Fully Automatic Organic Waste Composter

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by

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Declaration

This thesis is our original work and has not been submitted previously for a degree at this or any other university/institute. To the best of our knowledge, it does not contain any material published or written by another person, except as acknowledged in the text.

We assure that any work we submit with our names on it will reflect our own ideas and effort. We will properly cite all material that is not our own. We understand that there is no acceptable excuse for committing plagiarism.

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Abstract

Solid waste management is a Crucial factor for every local government authority to administrating their ruling areas in Sri Lanka and especially for the local government authorities such as local government authorities ruling the Urban areas such as Colombo, Gamapaha, Kandy and several other regions of the Western Province of Sri Lanka is severely impeded by ineffective processing of organic waste, leading to environmental pollution and over-dependence on imported chemical fertilizers. This study presents the design and development of a fully automated, IoT-based home composting system that has the potential to reduce the composting process by up to 60% compared to conventional methods, from 60–120 days to 10–15 days, while minimising human intervention and maintaining superior compost quality. The system features a three-chamber modular design, replicating the mesophilic, thermophilic, and curing stages, with dedicated temperature, humidity, moisture, and level sensors in required stages. Actuators, including a shredder motor, a motor for turning the compost pile, a heater, a water valve, and exhaust fans, are incorporated for real-time regulation of composting parameters through an ESP32-S3 microcontroller, which communicates with a Firebase real-time database.

Performance testing showed precise parameter control within set points, homogenous actuator response, and imperceptible integration with a Flutter-based mobile app for remote monitoring and control. Compared to existing works targeting partial automation or industrial-scale systems, this solution distinctively provides an affordable cost, space-saving dimensions around (3’ x 1.5’ x 5’), and an urban home-friendly composting paradigm with complete automation, odour control through activated carbon pellet filters. The machine can process 5–6 kg of organic waste per batch into nutrient-rich compost. The system facilitates a scalable solution towards sustainable urban farming. The findings confirm this smart composter as a promising alternative to manual composting and centralised waste treatment facilities, making a considerable contribution to environmental sustainability and circular economy practices in developing countries.

Keywords— MSW (Municipal Solid Waste), Circular Economy, Urban Sustainability, Aerobic Decomposition, Mesophilic, Thermophilic

List of Abbreviations

Abbreviation		Full Form
IoT	-	Internet of Things
MSW	-	Municipal Solid Waste
PWM	-	Pulse Width Modulation
TRIAC	-	Triode for Alternating Current
ESP32	-	Espressif Systems Microcontroller 32-bit
RTD	-	Resistance Temperature Detector
ADC	-	Analog-to-Digital Converter
MCU	-	Microcontroller Unit
PCB	-	Printed Circuit Board
GI	-	Galvanised Iron
MS	-	Mild Steel
SMPS	-	Switched-Mode Power Supply
RH	-	Relative Humidity
ASP	-	Aerated Static Pile
UI	-	User Interface
NPK	-	Nitrogen, Phosphorus, and Potassium (Nutrient Content)

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CHAPTER 1: Introduction

1.1 Background of the Study

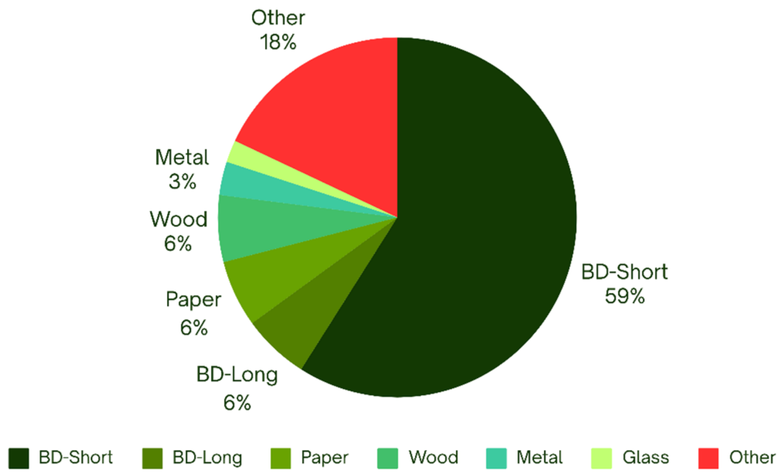

Figure 1.1 Waste Types and Ratio in Sri Lanka [6] [22]

Management of municipal solid waste (MSW) is one of the key environmental and operational concerns in Sri Lanka, particularly in densely populated cities such as Colombo and the Western Province. Sri Lanka has been estimated to produce a maximum of 7,000 metric tons of waste daily and Western Province accounts for near 60% of this production. [4], and Figure 1.1 illustrates that the ratio and waste types collected, which is more than 59% of it, is biodegradable organic waste [5]. But much of this resource is wasted due to improper segregation methods and the absence of running composting facilities. At the same time, Sri Lanka's agricultural sector continues to depend on foreign chemical fertilisers that result in long-term environmental degradation in the form of soil acidification as well as water contamination.

Composting a centuries-old process of recycling organic waste into nutrient-rich soil amendments—continues to be underutilised to its fullest potential in the nation due to its reliance on human labour, odour smells, and manual upkeep. While a couple of municipal compost plants in central municipalities are available, they are plagued by outdated equipment, inefficiencies of labour, and lack of accessibility to urban homes.

The intersection of intelligent technologies like the Internet of Things (IoT), automation, and sensor networks provides a disruptive opportunity to convert backyard-scale composting from dirty hands work to a simple day-to-day task like washing clothes using a washing machine. By using automated control of optimal composting parameters such as temperature, humidity, soil aeration and moisture and real-time monitoring and feedback, an IoT-based composting technology can make it possible for residences to assume complete responsibility for green waste management with superior quality organic fertiliser.

1.2 Literature Review

1.2.1 Municipal Solid Waste and Biodegradables in Sri Lanka

MSW management in Sri Lanka, particularly in the Western Province, is a significant problem owing to urbanisation and increasing population density. The Western Province produces more than 7,000 metric tons of waste daily, with around 59% of waste being biodegradable in a short time [3], [6]. Not only in the Sri Lankan Context but also globally, around 44% of waste is generated from Food and Greens [8]. Nonetheless, because of inadequate segregation at the source level and lack of awareness, a major considerable amount of organic waste ends up in landfills, leading to methane production and groundwater pollution [4].

1.2.2 Traditional Composting Techniques

Various methods of composting are employed globally, with varying degrees of efficiency, cost, and applicability based on the context. For instance: Windrow Composting, In Vessel Composting, Static Pile Composting, Wormi-Composting, etc.

1.2.2.1 Windrow Composting

Figure 1.2 Compost Turning Machine

Windrow composting is a traditional method in which biodegradable organic waste is filled into slender, elongated piles known as windrows. These piles are regularly turned with specialised machinery shown in Figure 1.2 to facilitate good aeration, enhance microbial action, and maintain uniform conditions of decomposition throughout the pile. This method is especially ideal for treating vast quantities of organic waste, like agricultural residues, municipal green refuse, and food processing industry by-products.

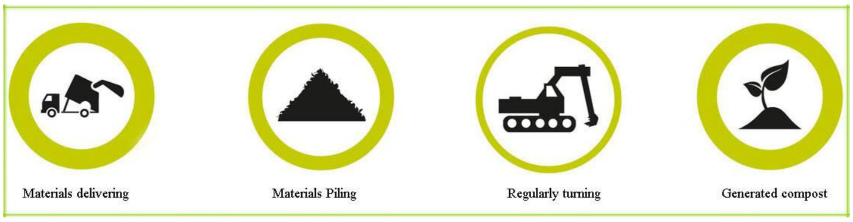

Figure 1.3 Windrow Composting Flow

Figure 1.3 shows the Windrow Composting Flow, which is carried out mainly in open fields and thus requires sufficient space and is therefore not practical in cities or where there is limited space. The open-air system is also susceptible to weather and potential odour release if not adequately controlled. Notwithstanding these constraints, windrow composting is still practised extensively because of its relatively low initial investment and technical simplicity in rural or semi-urban large-scale composting plants [9].

1.2.2.2 In-Vessel Composting

In-vessel composting is a modern, contained process that allows for effective and sanitary breakdown of organic waste under a closed vessel or drum. This system allows for tight control of critical environmental variables like temperature, aeration, and moisture, all of which are critical for maximum microbial activity and rapid composting. The contained nature of the system significantly reduces the risk of odour emission, pest infestation, and environmental contamination, and thus it is well suited for use in densely populated urban areas. Furthermore, in-vessel systems are highly susceptible to automation and real-time monitoring, allowing predictable and uniform compost quality. In-vessel systems also utilise much less space than open composting systems, and they are modular systems expandable or scalable depending on the amount of waste treated. Therefore, in-vessel composting is a modern and effective technology for organic waste management that is sustainable, especially in urban and institutional settings [10].

1.2.2.3 Static Pile Composting

Static pile composting is a method where organic materials are stacked and left to decompose without physical turning. Instead, aeration is provided by passive ventilation or, preferably, through the utilisation of forced aeration systems such as perforated pipes connected to blowers that supply oxygen across the pile. This approach dramatically reduces the need for labour over windrow composting, so it is potentially more beneficial for operations with restricted labour. However, as material isn't turned, temperature and water distribution across the pile could be patchy; thus, the rate of decomposition and quality of compost could be slower and inconsistent. Although these are the drawbacks, aerated static pile (ASP) systems are being increasingly utilised in urban and suburban locations due to their reduced space requirement, scalability, and odour control capabilities through appropriate design. Monitoring and aeration controls may be incorporated to enhance performance to allow semi-automated operation of the composting process [11]

1.2.2.4 Vermicomposting (Vormi Composting)

Figure 1.4 Vormi-Compost with Worms

Figure 1.4 shows the final output of Vormi- Compost, a green organic waste management process that makes use of earthworms to degrade biodegradable waste enzymatically. Earthworms consume organic residues roughly equal to their body weight per day. For example, one kilogram of worms can be used to degrade one kilogram of waste per day [12]. The resulting worm casts (vermicasts) are extremely nutrient-rich, with high concentrations of nitrate, phosphorus, potassium, calcium, magnesium, and high levels of useful microorganisms such as bacteria and actinomycetes [12]. The most common species utilised are Eisenia foetida and Lumbricus rubellus, which are most suitable for shallow, well-aerated beds maintained at temperatures ideal for earthworm activity [12].

