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Development of an IoT-Based Mobile Plastic Shredder for Optimized Waste Management in Batam

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ABSTRACT

Plastic waste management has become a critical environmental issue, with its improper handling leading to severe ecological and health impacts. This research addresses the challenge by designing and developing an IoT-based mobile plastic shredding machine aimed at improving waste management efficiency, particularly in Batam City, Indonesia. Utilizing Borg and Gall's R&D framework, this study integrates IoT technology to enhance the machine's functionality, enabling real-time data collection and remote monitoring through mobile applications. The machine comprises three functional levels: a storage area for raw plastic bottles, a shredding unit with proximity sensors, and a post-shredding storage compartment. Key innovations include weight sensors for automatic material handling and real-time data transmission via the Blynk IoT platform, controlled by an Arduino microcontroller. The modular design ensures portability, easy maintenance, and adaptability for use in various locations, including coastal areas. Prototyping involved integrating proximity sensors, load cells, relays, and motor control systems to ensure smooth operation. The machine demonstrated consistent performance during testing, with its IoT features enabling remote control and monitoring via smartphones. This facilitates optimized waste collection and contributes to reducing environmental pollution caused by plastic waste. The IoT-based mobile plastic shredding machine not only enhances waste management efficiency but also supports sustainability goals. Its portability and environmentally friendly design make it a practical solution for managing plastic waste in underserved areas. This innovation provides a significant step toward addressing the global plastic waste crisis, aligning with technological advancements to promote sustainable waste management practices.

I. INTRODUCTION

Plastic waste management is an increasingly urgent environmental issue in this modern era. Plastic waste, which is often not properly managed, can have a serious impact on the environment and ecosystems. According to Nurfitriyani [1], plastic waste takes a very long time to decompose, which is between 100 to 500 years, which shows the urgency in its management emphasized that microplastic pollution in coastal and marine areas is a complex problem and requires special attention, because it can interfere with the health of marine ecosystems and humans [2]. In addition, reports regarding the ingestion of plastic by animals and its impact on human health are increasing, suggesting that plastic pollution is a serious threat that needs to be addressed effectively [3]. Plastic pollution represents a significant environmental challenge with far-reaching consequences for ecosystems and human health. The accumulation of plastic waste in various environments leads to soil and water pollution, which can subsequently affect human health through the food chain.

Research indicates that microplastics and other plastic debris can disrupt nutrient cycles and harm aquatic and terrestrial organisms, ultimately posing risks to food safety and human health [4]; [5]; [6]. The interaction of microplastics with soil pollutants has been shown to create complex ecological dynamics that can further exacerbate the degradation of soil health and agricultural productivity [7].

Plastic waste that is not managed properly has a significant negative impact on the environment, human health, and ecosystem sustainability. First of all, plastic waste can pollute aquatic ecosystems, which are important habitats for various species. According to Nurhayati, plastic waste that is thrown carelessly often ends up in the waters, disrupting the balance of coastal ecosystems and threatening aquatic life [8]. In addition, Auliyah noted that plastic waste contributes to environmental pollution, with a very long decomposition time, causing an accumulation of waste that continues to increase every year [9]. This has the potential to damage the basic structure and function of ecosystems, which in turn can disrupt the food chain and lead to a decline in biodiversity [10].

The ongoing global plastic waste crisis is exacerbated by persistent challenges in managing plastic waste, despite various efforts to reduce single-use plastics and enhance recycling initiatives. The root of the problem lies in unsustainable patterns of plastic production, which have escalated dramatically over the past few decades. It has been reported that only 9% of the 353 million tons of plastic waste generated in 2019 was recycled, with a significant portion ending up in landfills or leaking into the environment due to inadequate waste management systems [11]; [12]. This situation is particularly dire in middle-income countries, such as China and Indonesia, where rapid economic growth has not been matched by the development of effective waste management infrastructure, leading to substantial leakage of plastics into ecosystems [13].

In recent years, many countries have taken steps to ban the use of single-use plastics in an effort to reduce plastic pollution. However, the success of plastic waste management depends not only on government policies, but also on technological innovations that can help in the collection, processing, and recycling process of plastic waste. Plastic reduction policies, such as those implemented in several regions in Indonesia, show that despite efforts from the government, challenges in plastic waste management remain, especially related to low resource capacity and high plastic use in the community [14].

