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Development of a Low-Cost Automated Injection Molding Device for Sustainable Plastic Recycling and Circular Economy Applications

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Abstract: In response to the critical demand for innovative solutions to tackle plastic pollution, this research presents a low-cost, fully automated plastic injection molding system designed to convert waste into sustainable products. Constructed entirely from repurposed materials, the apparatus focuses on processing high-density polyethylene (HDPE) efficiently without hydraulic components, thereby enhancing eco-friendliness and accessibility. Performance evaluations identified an optimal molding temperature of 200 °C, yielding consistent products with a minimal weight deviation of 4.17%. The key operational parameters included a motor speed of 525 RPM, a gear ratio of 1:30, and an inverter frequency of 105 Hz. Further tests showed that processing temperatures of 210 °C and 220 °C, with injection times of 15 to 35 s, yielded optimal surface finish and complete filling. The surface finish, assessed through image intensity variation, had a low coefficient of variation (≤5%), while computer vision evaluation confirmed the full filling of all specimens in this range. A laser-based overflow detection system has minimized material waste, proving effective in small-scale, community recycling. This study underscores the potential of low-cost automated systems to advance the practices of circular economies and enhance localized plastic waste management. Future research will focus on automation, temperature precision, material adaptability, and emissions management.

Keywords: plastic recycling; injection molding; circular economy; resource recovery; sustainable production; HDPE recycling; eco-friendly

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Citation: Sinchai, A.; Boonyang, K.; Simmala, T. Development of a Low-Cost Automated Injection Molding Device for Sustainable Plastic Recycling and Circular Economy Applications. *Inventions* **2024**, *9*, 124. https://doi.org/10.3390/inventions9060124

Academic Editor: Theocharis Tsoutsos

Received: 16 November 2024
Revised: 5 December 2024
Accepted: 9 December 2024
Published: 17 December 2024

1. Introduction

Plastic has become an integral part of modern life, finding applications in various sectors, from packaging to furniture. However, the widespread use of plastic has led to significant environmental challenges, particularly in waste management and pollution control [1]. The difficulty in decomposing plastic waste and its increasing volume poses serious threats to ecosystems and human health [2]. In response to these challenges, there is a growing interest in developing cost-effective and efficient methods for plastic recycling. One promising approach is the use of automatic plastic injection molding machines for recycling plastic waste into new products. This research work aims to address the plastic waste problem by designing and constructing a low-cost, fully automated plastic injection molding machine using second-hand materials.

The offered device is designed specifically for small-scale applications and localized recycling initiatives. While the device may not currently compete economically with large-scale industrial systems, its design prioritizes affordability, accessibility, and versatility, making it well suited for small-scale applications such as educational use, prototyping, or community recycling programs. It demonstrates a practical and accessible solution for promoting sustainability in resource management.

The proposed machine operates on the principles of injection molding, a manufacturing process widely used in the production of plastic parts. By applying this technology to recycling, we aim to transform plastic waste into various useful products such as flowerpots, vase blocks, and other household items. This approach not only reduces the volume of plastic waste but emphasizes the potential of decentralized recycling efforts and the creation of value from waste materials.

In the context of HDPE recycling, the thermal processing and melting stages may lead to the release of toxic gases. In addition to commonly discussed emissions, such as carbon dioxide (CO_2), other potentially harmful gases, including carbon monoxide (CO) and volatile organic compounds (VOCs), may also be produced during the degradation of HDPE. The exact composition of these emissions depends on factors such as temperature, oxygen availability, and material composition, including any additives present in the HDPE. While this study focuses on estimating the possible emissions based on known data, experimental validation is required to determine their presence and concentration in the developed system. Addressing these emissions is critical for ensuring the sustainability and safety of small-scale injection molding systems, as outlined in later sections of this paper. In addition, the recycling of plastics like HDPE through injection molding has the potential to reduce waste and minimize greenhouse gas emissions when compared with the production of virgin materials, contributing to global sustainability efforts [3,4].

This research offers several novel contributions:

1. Frugal innovation: we developed a low-cost automated recycling machine using reclaimed materials.
2. Industrial-grade safety: we integrated advanced safety features in a compact recycling device.
3. Circular economy: we transformed waste plastic into valuable products for sustainable management.
4. Innovative design: we operated without hydraulics, focusing on efficient thermoplastic processing.
5. Performance evaluation: we established key operational parameters for small-scale recycling technologies, highlighting the potential usage in localized and educational applications.

The structure of this article is as follows: Section 2 reviews the literature, followed by Section 3, which outlines the methodology. Section 4 presents the performance evaluation along with the experimental results. Section 5 discusses optimization insights, implications, and future directions, while Section 6 summarizes the key conclusions of the research work.

2. Literature Review

Global production and plastic disposal continue to pose significant environmental challenges. Borrelle et al. projected that plastic waste inputs to aquatic ecosystems could reach up to 53 million metric tons per year by 2030, highlighting the urgency of addressing this issue [5]. Microplastics, formed from the degradation of larger plastic items, have become a growing concern in particular. They have been found in marine organisms, potentially entering the food chain and posing risks to human health [6]. Brahney et al. found evidence of microplastic pollution in remote areas, demonstrating the pervasive nature of plastic contamination [7].

The effects of plastic pollution on marine ecosystems have been well documented. Shen et al. reviewed the impacts of microplastics on marine organisms, revealing potential threats to biodiversity and ecosystem functioning [8]. Furthermore, Yong et al. discussed the implications of plastic pollution on human health, emphasizing the need for comprehensive waste management strategies [9].

Recent advancements in recycling technologies have shown promise in addressing the plastic waste crisis. Ragaert et al. provided an overview of mechanical recycling processes for thermoplastics, highlighting the potential of injection molding in recycling applications [10]. The authors emphasized the importance of understanding material properties and processing conditions to ensure the quality of recycled products.

Injection molding involves melting plastic material and injecting it into a mold cavity, where it cools and solidifies into the desired shape. The process is versatile and can be used with various thermoplastic materials, making it suitable for recycling applications [11].

Conformal cooling channels (CCCs) have also emerged as a critical innovation in improving injection molding efficiency. These channels can achieve up to 62.9% better cooling performance compared with traditional systems, significantly reducing cycle times and improving thermal uniformity [12,13]. Despite these advancements, CCCs are typically complex and expensive, limiting their use in small-scale or low-cost applications.

In the context of injection molding, Zhao et al. investigated the use of recycled plastics in the process, focusing on the challenges and opportunities associated with using mixed plastic waste [14]. Their study demonstrated the feasibility of producing high-quality products from recycled materials through optimized processing parameters.

While industrial-scale recycling facilities leverage advanced automation technologies, smaller, low-cost systems remain underexplored. Automation systems, such as LabVIEW-based pneumatic injectors [15] and adaptive in-mold pressure controls [16], have improved process reliability and part quality in industrial applications. However, such systems often require significant investment and technical expertise, highlighting the need for simplified and cost-effective solutions tailored to localized recycling efforts.

While large-scale industrial recycling facilities exist, there is growing interest in developing small-scale, low-cost recycling solutions. These systems can be particularly beneficial in areas with limited access to centralized recycling facilities or for small businesses and educational institutions [17].

Zander et al. demonstrated the feasibility of constructing a low-cost plastic extruder for recycling purposes, using readily available components and open-source designs [18]. Similarly, Chong et al. developed a small-scale injection molding machine for educational purposes, highlighting the potential for such systems in promoting hands-on learning about plastic recycling and manufacturing processes [19].

Material and process innovations in hybrid composites have shown promise in improving the mechanical properties of recycled products. For example, wood fiber composites reinforced with glass and carbon fibers achieved tensile strength increases of 30–38% [20]. Rapid tooling technologies have further demonstrated up to 89% reductions in cooling times [21], paving the way for more efficient production cycles. However, these advances often target large-scale systems, leaving opportunities to adapt similar principles for small-scale recycling technologies. In addition, low-cost epoxy resin molds with enhanced cooling efficiencies have reduced cooling times by approximately 22%, showcasing practical innovations for cost-effective production [22].

The development of small-scale, low-cost recycling solutions has gained traction in recent years. Dertinger et al. presented an open-source design for a small-scale plastic recycling system, which included an injection molding component [23]. Their work showcased the potential for distributed recycling and additive manufacturing (DRAM) in promoting circular economy principles.

Likewise, Cruz Sanchez et al. explored the technical and economic feasibility of distributed recycling via additive manufacturing (DRAM) in rural areas [24]. Their findings suggested that such systems could provide both environmental and economic benefits to communities with limited access to centralized recycling facilities.

Despite the progress in recycling technologies, several challenges remain. Eriksen et al. identified key barriers to plastic recycling, including contamination of waste streams, degradation of material properties during recycling, and lack of standardized quality assessment methods for recycled plastics [25]. The authors emphasized the need for improved sorting technologies and design-for-recycling approaches to enhance the quality and value of recycled materials.

Advancements in compatibilization techniques for biopolymers from renewable resources show promise in overcoming challenges like brittleness and cost [26]. The review highlights strategies such as reactive methods and nanoparticle incorporation to enhance compatibility and performance in biopolymer blends. These developments enable significant improvements in properties like strength and elongation, making biopolymers more viable alternatives to traditional plastics.

In the realm of quality assessment, Vollmer et al. proposed a standardized methodology for evaluating the quality of recycled plastics, addressing a critical gap in the recycling value chain [27]. Their work contributes to efforts in establishing reliable quality standards for recycled materials, which is essential for increasing market acceptance and value.