Vermicomposting offers several operational advantages: no need for frequent turning due to the worms' tendency to burrow, even aeration, and high-quality compost in 6 to 12 weeks considerably faster compared to passive systems [12]. System size is kept moderate for efficiency's sake, and environmental conditions such as humidity and temperature are controlled appropriately to promote worm health. Vermicomposting is therefore a low-labour, space-effective and efficient process well suited to urban residential or small institutional settings with the aim of sustainable organic waste management.

1.2.3 IoT and Automation in Composting

IoT has revolutionised waste management sustainably by enabling real-time data acquisition, monitoring and control. Composting systems equipped with IoT capabilities can maintain the required composting parameters at an optimal level, such as:

- **Temperature (40°C–70°C):** Crucial for thermophilic microbial activity [8].
- **Moisture (50%–60%):** Required to support microbial metabolism and prevent anaerobic conditions [1].
- **Aeration:** Ensures aerobic decomposition and odour mitigation.

Nikoloudakis et al. [1] demonstrated a successful real-world IoT-based composting setup capable of remotely monitoring temperature and moisture data, significantly reducing manual intervention.

1.2.4 Automation Levels in Existing Systems [8]

Composting Method	Automation Level
Aerobic	~80%
Anaerobic	~3%
Undetermined	~11%

Table 1.1 Composting Automation Levels

Table 1.1 shows the composting methods and the percentage of automation implied in industrial-scale operations. As noted by Diaz-Quinto et al. [2], in-vessel systems offer the highest potential for full automation due to their closed-loop control environment and compatibility with compact electronics.

1.2.5 Identified Gaps in Existing Solutions

Despite advancements, several limitations persist:

- **Limited Availability of Household-Scale Systems:** Most automated systems are designed for industrial-scale composting [2], [1].
- **Partial Parameter Control:** Existing devices often lack complete integration for feedback-controlled moisture, aeration, and temperature [2].
- **High Cost and Complexity:** Automation and IoT add cost, limiting affordability in developing regions [4].
- **Odour and Space Constraints:** Household adoption is hindered by smell, size, and required maintenance [3].

1.2.6 Opportunities for Innovation

Recent studies encourage the development of modular and predictive systems:

- **Compact Modular Design:** Ideal for urban spaces [1].
- **Real-time IoT Monitoring:** Enables proactive control, error detection, and waste profiling.
- **AI/ML Integration:** Predictive tuning of composting parameters based on waste type and sensor feedback [2], [5].

Azis et al. [5] emphasised the future role of machine learning in adapting composting systems to varying waste input, allowing smarter and more efficient operation.

1.3 Review of Existing Composting Systems

The design study began with an extensive review of existing composting systems commercial products and research prototypes. The comparison included in-vessel composters, rotary compost drums, static bins, and semi-automated systems. Performance metrics were compared:

- Composting efficiency
- Space utilisation
- Odour control
- Maintenance requirements
- Cost and complexity

These results informed the prioritisation of the features of the proposed system, particularly the requirements for modularity, automatic control, and compact structure for urban houses.

1.3.1 Field Visit to Industrial Composting Centre.

Figure 1.7 At Composting Area

Figure 1.5 Fresh Windrow Compost pile

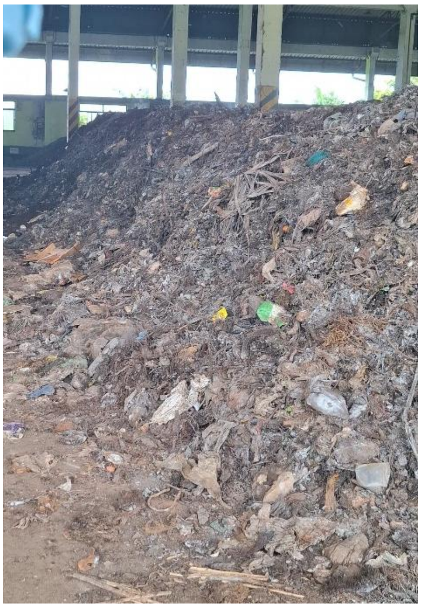

Figure 1.6 One Month Matured Compost Pile

Figure 1.8 Infront of MIHISARU Office

Figures 1.5, 1.6, 1.7 and 1.8 show snapshots of a field visit conducted to the Mihisaru Resource Management Centre at Karadhiyana, Western Province, to observe the composting process using Municipal Solid Waste (MSW). Some 300 metric tons of biodegradable waste daily are received by the centre from numerous local government councils, including Dehiwala-Mount Lavinia Urban Council, Kesbewa Urban Council, Maharagama Urban Council, Sri Jayawardenapura Kotte, Moratuwa, Homagama, and Boralesgamuwa. Of this, around 70 MT of waste is converted into organic compost per batch by the windrow composting process.

The composting duration at the centre is around 90 days. Temperature is one of the critical parameters that is either monitored daily or every other day by hand measurements using Resistance Temperature Detector (RTD) probes. Temperature is maintained between 65°C and 70°C during the thermophilic period. Where the temperature exceeds this, aeration is achieved by physically turning over the compost pile to preserve heat levels.

Figure 1.10 First quality Compost sorted by final sorting machine

Figure 1.9 Larger Compost particles rejected by final sorting machine

Figure 1.10 shows the final quality compost with fine powder particles, and Figure 1.9 shows the rejected compost, which has larger compost particles not suitable for commercial compost and can be used as an accelerator to increase microbial digestion for new batches or sold at a lower price

Figure 1.12 Compost Sorting Drum

Figure 1.11 Compost Sorting Conveyer

Figures 1.12 and 1.11 show the components of the composting sorting machine, including the compost sorting drum with nets to remove larger and unwanted particles from the compost, and a conveyor belt for feeding the compost to the sorting machine from the compost pile.

At 90 days of composting, the compost is sorted using a sorting machine equipped with sorting nets to remove large particles and uncomposed materials. Quality control at the end of the process is performed through analysis of pH, Escherichia coli, and nutrient content (NPK values) to ensure that the compost meets standards before packaging.

Currently, the composting process at the centre is purely reliant on manual operation, with no automation in place for monitoring or controlling composting parameters. Compost pile turning would be done by a backhoe loader, typically on a weekly schedule or where temperature increases trigger aeration. Control of Odours comes from the use of chemical sprays; nevertheless, this must be applied frequently (at least twice a day) and has only been moderately effective in preventing Odours.

1.4 Problem Statement

Despite numerous government schemes and people's campaigns, the practice of domestic-level composting is low due to some persistent challenges. Traditional composting systems are cumbersome, smelly, and time-consuming and not for the lifestyle of busy life in the modern city. Furthermore, only a handful of compact automated composting technologies have been invented to make them applicable for use in small space living with little time. All current systems require experienced staff to present the ideal composting environment, and this often leads to irregular results. Further, most composters do not have real-time monitoring mechanisms, so the process is reactive rather than proactive.

Though a few kitchen composters are available in the marketplace, they tend to focus on rapid removal of kitchen refuse typically 6 to 24 hours by subjecting the waste to excessive heat and mechanical shredding. The process may reduce the volume of the waste efficiently but does not contribute to the manufacture of quality compost through natural microbial processes. These limitations underscore the urgent necessity of an easy-to-operate, automated composting device which integrates real-time monitoring, accurate control systems, and effective green waste processing in a small, sustainable package.

1.5 Objectives

- Design and develop an IoT-enabled composting system tailored for domestic households.
- Automate key composting operations, including shredding, mixing, heating, aeration, and moisture regulation, to minimize human intervention.
- Ensure production of high-quality compost suitable for home gardening and small-scale agriculture by replicating mesophilic, thermophilic, and curing phases.
- Reduce composting time significantly (targeting 10–15 days vs. 60–120 days in traditional methods) while maintaining compost quality.
- Promote sustainable waste management by reducing landfill dependency and lowering the use of imported chemical fertilizers.

1.6 Scope and Limitations

1.6.1 Scope

The scope of this project entails the construction and development of an automated composting system that is tailored for residential and small institutional settings, including homes, schools, and community centres.

The system aims to optimise and streamline the composting process by a mix of automated procedures like mechanical turning of waste materials, controlled heating for accelerating microbial action, automatic water spraying for maintaining correct moisture levels, and inbuilt measures for controlling odours in order to offer a clean and easy operation. One of the distinguishing features of the system is that it includes IoT technology integration for real-time monitoring of important composting parameters including temperature, moisture, and humidity. The data will be available through a mobile platform, making it possible for users to monitor and control the process of composting easily and confidently from anywhere.

It is built on a three-chambered modular configuration that enables one to split the composting process into its natural stages active breakdown, curing, and maturation. The structure provides optimal environmental conditions for each stage, resulting in better efficiency and quality of the final product.

Besides, the project is interested in establishing an urban composting solution that is affordable and tailor-made for the Sri Lankan context. By prioritizing affordability, accessibility to the customers, and adaptability to the local environment, the system will be able to facilitate masses to embrace sustainable waste management in urban households across Sri Lanka.

1.6.2 Limitations

The system is designed to compost short-term degradable waste like fruit and vegetable peels, food waste, and similar organic substances.

It is not intended to be used for composting long-term degradation materials like coconut husks, wood, or fibrous plant residues that take more time to decompose and other microbial parameters. Also, the performance of the system and quality of the generated compost can be adversely affected by the dumping of large quantities of cooked food or oily waste because they can upset the microbial balance required to enable effective decomposition. It must also be kept in mind that the initial prototype shall not carry advanced features such as AI-based waste forecasting or solar-power viability. These aspects can be considered in later development stages, but the primary focus of the initial stage is stable, user-friendly, and automated composting of usual household organic waste on a small, affordable setup.