The problems faced by the Riau Islands Province, especially in the city of Batam, are increasingly urgent to be addressed along with significant population growth. In 2023, Batam's population is estimated to reach 1.240 million individuals and is projected to increase to around 2.8 million people by 2037 [15]. This rapid population growth has the potential to pose various challenges, especially in the fields of mental health, physical health, and social welfare.

With a projected significant population increase, Batam faces serious challenges in waste management, similar to the problems faced by other major cities in Indonesia. Every day, Batam produces around 900-1000 tons of waste, of which about 20 percent of the total consists of plastic or plastic-like materials [16]. This increase in the volume of plastic waste is a major concern due to the difficult nature of plastic, which can lead to a long-term environmental crisis if not managed properly [17]. With the above field conditions, research is needed that is expected to make a positive contribution to efforts to manage plastic waste that is more efficient, environmentally friendly, using the latest technology, and sustainable.

II. Research Method

Plastic waste management is an increasingly pressing challenge worldwide, especially with the increase in plastic production and consumption. One of the innovative solutions proposed is the development of a mobile plastic shredding machine, which is designed to reach locations that are difficult to access by conventional plastic waste processing facilities. This concept not only focuses on efficiency in waste management, but also utilizes Internet of Things [IoT] technology to increase the effectiveness and responsiveness of the waste management system.

The use of IoT technology in mobile plastic shredding machines can enable real-time data collection regarding the volume and type of plastic waste produced at certain locations. This is in line with research showing that IoT-based waste management systems can increase the efficiency of waste collection and processing, as well as reduce the environmental impact of this waste [18] , [19]. By utilizing sensors and mobile devices, this system can provide the information needed to optimize waste collection routes and increase public awareness about the importance of sustainable waste management [20]

The selection of Borg and Gall's R&D Framework [1983] as a methodology in developing an IoT-based plastic shredder machine is based on its ability to provide a systematic approach that is essential in developing complex technologies. This model consists of several systematic stages, including research and information gathering, planning, initial product development, field trials, and final product revisions. Each of these phases plays a crucial role in ensuring that the final product meets the stated objectives and effectively addresses the needs identified in the initial research stage.

In the first stage, research and information gathering, the main focus is to conduct an in-depth literature review and collect data relevant to the context of plastic waste management. This is important to understand user needs and gaps in existing solutions, as well as to identify technologies that can improve efficiency, such as the integration of the Internet of Things (IoT] which can assist in real-time monitoring and process automation [21]. This literature also includes research on the use of IoT in educational tools, which can improve user experience [22].

The method provides a structured and continuous approach, allowing for continuous revision and evaluation throughout the development process of an IoT-based plastic shredder machine. By integrating IoT, the machine is designed to improve operational efficiency, support sustainable plastic waste management, and provide key features such as real-time monitoring, process automation, and energy savings.

Although approaches such as Lean Startup and Design Thinking are also effective in product development, Borg and Gall's R&D Framework is more suitable for product research and development that requires in-depth evaluation and continuous revision based on the results of systematic field trials. This approach provides assurance that the technology being developed will function optimally and can be adapted according to needs that arise during field testing. The flow chart of this research can be seen in Figure 1 below.

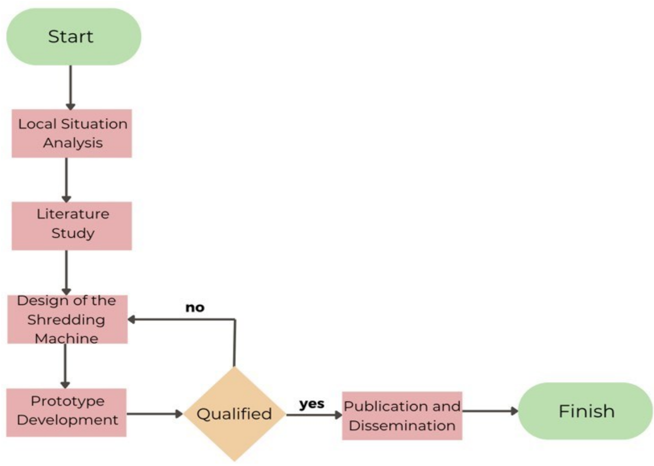

Figure 1. Research Flowchart

This research aims to design and develop a plastic shredding machine that is mobile and environmentally friendly. This machine uses rechargeable battery technology to drive the mechanical system rotary motor from the chopper. The concept of this shredder is designed in the form of a box with a height of 1.5 meters and a width of 1 meter, which is divided into three functional levels.