Furthermore, while optimization techniques like grey-based Taguchi methods have improved product quality by reducing warpage (16.42%) and birefringence (74.74%) [28], their application in low-cost, small-scale systems is limited. This highlights the need for simplified optimization frameworks for non-specialist users. Taguchi-based optimizations in injection molding have improved material properties and processing efficiency. For talc-filled polypropylene (TFPP), tensile strength increased by 10.5% and shrinkage reduced by 0.97% [29]. In non-pneumatic tire molds, a semi-annular conformal cooling channel design reduced pressure loss by 77%, cycle time by 9.6%, and shrinkage by 0.012%, enhancing cooling efficiency and tire quality [30].

Summary of Gaps and Opportunities

The literature reveals several opportunities for improvement:

1. Accessibility and cost: advanced technologies like CCCs and automated controls are prohibitively expensive for small-scale applications.
2. Localized recycling needs: there is a lack of systems designed for decentralized, community-based recycling efforts.
3. Simplified automation: most automation methods require technical expertise, creating barriers for non-specialist users.
4. Tailored optimization: existing optimization techniques for molding processes are not adapted for low-cost, small-scale setups.

This work therefore addresses these gaps by developing a cost-effective, fully automated injection molding system that utilizes reclaimed materials, eliminates hydraulic components, and integrates user-friendly automation and performance optimization tailored to localized recycling needs.

3. Methods

This outlines the conceptual framework, design principles, and implementation procedures for the automatic plastic injection molding machine. The methodology encompasses the structural design of the machine, component selection, control system architecture, and software development.

3.1. Structural Design of the Automatic Plastic Injection Molding Machine

The structural design of the low-cost automatic plastic injection molding machine comprises four primary components (see Figure 1) [31]. These components are the machine base, the control system unit, the plastic injection unit, and the heater control unit. The base is constructed from galvanized steel, with dimensions of 2 $\times$ 2 inches for the main structure and 1.50 $\times$ 1.50 inches for the four legs, each 84 cm in length. The legs are designed to be foldable for enhanced portability. The tabletop consists of a 1 cm thick hardwood board measuring 80 $\times$ 50 cm.

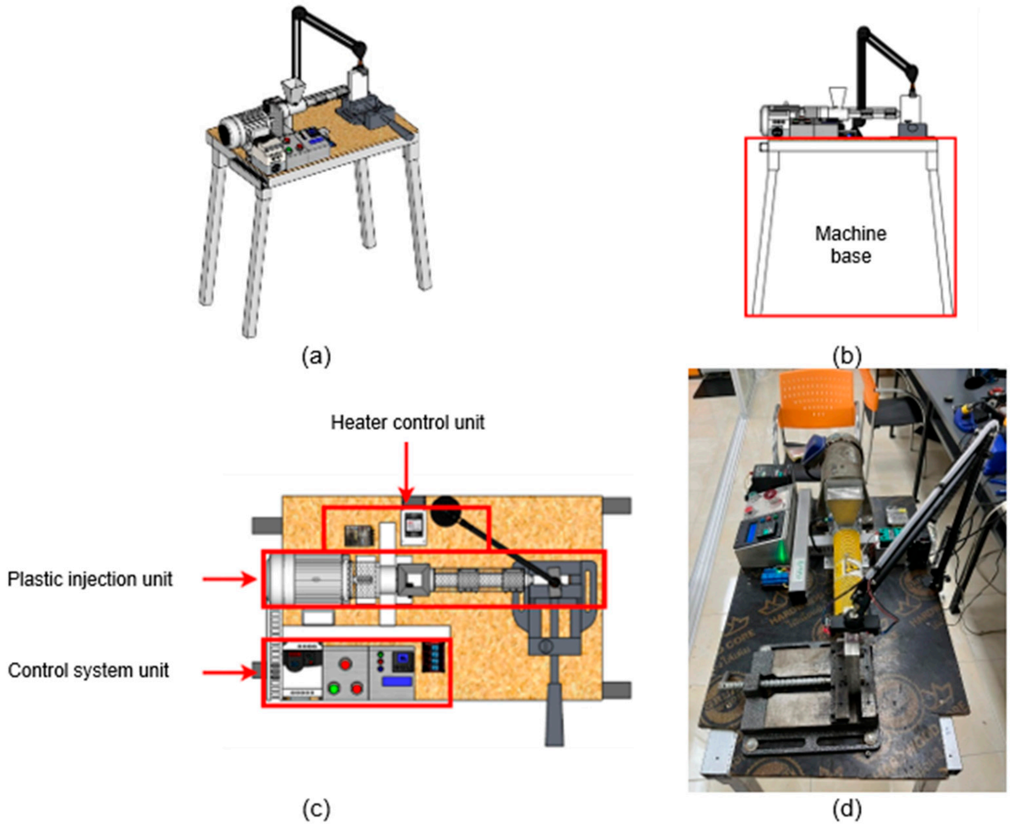


Figure 1. Structure and view of the automatic injection molding machine: (**a**) three-dimensional model of the machine; (**b**) front view—machine base; (**c**) top view—control unit; and (**d**) actual constructed machine.

3.2. Materials and Components

The research work utilizes a diverse array of components, including:

1. Inverter (220 V-3 phase 0.75/1 phase);
2. Gear motor (1/30 220 V 3 phase);
3. Stainless steel enclosures;
4. Push button switches (22 mm, 1NO 1NC);
5. Emergency switch (22 mm);
6. Temperature controller ("Primus" TMP-48-P-N-A);
7. Single-phase solid-state relay ("Primus" PS-01N-40);
8. Heatsink ("Primus" HP-03);
9. Cooling fan for electrical cabinet ("Primus" PMV115NP220);
10. K-type thermocouple ("Primus" TSK-13);
11. Band heater (Primus 5 W/cm^2 450 °C);
12. Wire duct;
13. Switching power supply (5 V/5 A);
14. Custom-made injection cylinder;
15. Drilling press machine vise (6 inches);
16. Terminal block (6 × 6 slots, 600 V/15 A);
17. Four-channel 5 V relay module;
18. Arduino mega 2560 R3;
19. IR infrared obstacle avoidance module (3–5 V DC);
20. Laser head sensor module (KY-008, 5 V);
21. Laser receiver module (5 V);
22. Custom-designed CNC mold;
23. LCD with I2C module (LCD2 2 × 16 V);

Input Material Preparation

The exact origin of the input material is unknown. However, the HDPE used in this work was sourced from post-consumer plastic products, such as bottles and containers. The material generally underwent the following preparation steps:

1. Shredding: the collected HDPE was shredded into uniform pellets to facilitate handling and further processing.
2. Cleaning: the shredded material was thoroughly cleaned to remove any contaminants, such as dirt, labels, and adhesive residues, ensuring the purity of the material.
3. Drying: after cleaning, the material was dried at 70 °C for 2 h to eliminate any remaining moisture, preparing it for subsequent use (see Figure 2).

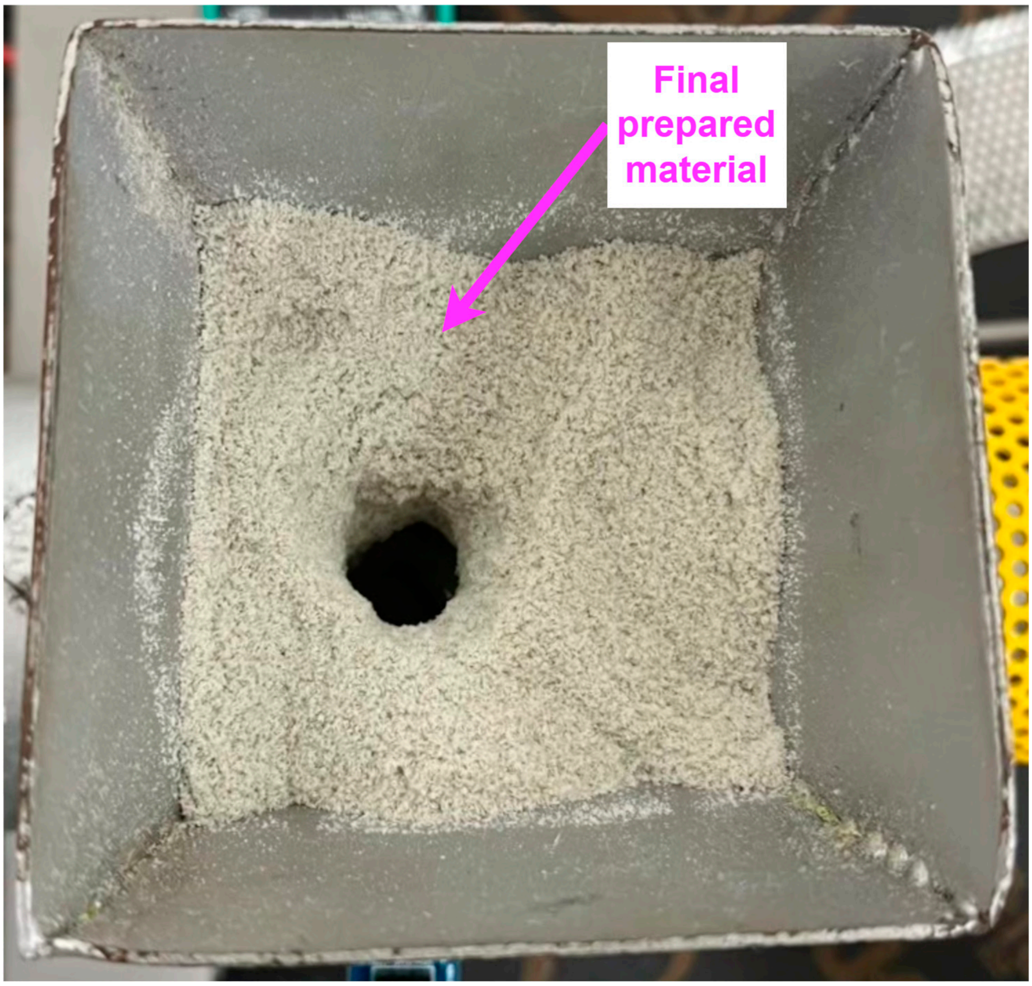


Figure 2. Final prepared material.