1.7 Significance of the Study

This project addresses an urgent national and global issue: environmentally sound disposal of organic waste in increasingly urbanised, densely populated metropolitan areas. By proposing a space-efficient, mechanised composting program, the project offers an effective method for minimising the environmental and social costs of current waste management practices. The system seeks to significantly reduce the utilisation of landfills, thereby minimising greenhouse gas emissions from the decomposition of organic matter in uncontrolled settings.

Besides, the project facilitates urban households to be part of the circular economy actively by recycling their daily organic waste into practical compost. Not only does it encourage proper consumption and waste management, but it also facilitates the encouragement of organic cultivation. By reducing dependence on chemical fertilisers, the system encourages healthier soil environments and prevents toxic discharge into water bodies, thereby saving the environment.

More broadly, the system is a scalable and replicable model for intelligent waste management in the developing world. It demonstrates that low-tech, locally available solutions can be applied to reverse big-scale environmental issues, paving the way to sustainable city living and long-term ecological resilience.

1.8 Summary

The literature strongly supports the potential of IoT and automation in transforming composting from a manual, odour-prone task to a clean, efficient, and intelligent process. However, a gap remains in implementing affordable, compact, and fully integrated composting systems for domestic use in developing countries. This project addresses that gap by proposing a fully automated, three-chamber IoT-enabled composting machine tailored to Sri Lankan urban households.

1.9 Thesis Organization

This thesis is structured as:

- **Chapter 1** formulates the background, problem statement, objectives, and purpose of the study.
- **Chapter 2** outlines the step-by-step design, development, and testing methodology.
- **Chapter 3** includes the test results, and discussion.
- **Chapter 4** summarizes the study and recommends future enhancements.

CHAPTER 2: Methodology

This chapter reveals the systematic approach utilised in conceptualisation, development and testing of a fully independent IoT-based composting machine for domestic use. The process was divided into different dependent phases including conceptual design, mechanical development, component choosing, electronics integration, control system implementation, and software implementation. All activities were carried out with sustainability, automation, convenience for users, and minimum maintenance in sight.

2.1 Design Study and Conceptualisation

2.1.1 Initial Sketching and Concept Development

Several freehand sketches were drawn to explore alternative design concepts. Alternatives were explored in:

- Chamber orientation (horizontal or vertical)
- Shaft positioning and turning mechanism
- Belt drive systems
- Sensor and actuator placement

Each sketch was critiqued in terms of mechanical viability, ease of manufacturing, and spatial limitations.

2.1.2 Final Design Selection and 3D Modelling.

Among the concepts drawn, the most promising design was selected with three horizontally positioned cylindrical composting chambers, a shaft-type mixing mechanism, and a pulley-belt drive mechanism. This design concept was created in SolidWorks for fit, alignment, and mechanical motion simulation.

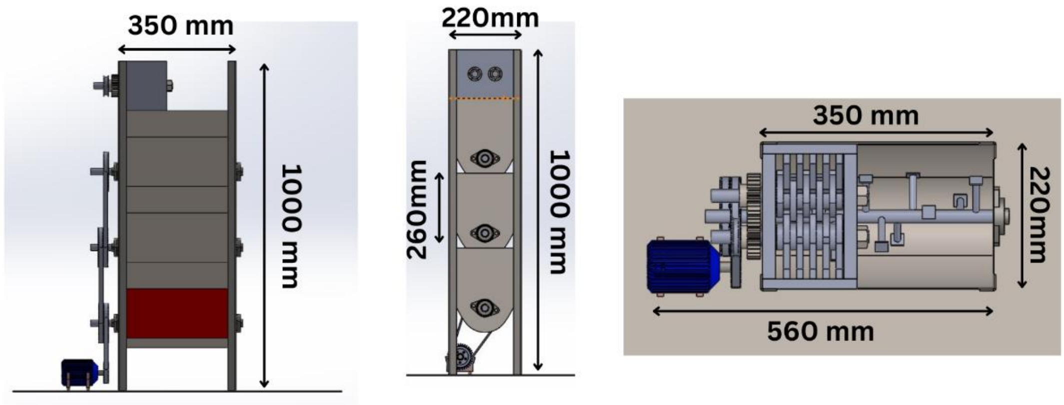

Figure 2.1 Top, Front and Side Views with Dimensions

Figure 2.1 shows the Top, Front and Side views from left to right, respectively, with the dimensions.

Figure 2.2 shows the other views not in Figure 2.1 and shows the pullies and belts

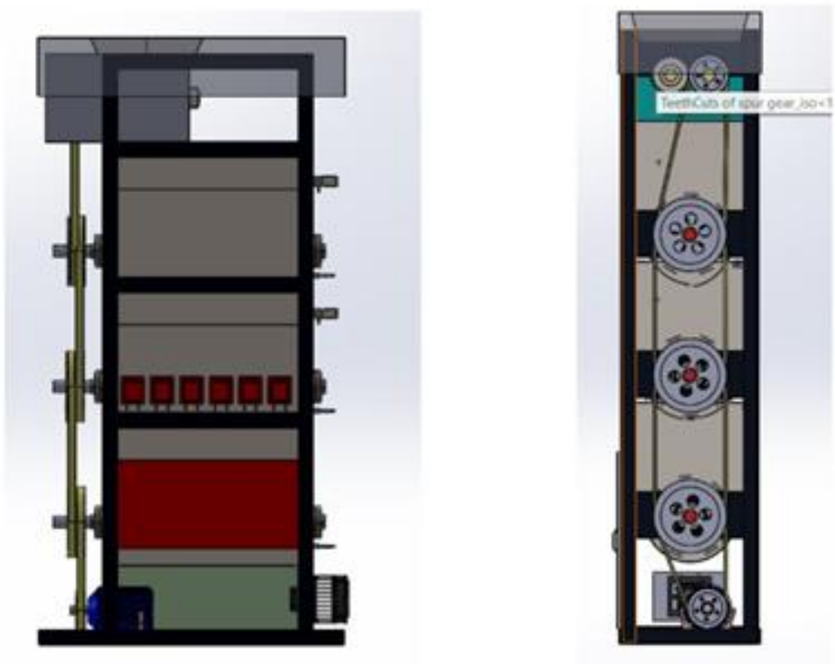

Figure 2.2 Other Side View and Pully Side View

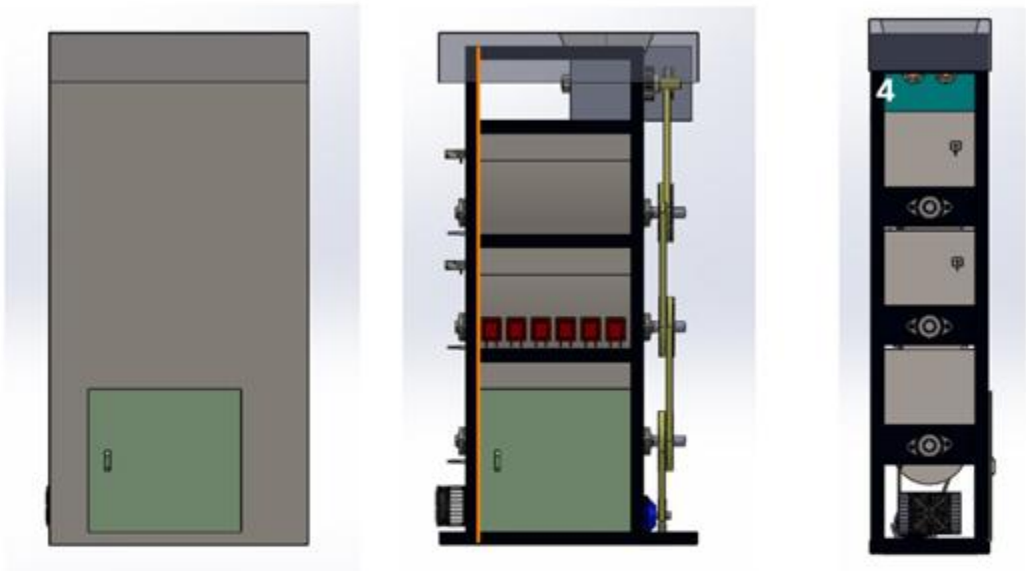

Figure 2.3 Compost Machine with Outer Casing

2.2 Mechanical Structure and Fabrication

2.2.1 Chamber Construction

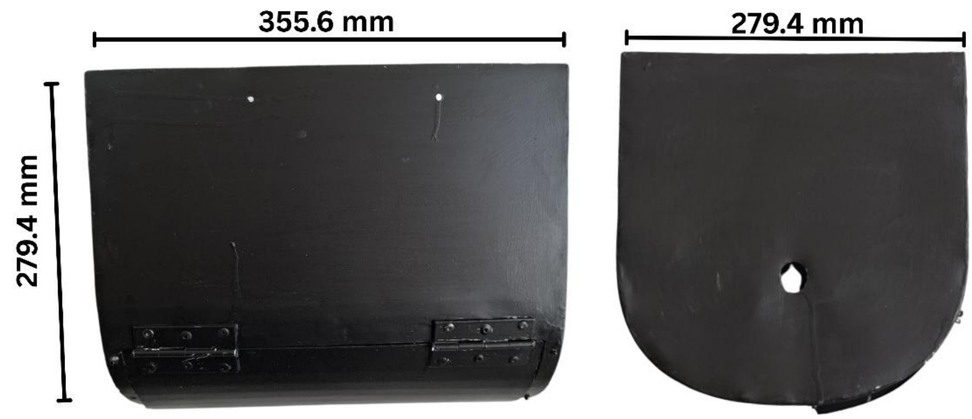

Figure 2.4 Fabricated Chamber

Figure 2.4 shows that the chambers were constructed from 1.2 mm zinc-coated mild steel (MS) sheets, which were chosen for their resistance to corrosion, structural integrity, and affordability. The sheets were cut, bent, and accurately welded together with the use of gas welding to create the chamber frame. After initial fabrication, the bottom part of each chamber was split into thirds or quarters, forming a semi-circular door that allowed the transfer of compost from one chamber to another. The doors were mounted on the chambers through hinges, which were held in place by blind rivets. To make them airtight and prevent accidental movement of compost between chambers, thin metal sheet strips, combined with rubber seals, were fitted along the edges of the chamber doors.