The first level is a storage area for raw plastic bottles before processing. To facilitate this process, there is a weight sensor or load cell 1 that functions to measure the weight of plastic bottle waste. When the weight reaches a certain threshold, this sensor will open the gate to the second level to direct the plastic bottle waste to the shredder.

The second level is where the crusher machine or shredding machine is located. Here, there is a proximity sensor that detects the presence of an object, in this case a plastic bottle, which then sets the ON/OFF of the shredder turning motor. The shredding process is carried out automatically after the object detection is performed.

The third level is a storage area for plastic that has been shredded. Here, there is a weight detection sensor or load cell 2 that functions to measure the weight of the waste shredding. Information about the weight of this shredded waste will be sent to the server through the Blynk platform to monitor the status of shredded plastic waste in real-time via smartphones, taking advantage of IoT (Internet of Things] technology.

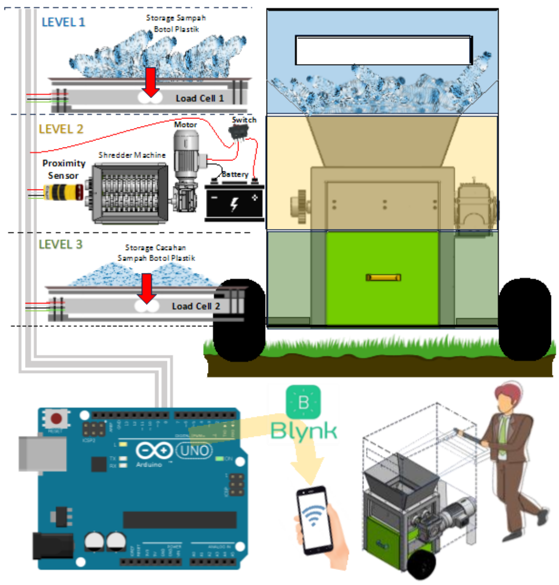

Figure 2. Design of IoT-based Mobile Plastic Shredding Machine

The entire control and monitoring process on this chopping machine is controlled through an Arduino microcontroller device. The engine is also equipped with caster wheels and wheels at the front that can be locked to maintain the stability of the engine while operating. With this concept, it is hoped that this plastic shredding machine can help in reducing environmental pollution due to plastic waste in an efficient and environmentally friendly way. The conceptual illustration of the design of this machine can be seen in the following Figure 2.

III. Results And Discussion

In this study, the performance of IoT-based shredder machine is compared with conventional machine to assess its operational efficiency, power consumption and impact on the environment. The following table provides a clear comparison between the two based on these key aspects as seen in table 1.

Steps in the Development of Borg & Gall's R&D Framework Model:

1) Research and Information Gathering Collect data related to the plastic waste problem in Batam and coastal areas, such as the daily volume of plastic waste (900-1000 tons), its environmental impact, and the decomposition time of plastics (100-500 years).