To save time, it is also possible to purchase the final prepared material (shredded, cleaned, and dried) directly from a recycling operator, which can streamline the material acquisition process.

3.3. Control Circuit and Heat Generation Circuit Design

This section describes the control circuit and heat generation circuit, both illustrated in Figure 3 to clarify their roles in the automatic plastic injection molding machine.

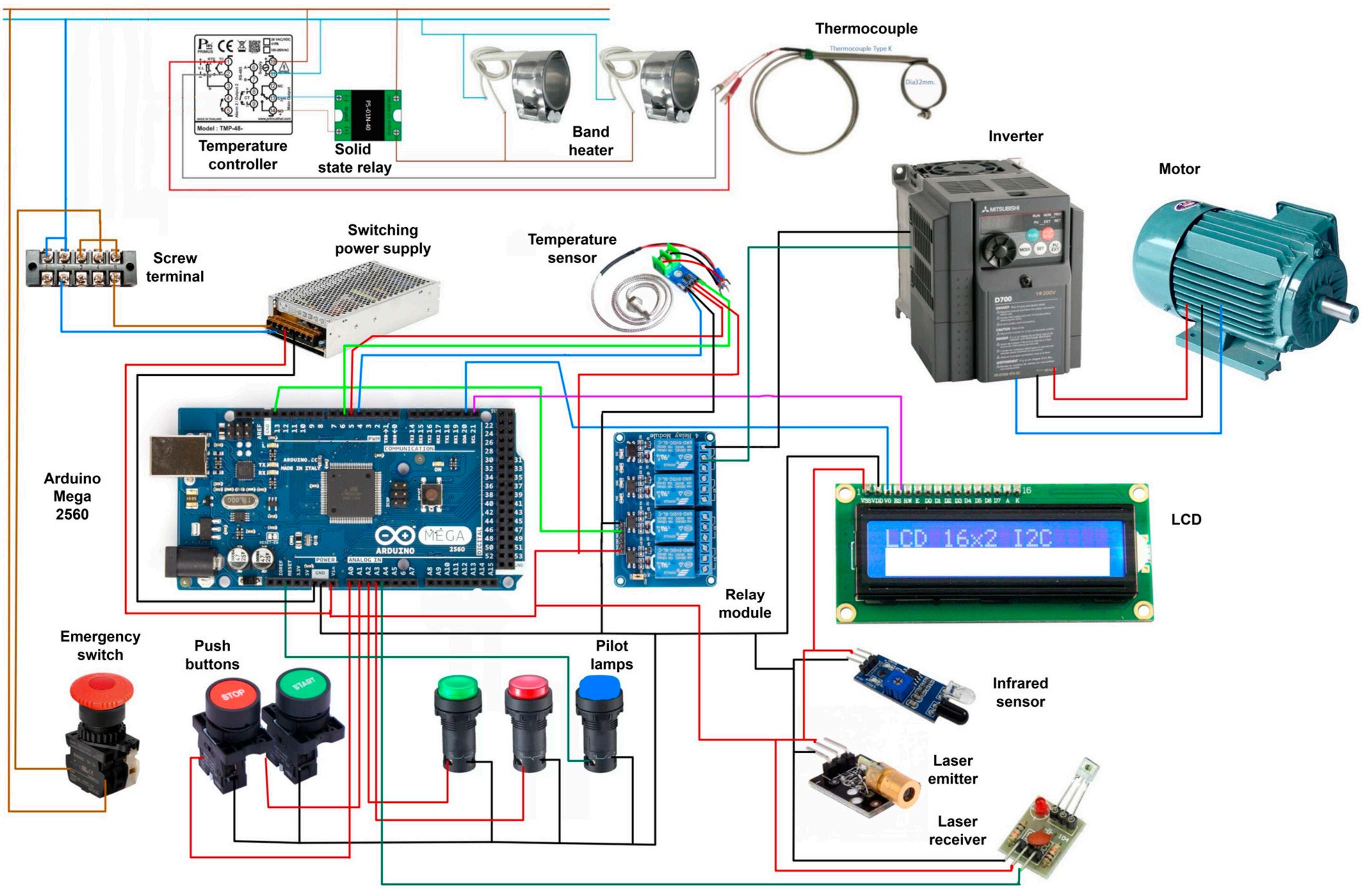


Figure 3. Overview of the device connections for the control circuit and heating circuit.

3.3.1. Control Circuit Design

The control circuit employs a switching power supply to convert 220 V AC (high voltage) to 5 V DC (low voltage) for use with control circuit components. The MEGA Arduino board serves as a power source for 5 V DC devices and controls the 5 V relay, which in turn activates the inverter. This configuration enables the three-phase motor to rotate, facilitating the transfer of plastic from the hopper into the injection cylinder.

3.3.2. Heat Generation Circuit Design

The heat generation circuit utilizes a temperature controller to manage the operation of a single-phase solid-state relay, which supplies power to the band heater [32]. Temperature regulation is achieved through feedback from a K-Type thermocouple sensor, ensuring stable and precise heating of the injection cylinder [33].

3.4. Mold Design

The mold is composed of two aluminum plates, as shown in Figure 4, with the front plate at the top and the back plate at the bottom [34]. Neither of the piecework images in the subfigures are to scale, nor are they perfectly aligned. To replicate this designed mold, each detail is explained. While this explanation applies to the current design, modifications can be performed to meet the specific requirements of each individual design preference. Each plate has the dimensions 140 mm × 90 mm × 11 mm. Each section is initially milled to a depth of 1.5 mm, forming a rounded rectangle with a length of 100 mm, a width of 45 mm, and an arc radius of 22.5 mm. The rounded rectangle is centered on each plate. During the formation of the rounded rectangle, a small 5 mm diameter cylinder bar, 1.5 mm in length, is formed on the right side of each plate, 11.25 mm from the edge and aligned with the horizontal centerline of the rounded rectangle. An inflow channel, 1–2 mm deep and wide, is milled as a straight line on each plate, approximately aligned with the vertical centerline of the rounded rectangle. On the front plate, the channel is at the lower horizontal edge, while on the back plate, it is at the upper horizontal edge (see Figure 4a,b). This inflow channel serves to feed melted plastic into the rounded rectangle inside the mold. In addition, two overflow channels are milled on both sides of the rounded rectangle along the horizontal centerline of both plates. The AMI alphabets are then milled to a depth of approximately 0.1 to 0.2 mm (see Figure 4b). A hole with a diameter of 5 to 5.5 mm is drilled at each corner, located 10 mm from both the horizontal and vertical edges of each plate. However, the drilling distance from each edge depends on the individual design of the hole size. These holes are used to secure the mold plates together with bolts at all four corners during injection.

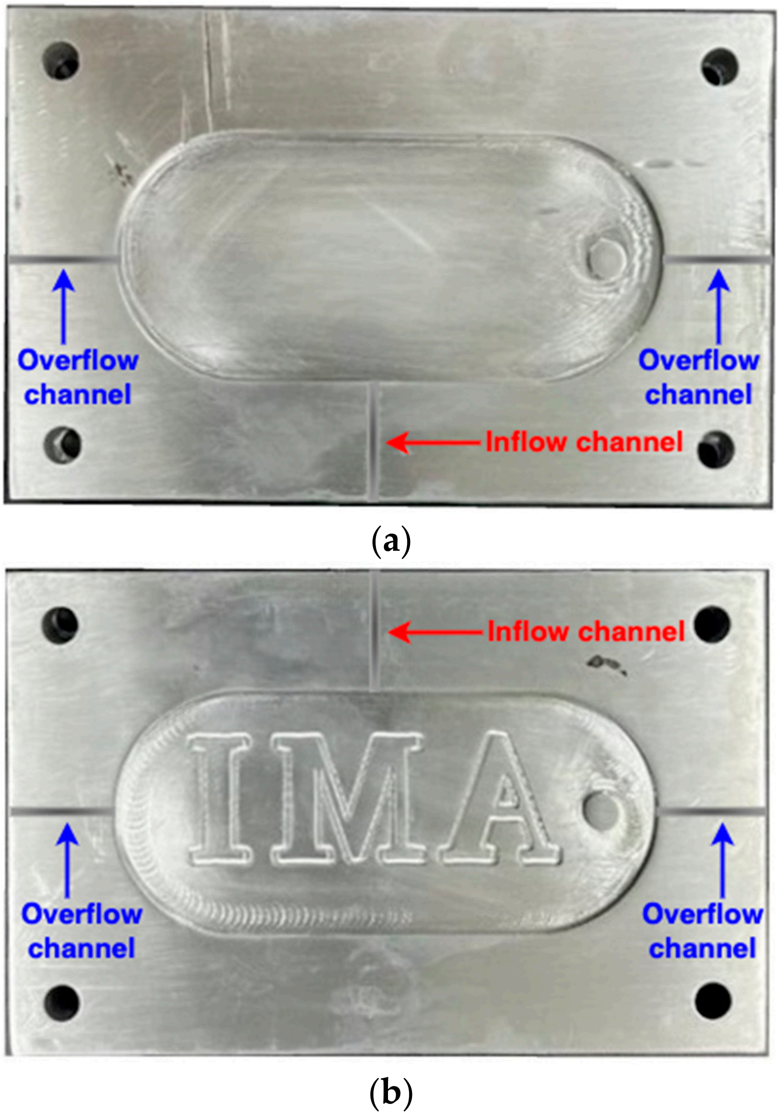


Figure 4. Designed mold: (**a**) front plate and (**b**) back plate.