Figure 2.5 Outside the chamber door opened

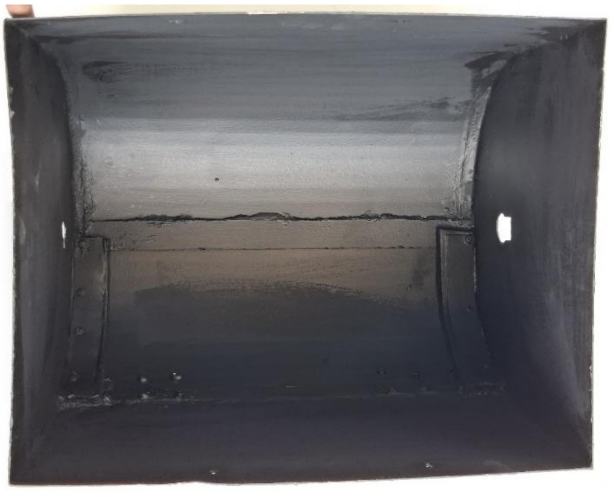

Figure 2.6 Inside the Chamber

Figure 2.7 Inside the chamber door opened

Figures 2.5, 2.6, and 2.7 show the chambers inside images when the door is opened and closed, showing the metal strips and rubber sealing fitted with the door and side view of the door while the door is opened.

Three chambers were built with the same dimensions and layouts to ensure uniformity in the composting process.

2.2.2 Turning and Shaft Assembly

2.2.2.1 Shaft

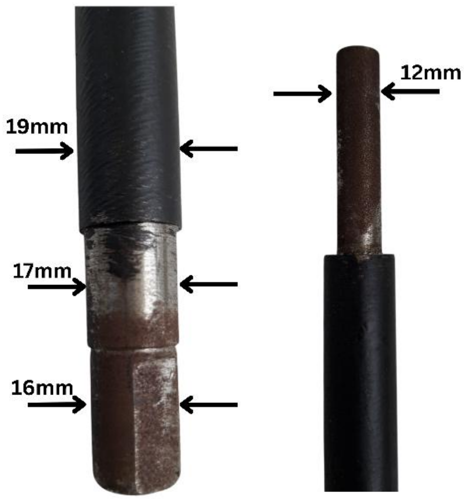

Figure 2.8 Lathe Manipulated Dimensions of Shaft

Figure 2.8 shows that the shaft was made from a steel rod of 19 mm diameter, machined at both ends to fit bearings of varying sizes. One end was turned to 12 mm to accommodate a 6201 bearing, and the other end was turned to 17 mm for a 6203 bearing. On the pulley end, the 17 mm end was further turned to 16 mm and also slightly flattened to provide a snug fit with the pulley so that there would be no slippage.

Figure 2.9 Shaft Welded with Nuts

Figure 2.9 shows that Nuts were also welded onto the shaft at nearly equal distances but in different orientations to enable the fitting of turning arms.

2.2.2.2 Turning Arms

Figure 2.11 Turning Arm

Figure 2.10 Turning Arm Connected with Shaft

Figure 2.10 shows that turning arms were made from threaded rods, divided into 3-inch segments. For added structural strength, a tiny square plate was attached via welding to one end of every segment. Figure 2.11 shows the arms were securely attached to the shaft by a system of fixed nuts welded to the shaft and adjustable nuts on the turning arms, thus providing a solid and stable attachment. The use of threaded rods was chosen for the ease of removal and adjustment of the arms with the possibility of adjusting as needed after installing the shaft in the chamber.

2.2.2.3 Pulley and Belt

Figure 2.12 4 Inch Double Pully with 16mm Bore for Shaft

Three types of pulleys were used: **Single 3-inch**, **Double 3-inch** and **Double 4-inch** pulleys. Figure 2.12 shows a 4-inch Double Pulley, made of cast aluminium due to its beneficial light-weight properties, convenience in handling, alignment flexibility, and economic feasibility compared to cast iron alternatives. The pulleys were turned on a metal lathe to match the shaft diameter, and a threaded hole was created using a tapping tool for attaching the pulley to the shaft using a bolt, thus ensuring a secure attachment to prevent any possible slippage.

Figure 2.14 A-36 V-Type Belt

Figure 2.13 Belt Closeup

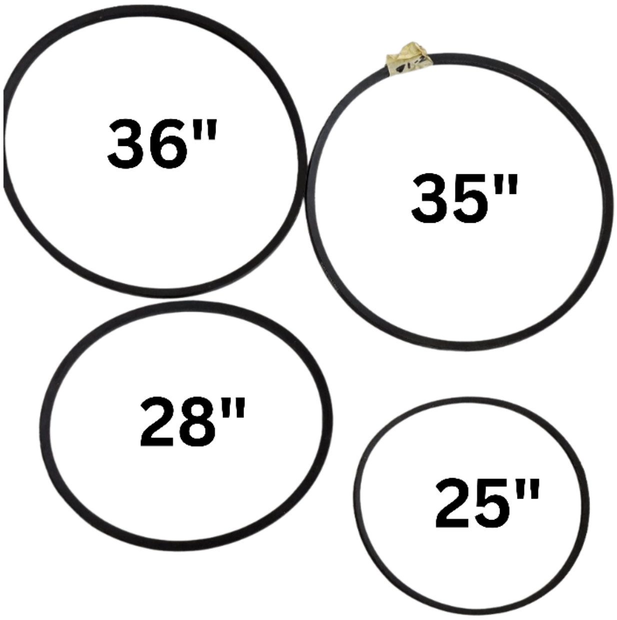

Figure 2.15 Belts used in the machine

Figures 2.13, 2.14 and 2.15 show that V-belts of type A were used in the machine. These belts are chosen due to their economy and simplicity of attachment and detachment. The sizes of the belts utilised were **25 inches** (***motor to gearbox***), **28 inches** (***gearbox to bottom chamber***), **35 inches** (***bottom to middle chamber***), and **36 inches** (***middle to top chamber***).

2.2.2.4 Bearings

Figure 2.16 Bearing - 6201-2RS

Figure 2.17 Bearing-6203-RS

Figures 2.16 and 2.17 show the two types of bearings used in the machine. The sizes of the bearings were selected based on the diameter of the shaft and the availability of reconditioned bearing housings, which were recycled from ceiling fans and washing machine motors. For the **pulley side**, A **6203-2RS** bearing (**Inner Diameter: 17 mm, Outer Diameter: 40 mm, Width: 12 mm**) having **dual rubber seals** was utilised. On the other side, a 6201-RS bearing (Inner Diameter: 12 mm, Outer Diameter: 32 mm, Width: 10 mm) having a single rubber seal was utilised.

Figure 2.18 Bearing Inside Casing

Figure 2.18 shows that a bearing was carefully installed into its respective housings with the aid of a rubber mallet to maintain proper alignment and ensure a secure fit.

2.2.3 Frame and Base Structure

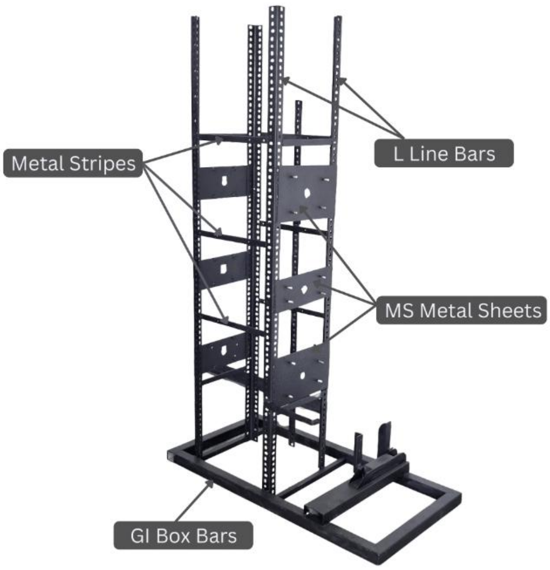

Figure 2.19 Frame with the Fabricated Parts Name

Figure 2.19 shows that the frame and base structure were designed using welding of L-line bars, galvanised iron (GI) box bars, and steel metal strips to create a robust framework to support the chambers, motor, and gearbox. For easier mobility, four hard plastic wheels were tightly welded at the bottom of the base to facilitate the easy transportation of the machine. Additionally, four mild steel (MS) sheets were welded on the two sides of the chamber-holding section within the frame as stable points to mount the bearing casings.

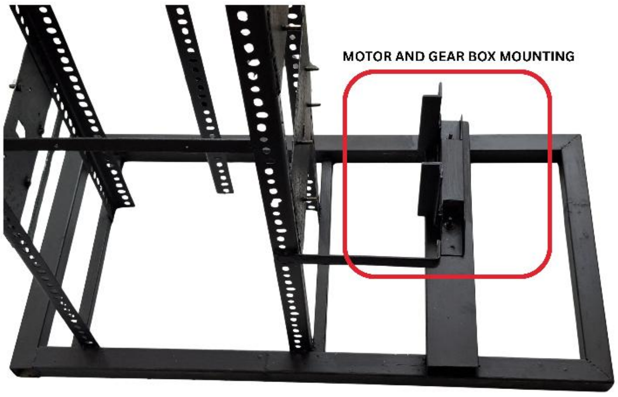

Figure 2.20 Motor and Gearbox Mount

Figure 2.20 shows the Mountings of Motor and Gearbox welded in the base and frame of the machine

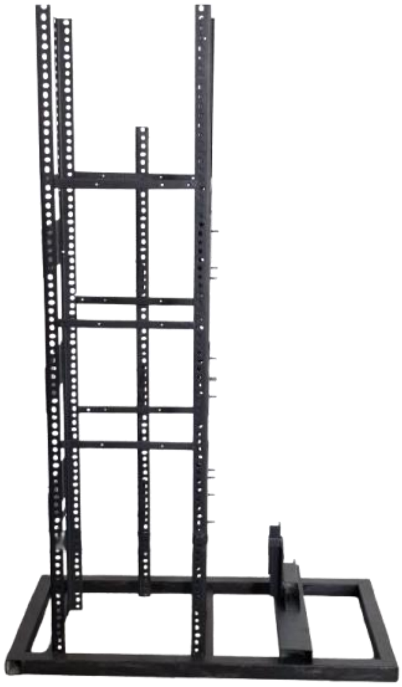

Figure 2.21 Frame Front View

Figure 2.21 shows the front view of Frame, and this frame configuration minimises the need for additional holes in the chambers and therefore minimises the need for supporting sealing to ensure watertightness. The chambers were riveted onto metal strips, welded to the front and rear of the machine, with bolts and nuts. This arrangement provides for simple disassembly and assembly, maintenance, and adjustment for use. Also, a mount was fabricated at the bottom of the frame to hold the Motor and gearbox for turning the compost pile.