TABLE 1.
COMPARISON THE PERFORMANCE OF IOT-BASED SHREDDER MACHINE IS COMPARED WITH CONVENTIONAL MACHINES

Aspect	IoT-Based Shredder	Conventional Shredder
Shredding Efficiency	- Equipped with proximity sensors and load cells for automated shredding process.	- Shredding is done manually or with limited control. [23] [24]
	- Automatic adjustment based on object detection and plastic weight.	- No automation in the shredding process. [25]
	- Remote monitoring via IoT application.	- Requires more intensive human supervision. [26]
Power Consumption	- Can optimize power consumption with automatic adjustment based on operational needs.	- Consumes power continuously during the shredding process. [27]
	- Only activates the motor when needed, based on sensor input.	- No automatic control to regulate power consumption. [28] [29]
Environmental Impact	- Reduces carbon footprint and environmental impact through efficient operation.	- Less efficient in power and material use. [30]
	- Remote monitoring ensures operation meets environmental standards.	- Less controlled operation increases carbon footprint. [31]
	- Portable design reduces the environmental impact of transporting plastic waste.	- Potentially greater environmental impact without automatic monitoring. [32]
Advantages	- Higher efficiency in time and power consumption.	- Simpler in design. [33]
	- Automatic control with IoT technology improves accuracy and monitoring.	- Does not require additional technology [IoT]. [34]
	- Reduces environmental impact.	- May be cheaper initially [without IoT investment]. [35]
Disadvantages	- Higher initial cost due to IoT technology.	- Lower efficiency in shredding and power consumption.[27]
	- Requires Wi-Fi infrastructure and applications for remote operation.	- Requires more human supervision.[36]
		- Lacks automatic control to minimize energy waste.[37]

2) *Planning* Plan the design of the IoT-based plastic *shredder* machine with specifications such as a capacity of 100-200 kg of plastic per day and a 500W motor power. Use a 12V lithium-ion battery for 8 hours of operation.

3) *Development of Preliminary Product Form.* Create a prototype of the machine with components such as proximity sensors, load cells, and a shredding motor. Develop an IoT system for control and monitoring via a mobile application (Blynk).

4) *Initial Field Testing Conduct initial trials in Batam,* with the machine capable of shredding 150 kg of plastic per day, operating for 8 hours, and achieving 90% processing efficiency.

5) *Main Product* Revision Based on the results of the *initial* testing, the machine is revised to enhance the sensors and improve plastic shredding efficiency. Improvements are made to the processing algorithms and automatic control system.

6) *Main Field Testing* Further field testing is conducted to ensure that the machine continues to perform efficiently, consuming 500W of power during 6 hours of operation per day and shredding 900 kg of plastic per week.

7) *Operational Product Revision* Revisions are made to optimize power usage and add an energy-saving mode. The IoT software is updated for more efficient remote control.

8) *Operational Field Testing* Further testing shows a 20% energy saving with stable machine performance and a power consumption of 350W during inactive periods.

9) *Final Product Revision* Finalize the design of the machine to ensure portability and ease of use. The IoT application is also updated to be more user-friendly, and the machine is tested for 30 days without technical issues.

10) *Dissemination and Implementation* The machine is distributed to a waste management location in Batam on Buluh Island, with training provided to one operator. Performance monitoring is carried out to ensure the machine reduces plastic waste by up to 80%.

The code begins by importing three essential libraries: ESP8266WiFi, WiFiClientSecure, and UniversalTelegramBot. The ESP8266WiFi library is used to connect the NodeMCU to a Wi-Fi network, enabling internet connectivity. The WiFiClientSecure library allows secure Wi-Fi communication through SSL certificates, ensuring the privacy and integrity of data transmission. The UniversalTelegramBot library is essential for creating a Telegram bot, which will be used to send and receive messages between the NodeMCU and a user's Telegram account.

Next, the pin definitions for various sensors and relays on the NodeMCU are established. The infrared (IR) proximity sensor is connected to pin D1, while the photoelectric proximity sensor is connected to pin D2. The relay that controls the machine is connected to pin D3. These pin assignments allow the program to interact with and control the physical components of the system, such as sensors and relays, based on the input it receives.

In the setup phase, Wi-Fi connection details, such as the SSID (Wi-Fi network name) and password, are defined to enable the NodeMCU to connect to the internet. Additionally, the Telegram bot token and the corresponding chat ID are set. The token is used to authenticate the bot, and the chat ID ensures that messages are sent to the correct recipient. The Wi-Fi connection and Telegram bot initialization are performed, ensuring that the system is ready to communicate over the internet.

The SendToTelegram() function is responsible for sending messages to the Telegram bot. If the NodeMCU is connected to Wi-Fi, messages are sent to the Telegram bot using Markdown formatting. However, if the Wi-Fi connection is not established, a message indicating the disconnection will be displayed in the Serial Monitor. This function ensures that the system can communicate its status to the user, even in the event of a connectivity issue.

Another crucial function, handleCommand(), handles the commands received from the Telegram bot. There are two main commands: "/on" and "/off". The "/on" command enables the machine by setting the machineAllowedToRun variable to true, and the system sends a confirmation message to Telegram. The "/off" command, on the other hand, disables the machine by turning off the relay (setting the relay pin to HIGH), and a confirmation message is also sent to Telegram. This allows users to control the machine remotely via Telegram.