3.5. Software Development and Operational Workflow

The software architecture for the automatic plastic injection molding machine consists of two primary components: an Arduino-based control program and a web-based monitoring and control interface, as depicted in Figure 5. These components work in tandem to execute the operational workflow of the machine.

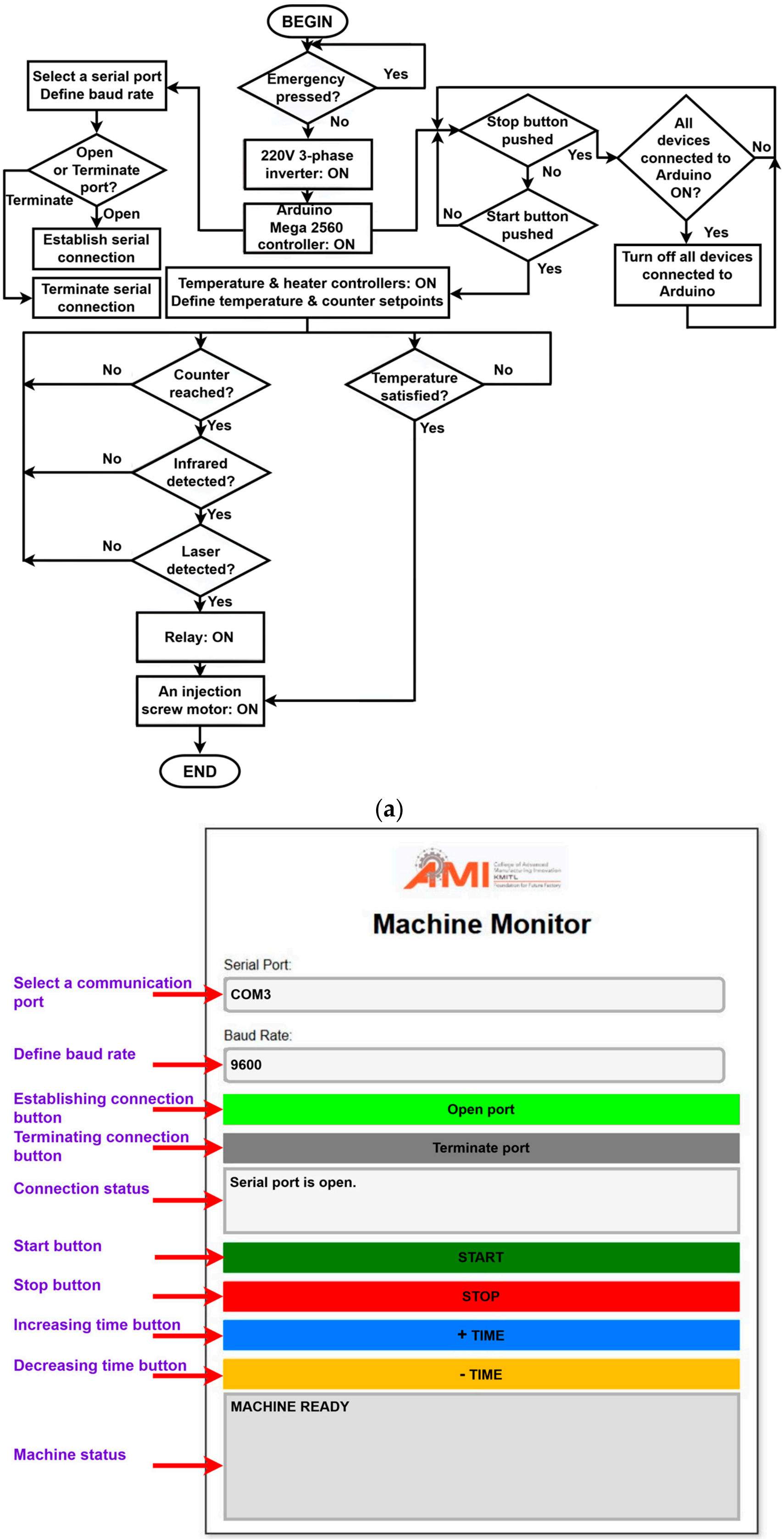


Figure 5. Workflow diagram of the program and control interface displayed via the web application: (**a**) workflow diagram and (**b**) control and display interface.

3.5.1. Arduino Control Program

The Arduino program, written in C++, manages the core functionality of the machine (see Figure 5a). Key features include:

- Real-time temperature monitoring and control using a PID algorithm;
- Injection cycle management with a configurable countdown timer;
- Sensor input processing for safety and operational feedback;
- LCD interface control for local status display.

The program implements a state machine architecture to manage different operational modes (e.g., idle, heating, injection, cooling). Error handling and safety checks are integrated throughout the control flow to ensure safe operation.

3.5.2. Web-Based Monitoring and Control Interface

A Flask-based web application provides a user-friendly interface for remote monitoring and control (see Figure 5b) [35,36]. The application features:

- Real-time data visualization of machine status and temperature;
- Remote control capabilities for start, stop, and parameter adjustment;
- A responsive design for access from various devices;
- A secure communication protocol for machine-to-interface data transfer.

The web interface is designed with a focus on intuitive operation and clear data presentation, enhancing the overall usability of the machine.

3.5.3. Operational Workflow

The operational workflow of the machine, as illustrated in Figure 5a, follows a systematic process to ensure efficient and safe plastic injection molding. The workflow is as follows:

1. System initialization: upon powering on, the machine performs a self-check of all components and sensors.
2. Temperature setting: the operator sets the desired temperature for the injection process through the interface.
3. Heating phase: the machine initiates the heating process, continuously monitoring the temperature until it reaches the set point.
4. Material loading: once the target temperature is achieved, the system is ready for material loading.
5. Mold closure: the mold is closed and secured, with safety checks to ensure proper closure.
6. Injection process: the machine initiates the injection process, moving the screw forward to inject molten plastic into the mold.
7. Cooling phase: after injection, the mold is cooled for a predetermined time.
8. Mold opening: once cooled, the mold is still opened manually.
9. Part ejection: the molded part is pulled out from the mold.
10. Cycle completion check: the system checks if the required number of cycles has been completed. (A). If yes, the process ends. (B). If no, the system returns to step 4 for the next cycle.
11. Emergency stop: at any point in the process, an emergency stop can be triggered, immediately halting all operations and requiring a manual reset.

This operational workflow ensures a systematic approach to plastic injection molding, maximizing efficiency while maintaining strict quality control and safety standards. The integration of automated processes with manual oversight capabilities allows for flexible operation adaptable to various production requirements.

3.6. Maintenance Protocols

Effective maintenance is essential to ensure the longevity and optimal performance of equipment, particularly in plastic injection molding processes as follows.

- Temperature regulation: After concluding operations, it is critical to set the temperature of the device to 0 degrees Celsius and allow it to cool to below 100 degrees Celsius. This practice not only preserves the heating system but also prevents thermal stress that could lead to component degradation or failure. Proper temperature management is vital as it minimizes the risk of thermal expansion and contraction, which can compromise the integrity of the machinery over time.
- Inspection of components: Regular checks of the material feeding hopper and laser sensor are imperative before and after use. Ensuring that these components are functioning properly helps to avoid production inconsistencies and potential safety hazards. Additionally, securely closing the material feeding hopper prevents foreign objects from entering the system, which could disrupt the injection process and damage equipment.

3.7. Safety Precautions

- Avoiding burns: During operation, it is crucial to avoid direct contact with the heated injection barrel and to refrain from handling the mold with bare hands due to accumulated heat. Always wearing gloves when interacting with these components is essential to prevent burns and ensure personal safety. This practice not only protects operators but also promotes a safer working environment by minimizing the risk of accidents related to thermal exposure.
- Troubleshooting procedures: In the event of a malfunction or operational failure, it is important to first press the reset button before investigating the root cause of the issue. This initial step helps to clear any temporary errors and may restore functionality. Following this, a thorough analysis should be conducted to identify and address the underlying problem. Understanding the reasons for equipment failure is vital for preventing future incidents and maintaining operational efficiency.

Emission Mitigation Strategies

Given the potential release of toxic gases (e.g., CO, VOCs such as aldehydes, benzene, and toluene) during HDPE melting, measures are necessary to ensure operator safety and environmental compliance [37,38]:

- Closed-system containment: install a gas containment hood to capture emissions at the source, preventing them from dispersing into the surrounding environment.
- Filtration and neutralization: equip the containment hood with activated carbon filters to absorb VOCs and catalytic converters to neutralize CO and aldehydes.
- Real-time monitoring: integrate gas sensors to detect concentrations of CO, VOCs, and other harmful gases, ensuring immediate alerts if thresholds are exceeded.
- Emergency response protocols: establish emergency protocols, such as immediate evacuation and ventilation shutoff, if high levels of toxic gases are detected.