2.2.4 Gearbox

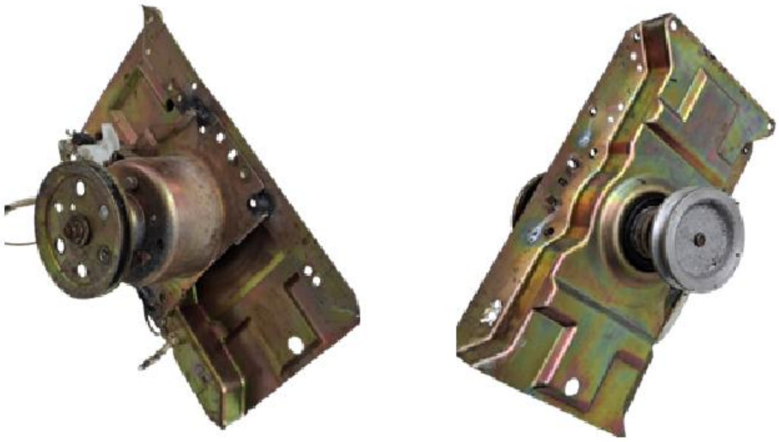

Figure 2.22 Gear Box

Figure 2.22 shows the input and output sides of the gearbox that were installed to achieve the desired reduction in rotational speed and boost in torque to be able to turn the compost pile effectively. A gearbox from an automatic washing machine was utilised. The motor is connected to the input shaft of the gearbox, and the compost turning unit is connected to the output shaft, which offers efficient power transmission and best performance of the composting system.

2.2.5 Motor

Figure 2.23 Turning Motor

Figure 2.23 shows the Motor that used for turning the compost pile and this motor is a **150W 220V 50Hz 1.6A** Motor with **10uF** Capacitor. Able to rotate at **1330RPM**.

2.3 Post-Fabrication and Finishing

Once again, after mechanical operations were finished, all surfaces which had been welded, drilled, and milled, together with any leftover metal residue, were washed and ground to offer a smooth finish. Small pores in welding regions were filled using metal fillers and then finally ground using sandpaper to offer a smooth surface. Next, all the mechanical components, including the chambers, frame and base, shaft, and turning arms, were coated with **zinc phosphate metal quick-dry (Q/D) primer** in **black**. The reason the primer was selected was for its ability to impart a nice aesthetic appearance with a dull monotonous black finish with good corrosion resistance.

2.4 Hardware and Electronic Subsystem

2.4.1 Sensor Integration

In the design of automated composting systems, accurate and reliable environmental parameters sensing is critical to make microbial action effective, compost quality consistent, and the system responsive. The following sensors have been selected after weighing several other available options against factors such as cost-effectiveness, accuracy, life expectancy in the environmental conditions, ease of interfacing with the ESP32 microcontroller, and suitability in the composting process.

2.4.1.1 DS18B20 – Waterproof Digital Temperature Sensor

Figure 2.24 DS18b20 Probe

Figure 2.24 shows the DS18B20 waterproof digital temperature sensor, to sense the temperature inside the compost chambers. Accurate temperature monitoring is important to ensure that the thermophilic stage of composting, during which microbial growth is at its maximum level between 45°C and 70°C, is maintained. The DS18B20 provides precise digital temperature readings accurate up to ±0.5°C[13][14], which is very much appropriate for detecting minor temperature fluctuations. Its waterproof, stainless steel enclosure allows long-term survivability in a high-moisture, organic environment where traditional analogue thermistors or RTDs would not survive. It also supports one-wire protocol to enable multiple sensors to be addressed in parallel to one microcontroller pin. It obviates wiring complexity and optimises GPIO usage in ESP32-S2. Its strength, accuracy, and digital communication make DHT22 a perfect choice for real-time thermal profiling in compost piles.

2.4.1.2 DHT22 – Humidity and Temperature Sensor

Figure 2.25 DHT22 Sensor Module

Figure 2.25 shows the DHT22 sensor, was selected for temperature and relative humidity measurement within the composting chambers. Composting conditions are typically high in humidity level, which makes DHT22 particularly useful since it has a high measuring range (0–100% RH) and ±2–5% RH accuracy [15]. In addition to humidity, it also senses ambient temperature, so redundancy and cross-checking may be performed in addition to the DS18B20. The DHT22, being distinct from its predecessor, the DHT11[21][15], possesses much improved resolution and operation range, especially under high-moisture environments. Its digital output eases microcontroller interfacing and eliminates its vulnerability to analogue noise, ensuring data integrity under harsh environmental conditions. This dual-function sensor is crucial in assessing chambers' air quality as well as moisture evaporation, which are both required to achieve optimisation of decomposition by microbes.

2.4.1.3 Capacitive Soil Moisture Sensor v2.0

Figure 2.26 Capacitive Soil Moisture Sensor V2.0

Figure 2.26 shows the Capacitive Soil Moisture Sensor v2.0, used to gauge the water level in the compost material. Maintaining moisture levels at the optimal level of 50–60% [1] is extremely crucial to maintain microbial activity during composting. It differs from resistive soil moisture sensors that degrade by corrosion, electrolysis, and organic acids with the passage of time. The capacitive sensor monitors moisture content by changes in the dielectric constant to enable non-contact corrosion-resistant operation. Vibration-dampening protective PCB coating to survive longer in composting conditions is also integrated into v2.0 model. Its analogue output enables precise control of the water spraying system for making real-time corrections by the microcontroller when moisture goes below the set point. This sensor maintains uniform moisture levels without degrading or giving faulty readings and is an industrious and dependable option for round-the-clock compost monitoring.

2.4.1.4 HC-SR04 – Ultrasonic Level Sensor

Figure 2.27 Ultra Sonic Sensor - HC-SR04

Figure 2.27 shows the HC-SR04 ultrasonic sensor, used to sense the level of compost fill in each chamber. Proper level sensing is required in order to avoid overfill, which might create anaerobic pockets and decrease the efficiency of composting. The HC-SR04 also offers non-contact measurement, which is particularly valuable in the wet, organic-rich composting environment where contact sensors may be fouled or damaged. It also measures in the range of 2 cm to 400 cm [16]and is highly accurate (±3 mm) [16] and can detect even minor compost height changes. It operates by transmitting ultrasonic pulses and measuring the return time of the echo, an effect that is insensitive to the presence of humidity or gases. Compared to IR sensors or mechanical indicators, HC-SR04 provides clean, maintenance-free operation and is quickly integrated into the ESP32 microcontroller using standard libraries.

2.4.2 Actuators

We have used several actuators for controlling the environmental parameters, such as Temperature, Aeration, and Moisture Level, which are suitable for composting.

2.4.2.1 AC series motor

The motor powers the compost turning machine, giving aeration as needed and enabling transferring of the compost pile from one chamber to another. With operation of the motor to rotate the compost pile, the material can be turned effectively towards the bottom chamber for smooth movement and treatment in composting. This motor is wired to control rotation in a bidirectional manner in both Clockwise and counterclockwise directions.

2.4.2.2 MG-996R Servo Motor with DIY Arm

Figure 2.28 MG-996R Servo Motor

To assist in moving the compost pile from the upper to the lower chamber within a predetermined time frame, a servo motor shown in Figure 2.28 was used to operate the bottom door of each chamber. The 4.8–7.2 V [17] servo motor produces a stall torque of 9.4 kg/cm[17], which is sufficient to reliably open and close the chamber doors under load by the compost pile. The motor includes internal metal gear wheels for extended life and to avoid slippage or damage caused by high torque. Three separate servo motors were installed, one for each chamber, for independent control of the door mechanisms.

Figure 2.29 Servo Motor with Door Closing Arm

Moreover, Figure 2.29 shows that the specifically manufactured arm is designed to contribute to the functionality of the servo motor. The arm consisted of aluminium strips and included a plastic support wheel, part of the servo motor set, to span the whole length of the door of the chamber. This arrangement ensures complete coverage and efficient functioning along the door surface to transfer compost smoothly and effectively.

2.4.2.3 Exhaust System with Odour Filter

Figure 2.30 Activated Carbon Filter

Figure 2.31 Exhaust Fan with Filter

Figure 2.32 Activated Carbon Pellets used inside the filter

A separate exhaust system for every one of the chambers was engineered to maintain appropriate aeration, promoting aerobic digestion and preventing the formation of anaerobic conditions, which is shown in Figure 2.30. Figure 2.31 shows a 12 V exhaust fan in every chamber that is actuated by an electromechanical relay module that is connected to a microcontroller. This is a provision for precise control of airflow to maintain appropriate composting conditions. In addition, an odour filter composed of activated carbon pellets, shown in Figure 2.32, was provided to capture and eliminate any odorous gases [20] that may be generated from minor anaerobic digestion to ensure effective odour control within the system.

