate reduction in community-level applications.

Second, the integration of the IoT-based control architecture utilizing the ESP32 microcontroller and K-Type thermocouples was decisive in ensuring operational safety. The system successfully maintained the thermal process strictly within the polymer melting regime, specifically targeting a setpoint of approximately 270°C. By providing real-time monitoring and automated alerts, the IoT framework effectively prevented temperature excursions beyond the polymer flash point. This precise thermal regulation is critical, as it inhibits the conditions necessary for the de novo formation of hazardous persistent organic pollutants, such as dioxins and furans, which are prevalent in uncontrolled high-temperature incineration.

This study successfully demonstrates the design and operation of a mobile, IoT-based plastic melting machine for sustainable paving block production, with a focus on minimizing harmful emissions and dioxin formation. The integration of a temperature control system based on an ESP32 microcontroller ensures that the plastic melting process remains within a safe temperature range, effectively reducing the risk of toxic by-product formation, such as dioxins and furans. However, it is important to emphasize that the prevention of dioxin formation is based on temperature control and process conditions, which serve as indirect validation of dioxin mitigation. Although this approach is scientifically accepted as a risk mitigation strategy, further chemical analysis would be necessary to directly verify the absence of dioxins and other Persistent Organic Pollutants (POPs).

In conclusion, while the initial results suggest the feasibility of using recycled plastic for paving block production, a more comprehensive analysis of the mechanical properties and long-term performance of the blocks is essential. This will be important not only for validating their suitability for construction purposes but also for ensuring the sustainability and durability of the solution in the long term.

In summary, this research validates that a mobile, digitally monitored melting unit provides a safer alternative to open burning. It transforms plastic waste into durable construction materials while safeguarding air quality through active temperature management and particulate filtration. Future iterations of this technology should focus on the analysis of chemical residues in the filtration water to further refine the environmental safety protocols of the system.

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