3.8. Plastic Injection Experimental Setup

The plastic injection experiments were designed to evaluate the performance of the automatic injection molding machine using HDPE material. Three temperature settings (190 °C, 200 °C, 210 °C) were tested, with 10 injection cycles conducted at each temperature. The injection time was fixed at 60 s, and the motor frequency was set to 105 Hz. A stabilization period of 3–5 min between each cycle ensured consistent temperature. Key outcomes, such as weight consistency and deviations, were assessed for each experimental condition.

3.9. Mold Injection Experimental Setup

This section outlines the setup for the mold injection experiments, which aimed to determine optimal conditions for producing high-quality molded parts. The experiments varied temperature (190 °C, 200 °C, 210 °C, 220 °C, and 230 °C) and injection time (15, 20, 25, 30, and 35 s), resulting in five samples for each temperature condition.

The motor frequency was kept constant at 105 Hz, and a laser sensor was used to detect overflow, halting the injection process if excess plastic was injected. The mold dimensions were designed to allow for the injection of a maximum volume of approximately 115 cm^3 [34]. These parameters were adjusted to assess the impact of temperature and injection time on mold filling, part quality, and the occurrence of overflow.

The estimated maximum volume of 115 cm^3 for the injection cylinder is calculated based on a 32 mm diameter and 190 mm length. The cylinder contains a 4-turn rotary auger drill bit with a shaft radius of 2.5 mm and 10.2 mm thick flights. The 190 mm total length is divided into 7 turns, each with a 20 mm pitch. This ensures a consistent axial distance between consecutive turns, with each twist and flute also covering 10 mm and 20 mm in length, respectively. The design maintains uniformity in material movement across the 7 turns. The turns are confined within a 190 mm working section of the bit, and the maximum volume is derived from the following calculations.

1. Injection cylinder volume (use $V = \pi \times r^2 \times h$; r and h represent the radius and height of an object, respectively):

$$V_{cylinder} = \pi \times (16\text{ mm})^2 \times 190\text{ mm} \approx 152{,}807.07\text{ mm}^3.$$

2. Auger shaft volume (use $V = \pi \times r^2 \times h$; r and h represent the radius and height of an object, respectively):

$$V_{shaft} = \pi \times (2.5\text{ mm})^2 \times 190\text{ mm} \approx 3730.64\text{ mm}^3.$$

3. Estimated auger flight volume based on the ring-like area, modified from [39]:
   - Outer radius of flight = 2.5 mm + 10.2 mm = 12.7 mm
   - Flight area (viewed from the top of the auger drill bit tip) (use $A = \pi \times ({r_{outer}}^2 - {r_{inner}}^2)$; r_{outer} and r_{inner} represent the outer and inner radii of an object, respectively):

$$A_{flight} = \pi \times ((12.7\text{ mm})^2 - (2.5\text{ mm})^2) = \pi \times (161.29\text{ mm}^2 - 6.25\text{ mm}^2) = \pi \times 155.04 \approx 487.07\text{ mm}^2.$$

   - Flight volume (A_{flight} × twist length × turns):

$$V_{flights} = 487.07\text{ mm}^2 \times 10\text{ mm} \times 7 \approx 34{,}094.9\text{ mm}^3.$$

4. Total auger volume:

$$V_{auger} = V_{shaft} + V_{flights} = 3730.64\text{ mm}^3 + 34{,}094.9\text{ mm}^3 \approx 37{,}825.54\text{ mm}^3.$$

5. Maximum approximate feeding volume:

$$\begin{aligned} V_{maximum} &= V_{cylinder} - V_{auger} \\ &= 152,807.07\text{ mm}^3 - 37,825.54\text{ mm}^3 \approx 114,987.53\text{ mm}^3 \left(\text{or } \approx 115\text{ cm}^3\right). \end{aligned}$$

3.10. Setup for Quality Inspection of Specimens

3.10.1. Inspection of Surface Finish in Molded Parts

To evaluate the surface finish, a profilometer is typically required to measure the roughness of each molded part. However, due to the unavailability of the profilometer, an alternative technique based on image processing—specifically intensity variation and standard deviation [40]—is adopted and modified for this work. The inspection is performed using MATLAB under a student license for image processing. First, a flat surface of each molded part, obtained from the side where the AMI alphabets are not visible, is selected. This surface is then captured using a digital camera and stored as an image file on a computer. The digital camera is mounted on a ball-head tripod, with its lens directed towards the workpiece, which is placed on a suitable inspection plate. The optimal distance between the camera and the workpiece is empirically determined to achieve the best resolution. The acquired image is cropped to define the region of interest, which is then converted into an 8-bit grayscale image. The region of interest covers only the right-angled rectangular part of the specimen, as it appears to be the flattest area (see Figure 4a). Finally, the average intensity and the coefficient of variation are calculated using the cropped grayscale image as the input. It is noted that the 8-bit grayscale has an intensity range from 0 to 255, where this range transitions from black (0) to white (255).

3.10.2. Inspection of Complete Filling in Molded Parts

For the quality inspection of the molded parts concerning complete filling to complete filling, Zebra Aurora™ Vision Studio v5.2.10.93510 Professional was employed to differentiate between fully formed and incomplete parts. The inspection involved evaluating the clarity of patterns on the mold. These patterns were then compared with a reference to assess part completeness, using an 80–20 training–test ratio derived from 35 workpiece images. The inspection criteria included a percent of area ≥ 60%, indicating a fully formed part.

The inspection process involved:

- Assessing the integrity of the samples.
- Cropping images to focus on specific areas of interest.
- Detecting characters through area-specific recognition.
- Consolidating outputs into a single channel to determine the completeness of the parts.

The results of these inspections were analyzed in relation to the injection parameters (temperature and time) to determine the most effective settings for part quality.

It is important to note that the Aurora Vision software used in this study was obtained under a student license and is intended exclusively for academic and research purposes. It is not authorized for commercial use.

4. Performance Evaluation and Experimental Results

The study focused on evaluating the performance of a low-budget automatic plastic injection molding machine using high-density polyethylene (HDPE) as the raw material. The experiments were conducted to assess the efficiency of the machine, identify factors affecting its performance, and determine optimal parameters for different types of raw materials. In addition, a repeatability and reproducibility (R&R) aspect was considered to assess the precision and reliability of the measurement system involved in the process [41]. The results and discussion are presented below.

4.1. Plastic Injection Experiments

As described in Section 3.8, plastic injection experiments were conducted using HDPE at three temperatures: 190 °C, 200 °C, and 210 °C. The results demonstrate the critical impact of temperature on the consistency and reliability of the injection process.

At 190 °C, the average sample weight was 36.7 g, with an absolute deviation of 6.85%. This moderate variability indicates that the lower temperature was insufficient for complete material melting, leading to inconsistencies in flow and injection.

At 200 °C, the average sample weight improved to 44.9 g, with a significantly reduced absolute deviation of 4.17%. This suggests that 200 °C is near-optimal for processing HDPE, achieving stable material flow and consistent results.

At 210 °C, the average sample weight increased further to 59.3 g; however, the absolute deviation rose to 7.85%. The higher temperature enhanced material fluidity but introduced variability, likely due to overfilling or excessive flow dynamics.

These results demonstrate that while 200 °C provided the most consistent and reliable outcomes, deviations increased at both lower and higher temperatures due to insufficient or excessive melting. Maintaining precise temperature control around 200 °C is essential for ensuring high-quality and consistent results in plastic injection molding.

4.2. Accuracy and Deviations in Plastic Injection

The results indicate that the experiment conducted at 200 °C demonstrated the highest accuracy and stability in plastic injection, with the lowest average absolute deviation of 4.17% being observed from the mean weight. The experiments at 190 °C and 210 °C exhibited higher absolute deviations, with values of 6.85% and 7.85%, respectively. This suggests that 200 °C may be the optimal temperature for this specific process, yielding the most consistent and uniform output.

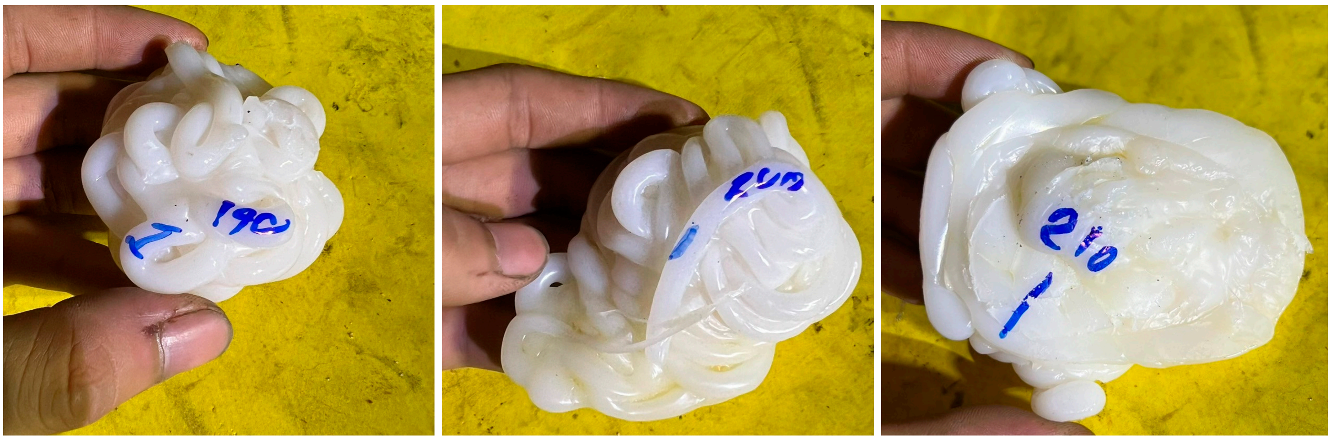
4.3. Effect of Temperature on Plastic Weight Stability

The lower percentage of deviation observed at 200 °C indicates that this temperature is the most optimal for the process, resulting in the most consistent and uniform output. In contrast, the experiments at 190 °C and 210 °C may not be as suitable, leading to greater variability in weight.