2.4.2.4 Heating System

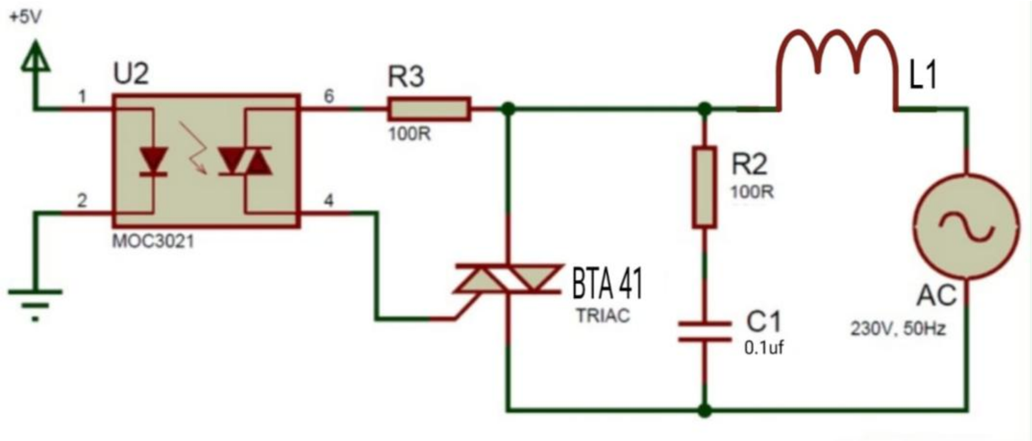

Figure 2.33 TRIAC Circuit for Control Heating Coil

A heating system was implemented to maintain the high temperatures required for the thermophilic phase. In the second chamber, temperatures exceeding 65°C are required. The system makes use of a Nichrome heating coil as the resistive heating coil, which was selected based on cost, ease of installation, and compatibility with pulse-width modulation (PWM) for fine-tuning of the heat. The heating coil is regulated by a TRIAC circuit shown in Figure 2.33 [18] that employs low-frequency PWM (burst firing) [19] to modulate the current flow for proper temperature control.

The heat generated from the Nichrome coil is enclosed in a PVC tube and distributed into the chamber via a blower fan. The blower fan, operating at 12 V, is controlled using a relay module for airflow control and efficient distribution of heat. This heating system is implemented only in the second chamber (thermophilic chamber), while the remaining chambers are equipped only with the exhaust system for aeration.

2.4.2.5 Moisture Control System.

Figure 2.34 Moisture Control Valve

A moisture control system was implemented to provide the optimal possible moisture content in the compost pile, in the second chamber (thermophilic chamber), since moisture content decreases during the thermophilic process. The system employs a 12 V solenoid valve shown in Figure 2.34**,** for water control, which allows water to be dripped into the chamber when the moisture content falls below 40%. The solenoid valve is mounted directly on the home water pipe and is controlled through an electromechanical relay module coupled with a microcontroller, giving precise and automatic control of moisture.

2.4.3 Microcontroller Configuration.

Figure 2.36 ESP32 MCU

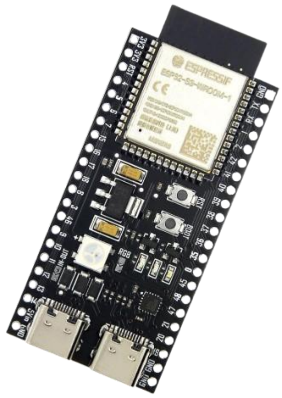

Figure 2.35 ESP-32-S3 MCU

The composting system uses two units of microcontrollers, namely the ESP32-S3 DevKit V1.0 and ESP32 DevKitC V4.0, shown in Figures 2.36 and 2.35, respectively. The ESP32-S3 is the central microcontroller unit (MCU) and is used for data acquisition and actuator control throughout the system. This module was selected due to the simplicity of its Wi-Fi-enabled interface to be conveniently integrated with IoT platforms, and due to its enhanced features, including more General-Purpose Input/Output (GPIO)[pins and Analogue-to-Digital Converter (ADC) channels compared to the regular ESP32.

ESP32 DevKitC V4.0 is used in regulating the heater via low-frequency Pulse Width Modulation (PWM). It is regulated by the ESP32-S3 through commands, and the two modules communicate via the I2C bus to facilitate synchronised and efficient system operation.

2.4.4 Power Supply for the Machine

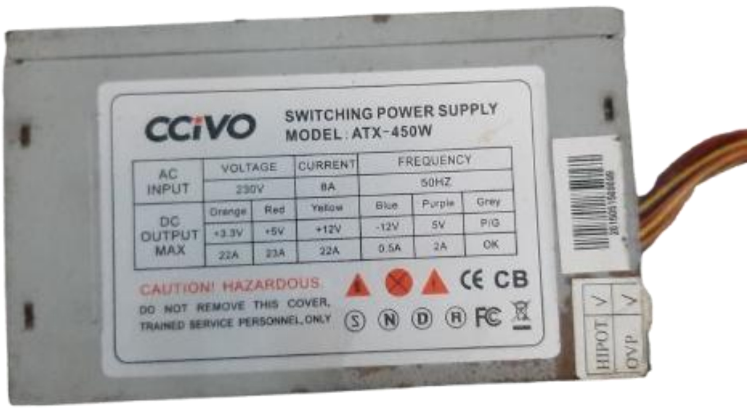

Figure 2.37 SMPS Used in the Machine

The composting system is powered by a Switched-Mode Power Supply (SMPS), which is shown in Figure 2.37, that provides multiple voltage outputs, which are 5V, 3.3V, and 12V. The power supply powers all sensors, actuators, and microcontroller units (MCUs), with each component receiving the appropriate voltage level via its respective VCC and GND pins. Signal lines of each device are connected to a prototype printed circuit board (PCB) where MCUs are integrated, which offers organised and efficient signal processing.

For continuous operation in case of power outages, there is a backup power system implemented only for the servo motors, sensors, and MCUs. A 5V power supply made of an 18650 Li-Ion battery pack is utilised for this implementation. To prevent power signal interference between the battery pack and the SMPS, there is a dual diode configuration that facilitates quick switching between the backup and main power sources.

2.5 Data Acquisition and Actuator Control System.

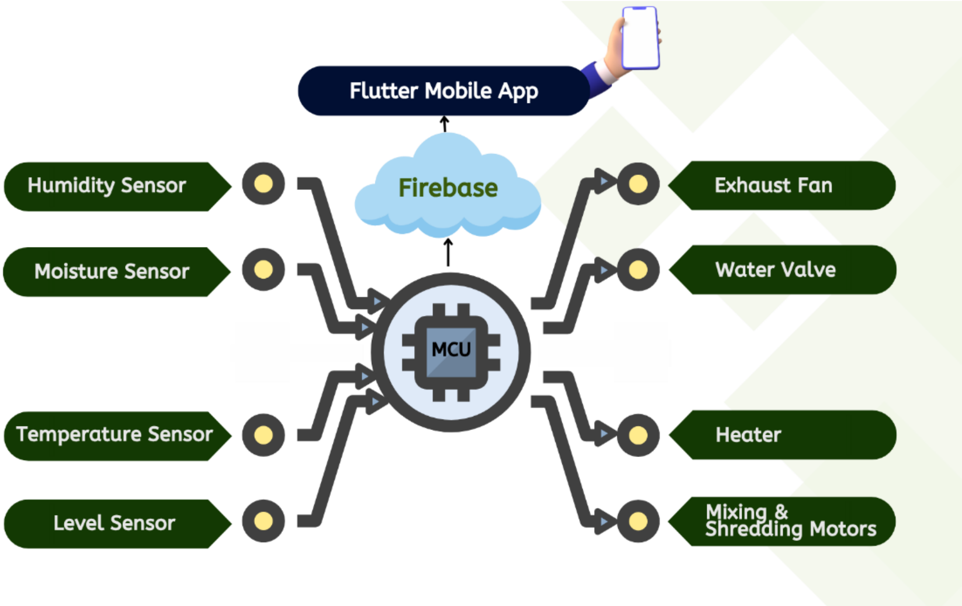

Figure 2.38 DAQ and Actuation Control Structure

2.5.1 Data Acquisition System

The data acquisition system, which is illustrated in Figure 2.38, is designed to periodically record, process, and retain sensor data to support automated and user-triggered decision-making processes within the composting system. The system employs the ESP32-S3 microcontroller unit (MCU) to record data from various sensors that track environmental conditions in the composting chambers. The data is transmitted to a Firebase real-time database via the ESP32-S3 onboard Wi-Fi feature for remote monitoring and access. On the user interface level, a mobile application provides real-time visualisation of sensor data and actuator states so that users can conveniently view the current operating state of each chamber. This sort of arrangement provides key environmental data instantly for analysis, thus facilitating informed decision-making for process optimisation of composting.

2.5.2 Actuator Control System

The actuator control system is set to automatically regulate actuators based on environmental parameters detected within every composting chamber to ensure optimum composting conditions. The system is primarily controlled by pre-determined thresholds and algorithms that respond to real-time sensor input, enabling it to run independently. Manual control is also available through a mobile application combined with the Firebase real-time database. Users can also bypass automatic settings and manually override actuator operations as needed using the app. Whenever an actuator status is updated in the Firebase database, the system reflects the physical actuators within a few seconds, with quick response times and synchronisation of the digital interface and physical system. The two-mode control (automatic and manual) enhances the composting process control flexibility and precision.

2.6 Composting Machine Workflow

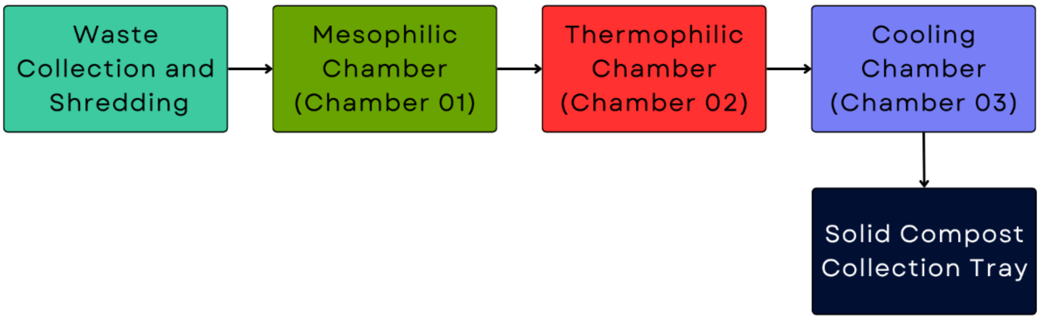

Figure 2.39 Machine Workflow

The composting machine operates through a sequential process, involving the collection, processing, and transfer of wastes in three specialised chambers: a mesophilic chamber, a thermophilic chamber, and a curing chamber. Each chamber is optimised for stages of the composting process to facilitate efficient decomposition and the production of good-quality compost. The workflow is illustrated in Figure 2.39 in terms of the stages of Waste Collection, Mesophilic Phase, Thermophilic Phase and final compost.