The setup() function initializes the serial communication for debugging, setting the baud rate to 9600. The pins for the IR sensor, photoelectric sensor, and relay are set up using the pinMode() function. The relay is initially set to HIGH to ensure that the machine is off when the system starts. The Wi-Fi connection is then established by calling WiFi.begin(ssid, password), and the system will display dots in the Serial Monitor while attempting to connect. Once connected, the Telegram bot is initialized by setting the SSL certificate validation to insecure, allowing for communication with the bot.

In terms of timing, the program uses variables like irCheckInterval and peCheckInterval to control the interval at which sensors are checked. These intervals are set to 5 seconds, allowing the program to periodically read the status of the sensors and update the system accordingly. This periodic checking ensures that the system can react to changes in sensor status without continuously monitoring them, thus improving efficiency.

The loop() function is the main section of the program and runs repeatedly. It first checks for new messages from the Telegram bot using the getUpdates() function. If new messages are received, the handleCommand() function is called to process the commands. Based on the received commands, the program will either turn the machine on or off by controlling the relay

In addition to checking for new Telegram messages, the program reads the status of the IR sensor and the photoelectric sensor using digitalRead(). If both sensors detect an object (status LOW), the relay is activated (set to LOW), which turns on the machine. If one or both sensors do not detect an object, the relay is deactivated (set to HIGH), turning off the machine. This sensor-based control ensures that the machine operates only when the necessary conditions are met.

The machine control algorithm is crucial for determining whether the machine should be turned on or off based on sensor readings. If the machineAllowedToRun variable is true, the program checks the sensor status to decide whether to activate or deactivate the relay. If the machine is not allowed to run, the relay remains off regardless of sensor readings. This ensures that the machine can only operate when authorized, adding an additional layer of control to the system.

Lastly, the program includes a 1-second delay before the loop repeats, providing time for the sensors to stabilize and for the system to process any new messages or changes in sensor status. This delay helps prevent rapid cycling of sensor readings and message handling, ensuring the system operates smoothly and efficiently.

After the modules are assembled, they are combined into one integrated prototype for operating an IoT-based mobile counting system. The hardware schematic is illustrated as in the figure above. In this system:

Infrared Proximity Sensors and Photoelectric Proximity Sensors are used to detect the presence of objects in the chopper's path. These two sensors are connected to a microcontroller which regulates machine operation based on sensor detection.

4 Channel Relay Module functions as an on/off controller for various devices, including motors on chopping machines. This relay receives signals from the microcontroller to turn on or turn off the machine.

Load Cell and Load Cell Amplifier (HX711) are used to measure the weight of objects entering the chopping machine. The output from the Load Cell Amplifier is forwarded to the microcontroller to process heavy data.

Microcontroller (Arduino) acts as a central controller, receiving input from proximity sensors and Load Cells, and providing signals to relays to activate or deactivate connected devices.

The ATV12 inverter at the top of the figure is responsible for controlling the motor speed based on signals from the microcontroller.

Power Supply and Stepdown Module are used to provide stable voltage to various system components, ensuring that all devices function properly. The stepdown module lowers the battery voltage to a level suitable for electronic components such as microcontrollers and sensors.

Overall, this system allows automatic control of the chopping machine based on proximity sensors and object weight, with relays that regulate the motor operation process which can be seen in Figure 3.

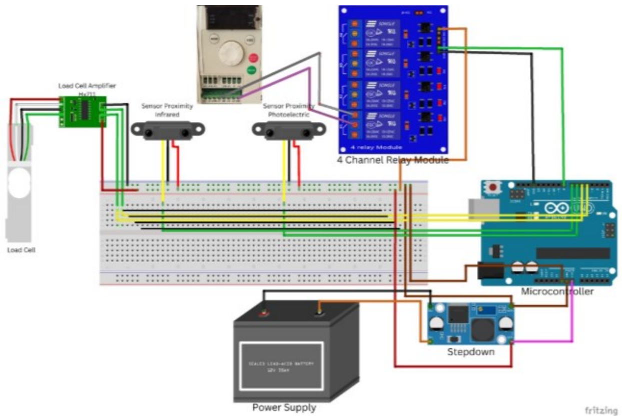

Figure. 3 Hardware Schematic

After all the modules are combined and the machine is assembled, the final result of the IoT-based mobile shredding machine prototype is shown in Figure 4.