This deviation can be linked to the properties of the material at different temperatures. At lower temperatures, the plastic may not fully melt, causing incomplete injection, while higher temperatures increase fluidity, leading to overfilling and inconsistencies. Research in materials science supports the notion that optimal processing conditions significantly impact the quality of the final product. It is important to note that the optimal temperature of 200 °C is specific to HDPE, and other materials, such as polypropylene (PP) or polystyrene (PS), would require further testing to determine their ideal processing temperatures.

4.4. Physical Characteristics of Injected Plastic

The investigation into the physical characteristics of plastic samples revealed significant variations across three temperature regimes. At 190 °C, a sample weighing 35 g displayed a pronounced fibrous texture (see Figure 6a), indicating incomplete melting due to inadequate fluidity, which compromised structural integrity. In contrast, the sample produced at 200 °C, weighing 45 g, exhibited a notably smoother texture with reduced filament thickness (see Figure 6b). This improvement reflects better melting and flow characteristics, resulting in a more uniform distribution of plastic within the mold.



(**a**) (**b**) (**c**)

Figure 6. Physical characteristics of injected plastic: (**a**) sample at 190 °C, (**b**) sample at 200 °C, and (**c**) sample at 210 °C.

At the highest temperature of 210 °C, the sample weighed 61 g and demonstrated a much more liquid consistency, characterized by minimal filament presence (see Figure 6c). This outcome is attributed to enhanced fluidity, enabling more complete melting and flow of the plastic material. These findings underscore the critical role of temperature in shaping the physical properties of injection-molded plastics, with 200 °C emerging as the optimal temperature for balancing fluidity and structural integrity. Temperatures below this threshold result in poor melting and flow, while those above may lead to excessive fluidity, compromising the structural properties of the final product. The weight variations across the temperatures highlight the necessity of precise temperature control for consistent product quality.

4.5. Mold Injection Experiments

As described in Section 3.9, mold injection experiments were conducted to determine the optimal parameters for producing high-quality molded parts.

At lower temperatures (190 °C and 200 °C), incomplete mold filling was observed, especially at shorter injection times (15 and 20 s). At these temperatures, the plastic struggled to flow properly into the mold, leading to parts with voids and rough surfaces.

At higher temperatures (220 °C and 230 °C), the mold filling improved, but the risk of overflow increased, especially at longer injection times (30 and 35 s). The temperature of 220 °C provided a good balance between complete mold filling and part quality, with optimal injection times of 15–35 s.

The best results in terms of part quality, including surface finish and mold filling, were observed at 210 °C to 220 °C. However, at 230 °C, some parts exhibited signs of overheating, such as slight discoloration or warping, indicating that temperatures beyond this point could negatively affect part integrity.

These findings demonstrate the importance of optimizing both temperature and injection time. A balance must be struck to ensure complete mold filling while avoiding overflow or defects in the molded parts.

4.5.1. Analysis of Results

The results of the mold injection experiments revealed several important findings:

(a) Temperature effects

- Lower temperatures (190 °C and 200 °C) generally resulted in incomplete mold filling, especially at shorter injection times.
- Higher temperatures (220 °C and 230 °C) improved mold filling but increased the risk of overflow and potential part defects.
- The middle temperature range (210 °C) appeared to offer a good balance between mold filling and part quality.

(b) Injection time effects

- Shorter injection times (15 and 20 s) often resulted in incomplete parts, particularly at lower temperatures.
- Longer injection times (30 and 35 s) improved mold filling but increased the risk of overflow, especially at higher temperatures.
- The optimal injection time varied depending on the temperature, with higher temperatures generally requiring shorter injection times for complete mold filling.

(c) Part quality observation

- Parts produced at 190 °C showed clear signs of incomplete filling, with visible voids and rough surfaces (Figure 7a).
- Parts produced at 200 °C showed improved filling but still exhibited some imperfections (Figure 7b).
- The best overall part quality was observed in the 210 °C to 220 °C range, with good surface finish and complete mold filling (Figure 7c,d).
- At 230 °C, some parts showed signs of overheating, such as slight discoloration or warping (Figure 7e).

To sum up, the experimental findings underscore the intricate relationship between temperature, injection time, and the resultant quality of molded parts. At lower temperatures (190 °C and 200 °C), incomplete mold filling was prevalent, particularly during shorter injection durations. This phenomenon can be attributed to the insufficient fluidity of the material, which hampers its ability to fill the mold cavity effectively.

Conversely, the higher temperature range (220 °C and 230 °C) facilitated improved mold filling; however, it introduced challenges related to overflow and potential defects in the final product. This highlights the critical need for a careful balance between temperature and injection duration to optimize manufacturing outcomes.

The analysis of injection times revealed that shorter durations (15 and 20 s) frequently led to incomplete parts, particularly at lower temperatures. In contrast, extending the injection time to 30 and 35 s generally enhanced filling but raised the risk of overflow, especially at elevated temperatures. Notably, the optimal injection time was found to be temperature-dependent, with higher temperatures necessitating shorter injection periods to achieve complete mold filling.

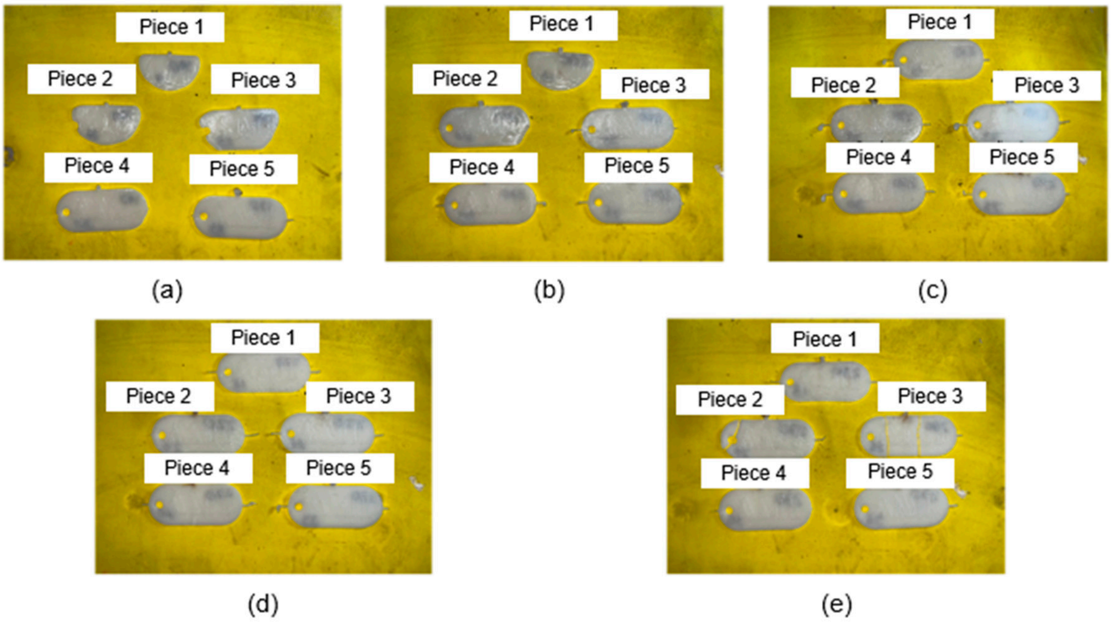


Figure 7. Characteristics of plastic samples injected at various temperatures and time intervals: (**a**) 190 °C for 15, 20, 25, 30, and 35 s (pieces 1–5); (**b**) 200 °C for 15, 20, 25, 30, and 35 s (pieces 1–5); (**c**) 210 °C for 15, 20, 25, 30, and 35 s (pieces 1–5); (**d**) 220 °C for 15, 20, 25, 30, and 35 s (pieces 1–5); (**e**) 230 °C for 15, 20, 25, 30, and 35 s (pieces 1–5).

Regarding the assessment of part quality through visual inspection and tactile examination, the parts produced at 190 °C displayed significant defects, such as voids and rough surfaces, while parts at 200 °C showed modest improvements yet still retained imperfections. The optimal quality was achieved within the 210 °C to 220 °C range, characterized by a superior surface finish and complete filling. However, at 230 °C, signs of overheating—such as discoloration and warping—were evident, underscoring the importance of precise temperature control in the injection molding process. The evaluation of part quality in terms of quantity is discussed in Sections 4.6.1 and 4.6.2.

These insights contribute valuable knowledge to the optimization of mold injection parameters, which is crucial for enhancing product quality and overall manufacturing efficiency.