2.6.1 Waste Collection and Preliminary Processing

Kitchen waste is initially stored within a collection chamber, divided into two halves based on Varied properties of waste. The first half allows for the direct addition of smaller-sized or proportionate kitchen waste. The second half offers a grinding facility, including a motor and grinding plates, for handling larger or bulky waste materials. On the addition of bulk kitchen waste, the grinding mechanism is triggered by pressing a pushbutton, shattering the waste into smaller pieces. These processed small particles are transferred into the mesophilic chamber when the mesophilic decomposition chamber is ready to take new inputs.

2.6.2 Mesophilic Chamber Processing

The mesophilic chamber retains the processed kitchen waste and retains it for roughly 4 to 5 days for triggering decomposition under mesophilic conditions. Once prepared, the chamber can now accept new waste. The compost material is transferred to the next stage by a servo motor that opens a bottom door for the material to pour into the thermophilic chamber. The automatic transfer allows seamless material flow and prepares the mesophilic chamber for the introduction of the next waste.

2.6.3 Thermophilic Chamber Processing

Within the thermophilic chamber, the compost pile is subjected to a second decomposition for an additional 4 to 5 days under controlled high-temperature conditions of between 65°C and 75°C to promote thermophilic microbial growth. When temperatures fall below 50°C, an in-built heating device goes on to raise the temperature to the range of 65°C. Also, if the moisture level goes below 50%, an automated water valve opens to allow water to be sprinkled within the chamber to reach adequate moisture levels. Meanwhile, a rotating mechanism (also referred to as the stirring mechanism) is working in delivering uniform heat and moisture distribution within the compost pile for aerobic breakdown to occur. This mechanism operates in instances of heating and wetting to maintain homogeneity and maximise breakdown conditions.

2.6.4 Curing Chamber Processing

After thermophilic processing, the compost pile is introduced into the curing chamber, where it is matured to completion. The curing chamber offers cooling of the compost to ambient room temperature in approximately 5 days, completing the composting process. The curing chamber features a specialised heat reduction and exhaust system that includes activated carbon pellet filters to reduce odours when in use.

2.6.5 Environmental Control and Aeration

All three chambers—mesophilic, thermophilic, and curing—are equipped with separate exhaust systems that incorporate activated carbon filters for odour suppression. In case temperature decrease is necessary for any specific chamber, its associated exhaust fan is turned on, and the turning device is operated simultaneously for 30 seconds to 1 minute, or longer if possible. This turning helps in aeration of the compost pile, promoting aerobic degradation at the expense of conditions favourable to anaerobic processes. The concurrent operation of the turning and exhaust mechanisms provides ideal environmental conditions within every chamber.

2.6.6 Final Output and Compost Transfer

Bottom doors are opened by servo motors to transfer compost from one chamber to another. Upon transferring material from the top chamber to the bottom chamber, the turning mechanism is operated in the return direction to facilitate complete transfer of the compost pile. After the curing process is complete, the system notifies the user via a mobile app to harvest the finished compost fertiliser manually. Manually harvesting the product is achieved by entering a command using the mobile app, which will open the curing chamber for the removal of compost. The user interface is intuitive and makes it simple to interact with the system and harvest the product.

2.7 Control System Workflows

2.7.1 Temperature Control System for Thermophilic Chamber.

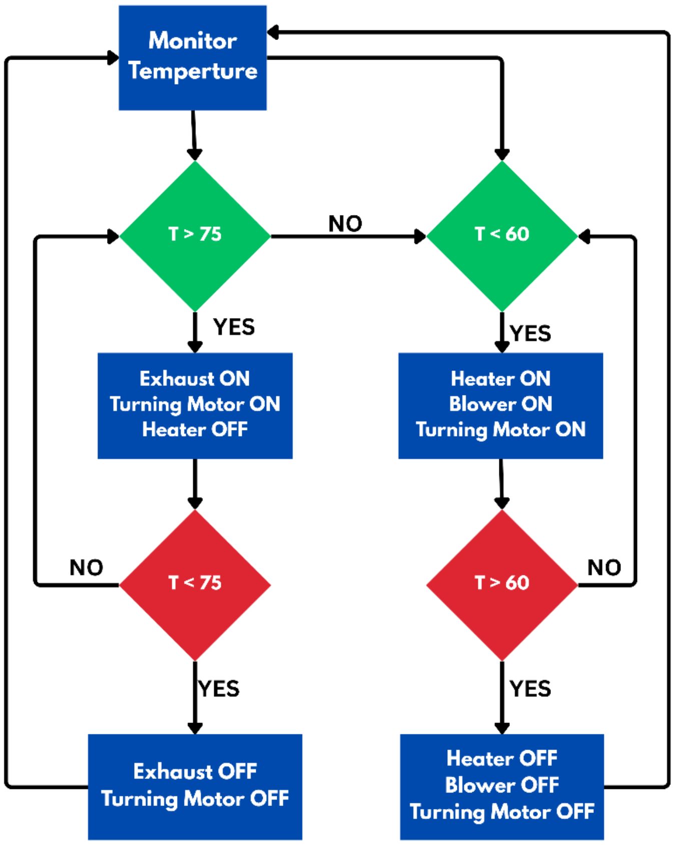

Figure 2.40 Temperature Control Flow Diagram

Figure 2.40 illustrates the temperature control system, which is a continuous finite state machine that continuously monitors temperature from a sensor (mounted inside the thermophilic chamber to monitor compost pile temperature). If the temperature increases beyond the upper limit, the exhaust fan turns on and the motor runs, but the heater remains off. When the temperature is below the lower threshold, it sends an I2C command to turn on the heater and also runs the motor to enhance air circulation. The system monitors temperature changes at regular intervals and toggles between control states (e.g., FAN_ON, LOW_TEMP_ACTION) to determine whether it should reheat, cool, or enter idle mode.

2.7.2 Moisture Control System for thermophilic Chamber

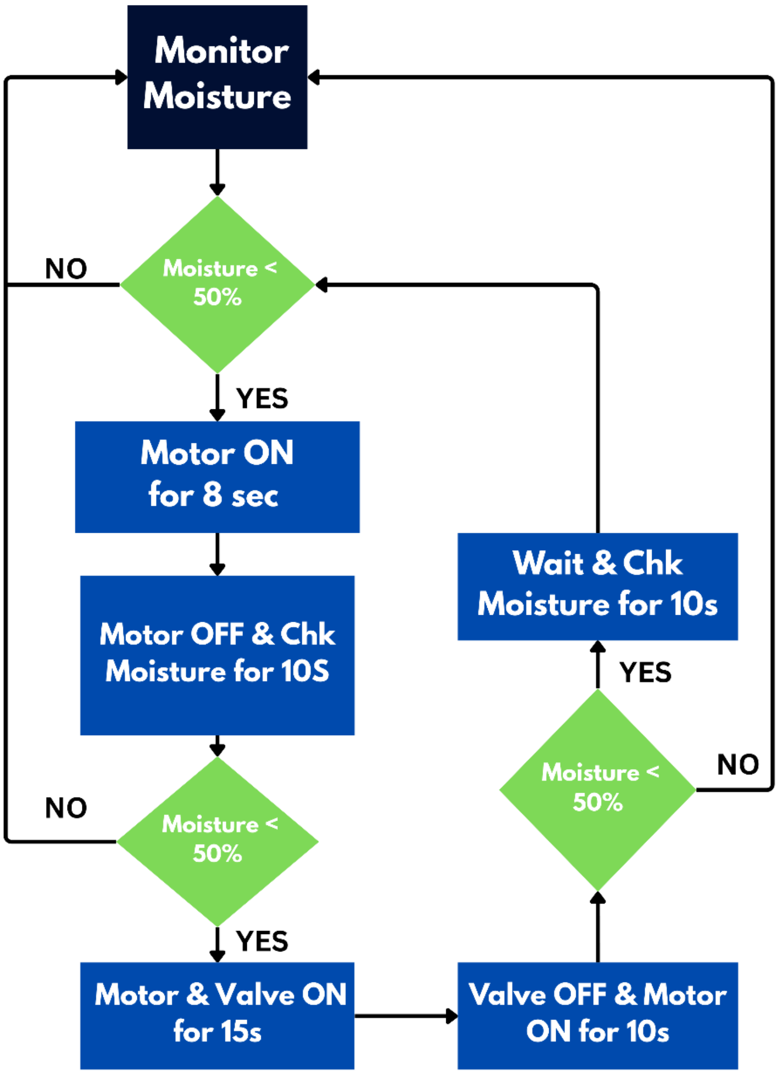

Figure 2.41 Moisture Control System

Figure 2.41 Elaborates on the moisture control system operation on a step-by-step control sequence that automates irrigation by continuously reading soil moisture levels. It begins by taking a reading of the moisture from a Thermophilic Chamber sensor. If the moisture level is below a specific value, the system activates a motor pump for a predetermined period. It then waits before rereading the moisture. If there is an unsatisfactory level of improvement, the system opens a valve and the motor runs again to supply more water. After completing the full watering cycle, the system rechecks the moisture level; if it is still too low, it waits for a short time before repeating the process. Every step in the sequence is controlled logically based on sensor readings, and all motor and valve activity is logged to Firebase for remote monitoring.