Figure 4. Final Result of IoT-based Mobile Plastic Shredding Machine

Remark:

1. *Load cell sensor*
2. *Storage drawer*
3. *Proximity sensor*
4. *Hopper*
5. *Shredding tool*
6. *DC Motor*
7. *MCU Microcontroller*
8. *Inverter*
9. *Voltage stepdown*
10. *Power supply*
11. *Electrical panel*
12. *Emergency button*
13. *Battery 12V*
14. *Battery status indicator*

This prototype is equipped with wheels so it is easy to move and has a control panel equipped with buttons to operate the machine. This prototype design has been tested to ensure all components function properly, including proximity sensors, relays, and IoT components that enable remote control via mobile devices. In addition, the engine casing is designed in such a way that it is durable and safe to use. Usability testing shows that this machine can be operated easily by users, either manually via buttons on the control panel or remotely via an IoT-based application. After combining all the modules, the machine functioned smoothly, with consistent performance throughout testing. The modular design also allows for easier maintenance and component replacement.

In this study, the main findings related to the development of the IoT-based plastic shredding machine are as follows:

1. *Effectiveness of the IoT-Based Plastic Shredding Machine:* The machine has proven effective in reducing plastic waste by shredding plastic in significant quantities (150 kg per day during the initial trial). Although not all findings are presented in numerical data, the testing process shows that the machine can handle plastic efficiently, with a shredding efficiency of up to 90% of the total plastic waste processed.

2. *Use of IoT Technology:*The application of IoT technology enables real-time monitoring and remote control through a mobile application. Using platforms like Blynk, data regarding the weight of shredded plastic can be monitored, providing a clear picture of the machine's performance. This becomes a significant finding as it provides a better solution for control and monitoring compared to conventional plastic waste management methods, which typically require manual supervision.

3. *Energy Savings*: One of the significant findings from the testing is the machine's ability to save energy. Through a more efficient design and IoT-based automation system, the machine consumes power only when needed. During the field trial, an energy saving of about 20% was recorded, showing an improvement in power efficiency compared to conventional plastic shredding machines, which continuously consume power.

4. *Portability and Modular Design*: The developed machine has a modular and portable design, making it usable in various locations, including coastal areas or regions that are difficult to access by conventional waste management facilities. This design allows the machine to be easily moved and operated in *places that require more efficient* plastic waste management.

5. *Environmental Impact Reduction*: One of the key findings is that this machine is capable of reducing the environmental impact related to plastic waste management. This IoT-based machine not only reduces energy consumption but also has an environmentally friendly design

by minimizing carbon emissions and reducing the need for transporting waste to distant disposal sites. This shows that this technology is not only operationally effective but also more sustainable in the long run.

6. Potential Application in Specific Locations: During trials in Pulau Buluh, Batam, the machine showed the ability to reduce about 80% of the total plastic waste generated at that location. This finding demonstrates that the IoT-based plastic shredding machine can be successfully applied in various locations with similar plastic waste problems, such as coastal areas facing plastic waste challenges.

IV. CONCLUSION

This IoT-based mobile plastic shredding machine prototype was successfully designed and built by integrating several main modules, such as proximity sensors, load cells, relays, and Arduino microcontroller devices. With the help of IoT technology, this machine can be controlled remotely via a mobile application, providing high flexibility in operation. The modular design of this machine allows for easy maintenance and component replacement, while ensuring stability and safety during use. Prototype testing shows that all components function optimally, starting from sensors that detect the presence of objects to the control system that regulates the enumeration process automatically.

This machine is designed not only for efficiency in processing plastic waste, but also to support efforts to reduce environmental pollution in an environmentally friendly way. Equipped with wheels and a portable design, this machine can be used in various locations, especially in coastal areas such as those that are the focus of research.

Overall, this IoT-based plastic shredding machine prototype is an innovative solution that can help handle plastic waste more efficiently, while providing ease of control and monitoring through IoT technology.

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