4.5.2. Gas Emission Analysis During HDPE Melting

The thermal degradation of HDPE during the injection molding process results in the emission of various gases. For a continuous injection cycle using 108.1 g of HDPE (equivalent to the maximum feeding volume of 115 cm^3), the following emissions are estimated [42,43]:

HDPE input data
Volume of molten HDPE: 115 cm^3
Density of HDPE: 0.94 g/cm^3
Mass of HDPE melted:

$$\text{Mass} = \text{Volume} \times \text{Density} = 115\ \text{cm}^3 \times 0.94\ \text{g/cm}^3$$

1. Carbon dioxide (CO_2)

   Emission factor: combustion of HDPE typically produces 3.14 g of CO_2 per g of HDPE.
   Calculation based on stoichiometry [44]:

$$CO_2 = \text{Mass of HDPE} \times 3.14 = 108.1\ \text{g} \times 3.14 = 339.43\ \text{g}$$

Emission factor of CO_2 equivalent (CO_2e): 6.71 kg of CO_2e per kg of HDPE, as adopted from [45].
Calculation:

$$CO_2e = \text{Mass of HDPE} \times 6.71\ \text{kg} = 108.1 \times 10^{-3}\ \text{kg} \times 6.71 = 0.73\ \text{kg}\ (\approx 730\ \text{g})$$

2. Carbon monoxide (CO)

Emission factor: partial combustion or thermal degradation of HDPE produces ≈ 0.0025 g of CO per g of HDPE, as derived from [46].
Calculation:

$$CO = \text{Mass of HDPE} \times 0.0025 = 108.1\ \text{g} \times 0.0025 = 0.27\ \text{g}$$

3. Volatile organic compounds (VOCs)

Emission factor: thermal degradation produces ≈ 0.00247 g of VOCs per g of HDPE, as derived from [47].
Includes: acrolein, aldehydes (e.g., formaldehyde), benzene, toluene [48]
Calculation:

$$VOCs = \text{Mass of HDPE} \times 0.00247 = 108.1\ \text{g} \times 0.00247 = 0.267\ \text{g}$$

In a single injection cycle, the combustion and thermal degradation of HDPE release approximately 730 g of CO_2e, which represents the total greenhouse gas emissions, including CO_2, methane, and other gases. Additionally, approximately 0.27 g of CO and 0.267 g of VOCs (including acrolein, aldehydes, benzene, and toluene) are emitted. While these quantities may seem small, they contribute to global warming, respiratory issues, carcinogenic risks, and air pollution. Effective emission control is crucial to mitigate these environmental and health impacts.

The thermal degradation process, influenced by the operating temperature (ranging from 190 °C to 230 °C), determines the types and amounts of gases released. At lower temperatures (190 °C to 200 °C), emissions are generally lower, but more toxic gases like aldehydes, VOCs, and acrolein can form due to incomplete combustion. Higher temperatures (220 °C to 230 °C) result in a broader range of emissions, including CO_2, which contributes significantly to climate change; CO (which is toxic even at low concentrations); and benzene. This variety of gases—ranging from CO_2, a greenhouse gas, to VOCs, which can be harmful or toxic—highlights the need for careful control of the thermal process and appropriate safety measures.

Among these gases, CO_2 is the most significant contributor to greenhouse gas emissions, exacerbating climate change concerns. Managing these emissions is crucial for aligning injection molding processes with sustainability goals.

This analysis underscores the importance of managing emissions in continuous injection operations. Successive cycles without the introduction of new final prepared HDPE can lead to cumulative emissions and increase the risks of harmful gas buildup, especially in poorly ventilated environments. Effective containment and filtration solutions, as discussed in the Section Emission Mitigation Strategies and in Section 5.5, are essential for mitigating these risks.

4.6. Quality Inspection of Specimens

As described in Section 3.10, quality inspections of the molded parts were conducted using Aurora Vision software and image processing techniques. The inspections focused on the part completeness, with a percent of area ≥ 60% indicating a fully formed part, and surface finish, assessed through intensity variation and standard deviation.

The results were analyzed in relation to injection parameters (temperature and time) to determine optimal settings for part quality.

4.6.1. Surface Finish in Quantity Measurement

At various temperatures, the surface finish of the specimens (see Figure 7) was evaluated based on the average intensity and coefficient of variation. At 190 °C, only two specimens were evaluated, with an average intensity of 165.44 and a coefficient of variation of 8.54%. At 200 °C, three specimens showed an average intensity of 183.10 and a coefficient of variation of 9.65%. At 210 °C, all specimens were evaluated, yielding an average intensity of 190.88 and a significantly lower coefficient of variation of 1.66%. At 220 °C, the average intensity of all specimens increased to 196.65, with a further reduction in the coefficient of variation to 0.88%. At 230 °C, the average intensity of four specimens was 179.60, and the coefficient of variation was 1.76%. The coefficient of variation serves as an indicator of surface roughness, with lower values corresponding to smoother surfaces. A coefficient of variation below 5% suggests low roughness, while values above 5% indicate higher roughness [49]. Overall, the surface finishes at 210 °C, 220 °C, and 230 °C exhibited better quality compared with those at 190 °C and 200 °C, as evidenced by the lower coefficient of variation values at higher temperatures.

4.6.2. Temperature and Injection Time

- At 230 °C with 30 s of injection time (Figure 8a): the part shows good quality, passing the inspection criteria with a high percent of area value.

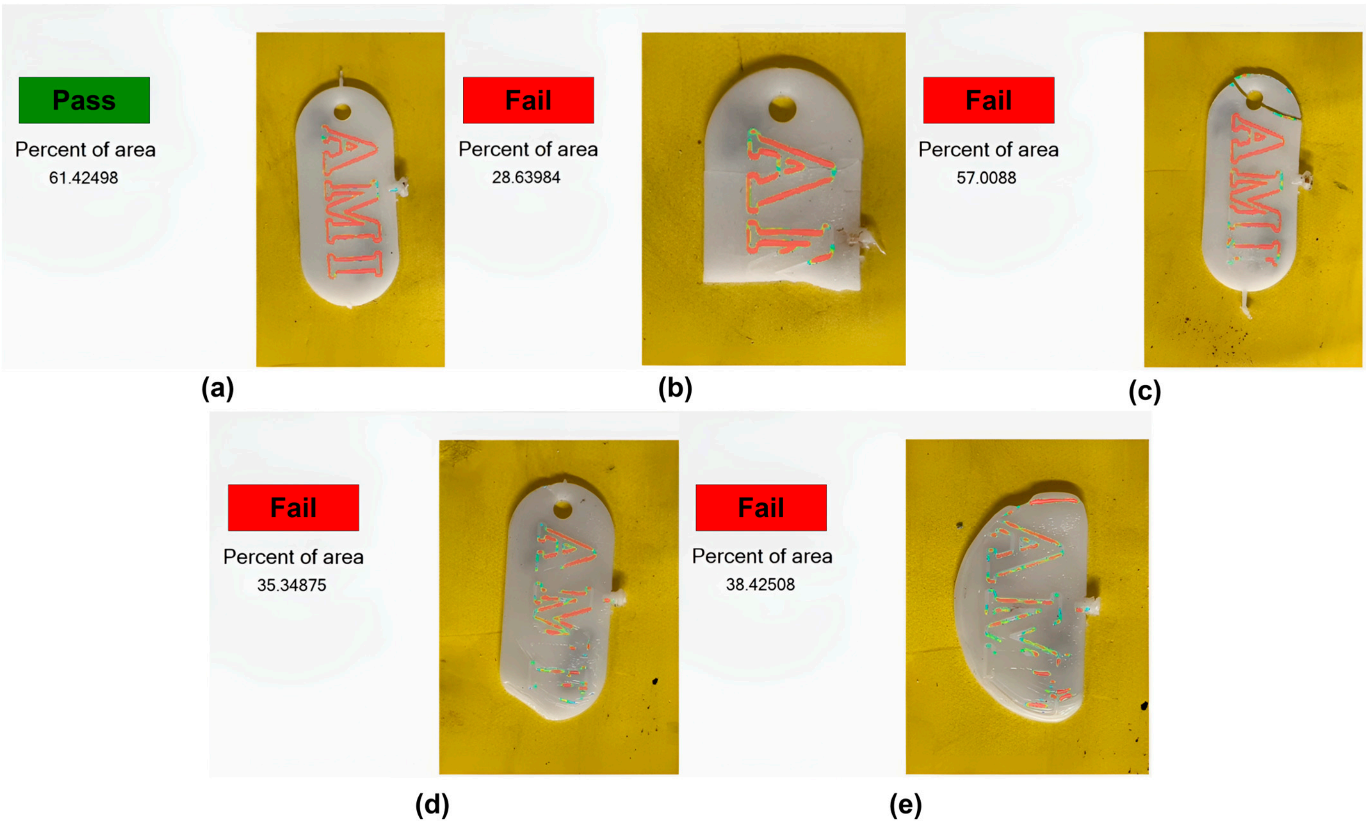


Figure 8. Quality of plastic samples injected at 230 °C and 200 °C across various time intervals: (**a**) sample at 230 °C for 30 s, (**b**) sample at 230 °C for 25 s, (**c**) sample at 230 °C for 20 s, (**d**) sample at 200 °C for 20 s, and (**e**) sample at 230 °C for 15 s.

- At 230 °C with 25 s of injection time (Figure 8b): the part shows good quality only in the upper part, like the first case, but the lower part is missing, so it fails the inspection criteria.
- At 230 °C with 20 s of injection time (Figure 8c): the part still maintains good quality, but there is a crack at the top, so it fails the inspection criteria.

- At 200 °C with 20 s of injection time (Figure 8d): the part shows improved quality but may not be as perfect as those injected at higher temperatures.
- At 200 °C with 15 s of injection time (Figure 8e): the part fails the inspection criteria, indicating incomplete injection.

4.6.3. Complete Filling in Quantity Measurement

The classification performance of Aurora Vision software demonstrates high accuracy, with most specimens being correctly identified (see Table 1). The results for unseen specimens, which the software had not previously processed, reveal 15 true passes (true positives), 9 true fails (true negatives), and 1 false pass (false positive), with no false fails (false negatives) (see Figure 7).

Table 1. Confusion matrix of classification.

	Predicted Pass	Predicted Fail
Actual pass	15 (TP)	0 (FN)
Actual fail	1 (FP)	9 (TN)

The absence of false fails and the relatively low number of false positives suggest that the system is effective at distinguishing between acceptable and defective parts. The single false positive may be attributed to variations in the appearance of defects or inconsistencies in defect presentation, such as lighting conditions, surface texture, or the type of defect. In terms of classification metrics, the software achieved an accuracy of 96%, a precision of 93.75%, a recall of 100%, and an F1-score of 96.8%. These values indicate that the software is highly effective, with no false negatives and a strong balance between precision and recall.

Regarding the assessment of part quality, the specimens produced within the optimal temperature range of 210 °C and 220 °C demonstrated high-quality injection molds, characterized by complete filling and superior surface finishes. This confirms that the injection molding process was well controlled in this range, resulting in well-formed parts that met the quality standards. These results align with the classification outcomes, as the software correctly identified these parts as passes. In contrast, parts produced at 190 °C and 200 °C exhibited incomplete filling and surface imperfections, such as voids and rough surfaces, indicating that these temperatures were suboptimal for achieving complete filling and quality molding. At 230 °C, although the filling was complete, the parts showed signs of overheating, such as discoloration and warping, highlighting the need for precise temperature control to avoid defects.

These findings suggest that Aurora Vision software can reliably assess part quality, confirming the successful correlation between temperature control, complete filling, and injection mold quality in the optimal range.

While the system performed well with this dataset, further testing with a larger and more diverse sample is needed to assess its robustness and reliability under varying conditions.

4.6.4. Temperature Effects

The results indicate that 230 °C consistently produced better-quality parts than 200 °C, particularly when paired with the appropriate injection time. This aligns with the characteristics of HDPE HD2308J, which has a melting point of 131 °C, making higher temperatures more suitable for ensuring full material flow and mold filling.

4.6.5. Injection Time Effects

Injection time significantly influenced part quality. For 230 °C, 25–30 s of injection time produced the best results, ensuring complete mold filling. Conversely, 15 s injection times were insufficient, leading to incomplete parts, especially at lower temperatures like 200 °C.

4.6.6. Quality Inspection System Efficiency

Aurora Vision software effectively distinguished between fully formed and incomplete parts by analyzing image clarity and comparing the percent of area. The system proved to be a reliable tool for assessing part completeness and provided valuable insights into the injection molding process.

4.6.7. Relationship with Production Parameters

The results highlight the importance of fine-tuning production parameters such as motor speed (525 RPM) and inverter frequency (105 Hz). These settings had a direct impact on material flow, mold filling, and part quality, underscoring their role in achieving consistent outcomes.

4.6.8. Material Properties

The performance of HDPE HD2308J material, with a melting point of 131 °C and a density of 0.94 g/cm^3, was key in determining the optimal processing conditions. The properties of the material influenced the ideal temperature and injection time required to produce parts with minimal defects and consistent quality.

4.6.9. Equipment Specifications

The specifications of the gear motor (1 HP, 525 RPM), inverter (1 HP, 105 Hz), and injection screw (1 inch diameter, 25 mm pitch) played a critical role in the injection process and the resulting part quality. These components ensured the proper flow of material and facilitated consistent molding under varying conditions.

4.6.10. Limitations and Development Opportunities

While the experiments demonstrated the ability to produce high-quality parts, several areas for improvement remain:

- Enhancing temperature control precision could reduce material degradation and improve consistency across production runs.
- Expanding the range of materials that can be processed by the machine would allow for broader applications and more versatile production capabilities.

5. Optimization Insights, Implications, and Future Directions

This section delves into the broader implications of the study, focusing on the optimization strategies identified, the observed machine performance, and the behavior of HDPE under various processing conditions. It highlights the practical significance of the findings in optimizing injection molding processes and explores the potential for further advancements. Moreover, limitations and areas for future research are discussed with the aim of enhancing the versatility and performance of the machine while contributing to sustainable recycling practices.

5.1. Optimal Processing Parameters

The results suggest that for the HDPE material used in this study, a temperature range of 200 °C to 210 °C provides the best balance between consistent weight, good mold filling, and part quality. This temperature range allows for adequate material flow while minimizing the risk of overheating and associated defects.

For the specific mold used in the later experiments, a temperature of 210 °C to 220 °C with an injection time of 15 to 35 s appears to yield the best results. However, these parameters may need to be fine-tuned based on the specific geometry part and desired characteristics.

5.2. Machine Performance

The low-budget automatic plastic injection molding machine demonstrated reasonable performance, with the ability to produce consistent parts under optimal conditions. The integration of a laser sensor for overflow detection is a valuable feature that helps prevent mold damage and material waste.

However, the variability observed in weight and part quality across different temperature settings suggests that there is room for improvement in temperature control and overall process stability. Enhancing the temperature regulation capabilities of the machine could lead to more consistent results across a wider range of operating conditions.

5.3. Material Behavior

The experiments provided valuable insights into the behavior of HDPE under different processing conditions. The clear differences in material flow and part characteristics across the temperature range tested highlight the importance of carefully selecting processing parameters for this material.

The strand-like features observed at lower temperatures and the more homogeneous texture at higher temperatures demonstrate how temperature affects the flow behavior of the material and the final part structure. This information can be crucial for optimizing part design and mold-filling strategies.

5.4. Process Optimization

This study underscores the importance of systematic experimentation in optimizing injection molding processes. By methodically varying temperature and injection time, it was possible to identify the most suitable processing window for the given material and mold design. This approach can be applied to other materials and part designs, allowing for efficient process optimization without the need for expensive simulation software or extensive trial-and-error testing.

5.5. Limitations and Future Work

This study presents a low-budget automatic plastic injection molding machine with significant potential but identifies several limitations and areas for future inquiry. Key considerations include the necessity to expand the material range beyond high-density polyethylene (HDPE) to achieve a more comprehensive understanding, as well as the evaluation of more complex mold designs to assess machine performance. Preliminary tests suggest that the machine could also process other thermoplastics such as polypropylene (PP), polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET), and acrylonitrile butadiene styrene (ABS), with estimated optimal processing temperatures for these materials ranging from 200 °C to 250 °C. Additional detailed evaluations are planned to confirm these capabilities.

Furthermore, conducting long-term stability tests would provide insights into consistency over extended production runs. The effects of cooling rates on part quality require further exploration, alongside opportunities for enhancing automation to improve overall efficiency. This study also raises concerns regarding the smoke and gas emissions generated during operation, highlighting the limitations of relying solely on ventilation and personal protective equipment such as masks and gloves. Advanced strategies, including closed-system gas containment and filtration systems, are essential for ensuring safety and minimizing environmental impact.

Future research will prioritize emissions management. This includes conducting experimental studies to precisely quantify the types and concentrations of gases emitted during HDPE processing. A focus will also be placed on designing and testing a gas containment hood equipped with advanced filtration systems to neutralize toxic gases. Moreover, alternative thermoplastics with lower emission profiles will be investigated as part of the effort to improve the sustainability of this technology. In addition, specific attention will be given to greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), which significantly contributes to climate change [3,4]. Strategies to minimize GHG emissions during processing will include optimizing thermal degradation conditions and exploring materials with lower carbon footprints.

Overall, while the research demonstrates acceptable results under optimized conditions, future efforts should focus on addressing these limitations to enhance machine capabilities and ensure user safety.

6. Conclusions

The research on a low-cost automatic plastic injection molding machine, developed using second-hand materials, has shown promising results, particularly in addressing plastic waste recycling. This machine successfully converted high-density polyethylene (HDPE) into valuable products, with optimal operating temperatures being identified between 200 °C and 210 °C, which minimized weight variations and ensured consistent quality.

In experiments with a customized mold, a temperature range of 210 °C to 220 °C, along with an injection time of 25 to 30 s, yielded the best results for mold filling and product quality. In contrast, lower temperatures (190 °C and 200 °C) led to incomplete filling, while higher temperatures (230 °C) caused defects such as warping and discoloration. These results highlight the significant impact of temperature and injection time on the quality of molded parts.

The addition of a laser sensor for overflow detection reduced material waste and mold damage, improving overall efficiency. Aurora Vision software effectively ensured part quality during production. While the machine performed well under optimized conditions, enhancements in temperature control, long-term stability, and automation are needed. Future research should focus on testing additional materials and addressing emission mitigation strategies and safety concerns for safe operation.

Author Contributions: Conceptualization, A.S., K.B. and T.S.; data curation, A.S., K.B. and T.S.; methodology, A.S., K.B. and T.S.; formal analysis, A.S.; investigation, A.S.; software, K.B. and T.S.; resources, K.B. and T.S.; validation, A.S.; visualization, K.B. and T.S., writing—original draft, A.S., K.B. and T.S.; writing—review and editing, A.S.; supervision, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Acknowledgments: The authors thank the College of Advance Manufacturing Innovation at King Mongkut's Institute of Technology Ladkrabang for partial financial support.

Conflicts of Interest: The authors declare no competing interests. The authors also declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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