2.7.3 Compost pile turning system.

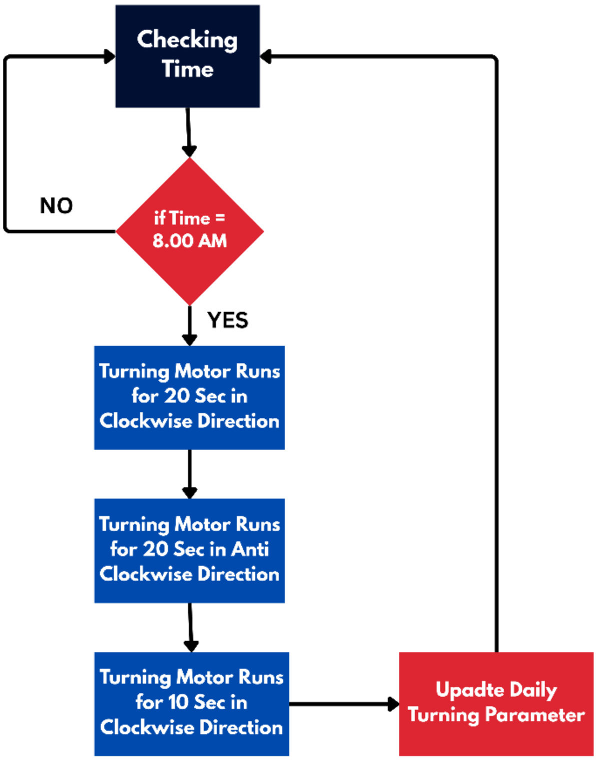

Figure 2.42 Compost pile turning system.

Figure 2.42 illustrates the compost pile turning process. It will activate every day at 8.00 AM and turn the compost for 40 seconds to ensure aeration. When turned on for the first time, it will turn the compost in a clockwise direction for 20 seconds, then start to turn in an anticlockwise wise for 20 seconds and finally turn the compost in a clockwise direction for 10 seconds, completing the cycle and updating the Daily Turning parameter to high with a completed time stamp for a log.

2.7.4 Compost Transferring Function.

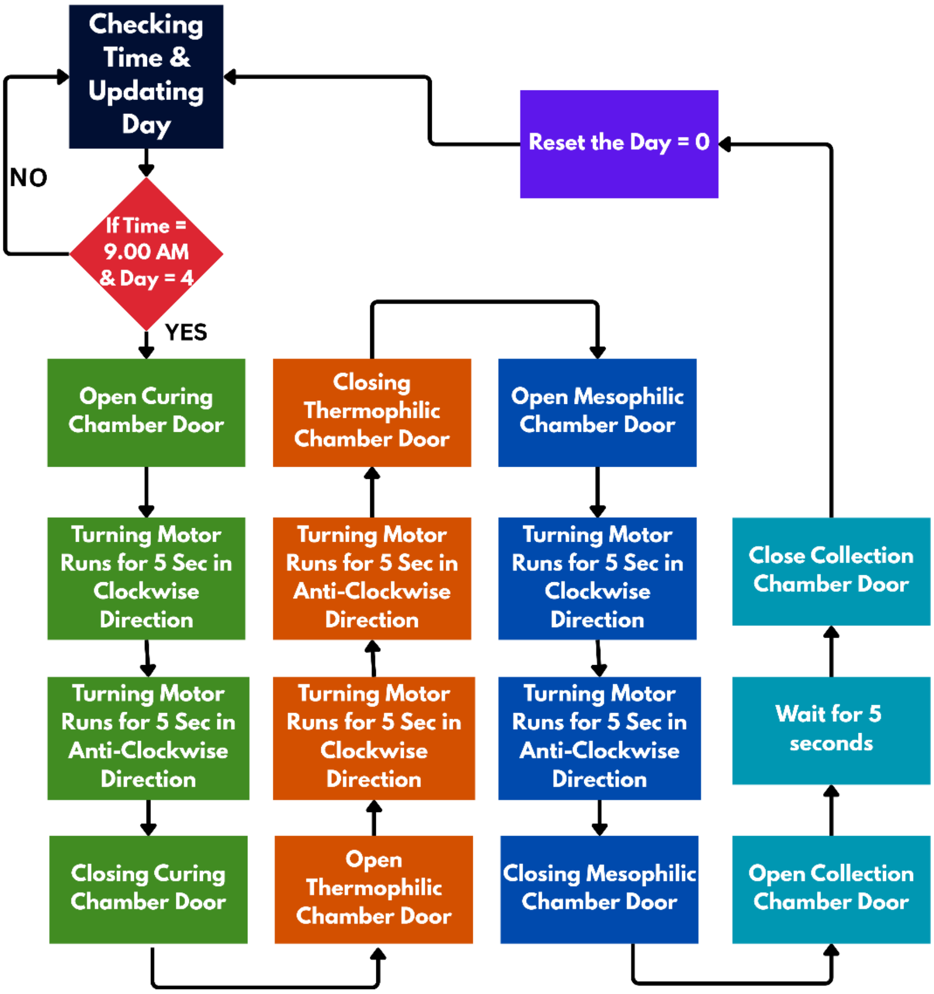

Figure 2.43 Compost transferring system workflow.

Figure 2.43 shows the complex step-by-step compost pile transferring process, which is automatically triggered when the current time is 9:00 AM and the Day parameter is 4—i.e., the operation occurs every four days. Transferring compost from the curing chamber to the compost collection tray is the first step in the process. This involves opening the chamber door, powering the motor to rotate clockwise and anticlockwise for 5 seconds and then closing the door. The same process is carried out to transfer compost from the thermophilic chamber to the curing chamber, and from the mesophilic chamber to the thermophilic chamber. Once all the transfers are completed, the Day parameter is reset to 0 and increases each day until it reaches four (4) again, at which point the cycle is resumed.

2.8 Circuit Board Design and Electrical Wiring

The circuit board design and electrical wiring of the composting system were developed with particular care to facilitate correct, safe, and reliable operation and precise data measurement. This encompasses the wiring layout for the motor control systems, sensors, and water-proof features, the optimal location of the sensors, and direct wiring to microcontroller and power supply.

2.8.1 Sensor Wiring and Protection

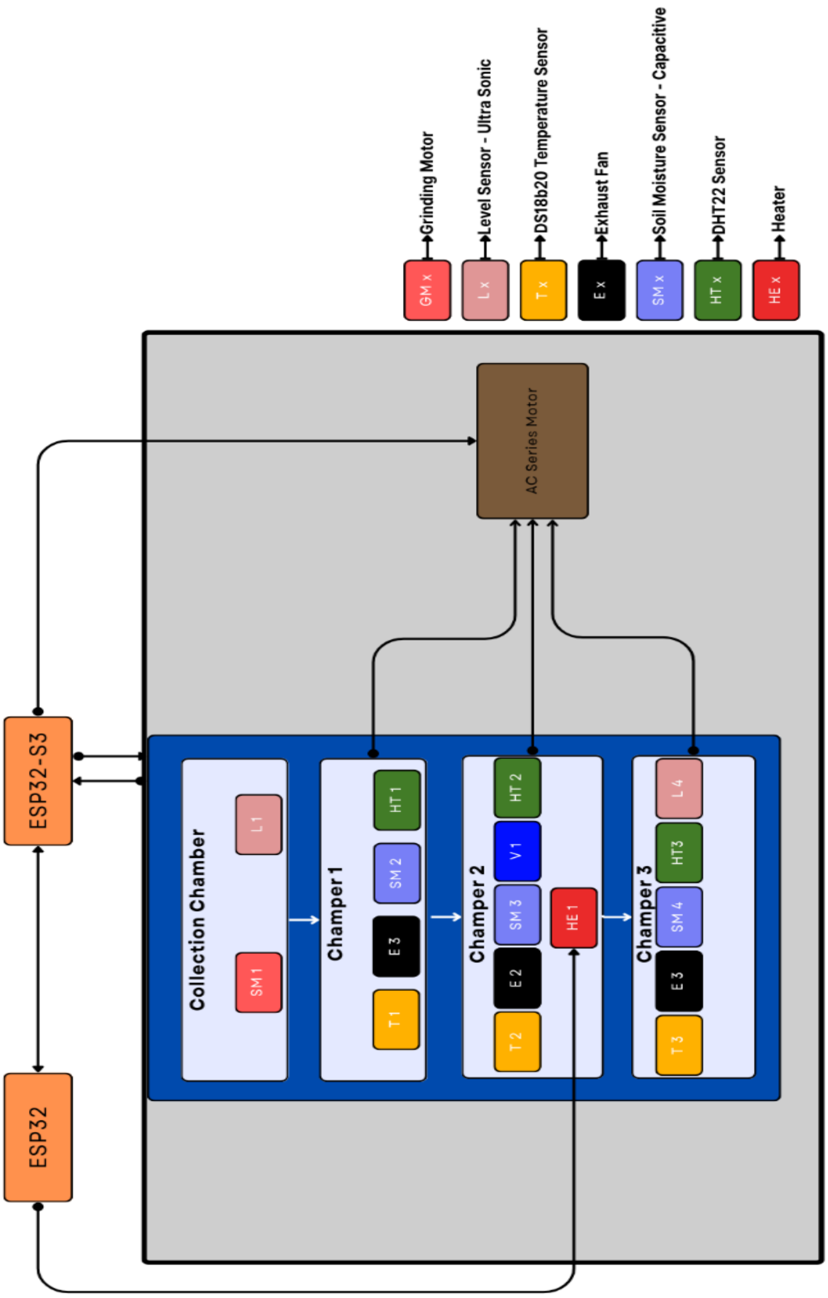

Figure 2.44 Sensors and Actuators placing plan

Figure 2.44 illustrates the sensor and actuator placement plans for each chamber. For the sake of reliability and durability, a water-resistant or waterproof covering was provided to all sensors. Electronic sensor components and data cables were sealed with heat-shrink tubing and silicone adhesive to avoid the ingress of moisture, which is a necessity considering the humid conditions inside the compost chambers. Sensors' wires were also made longer to allow them to be connected to a Switched-Mode Power Supply (SMPS) for power and a microcontroller for communication of signals, which is illustrated in Figure 2.45.

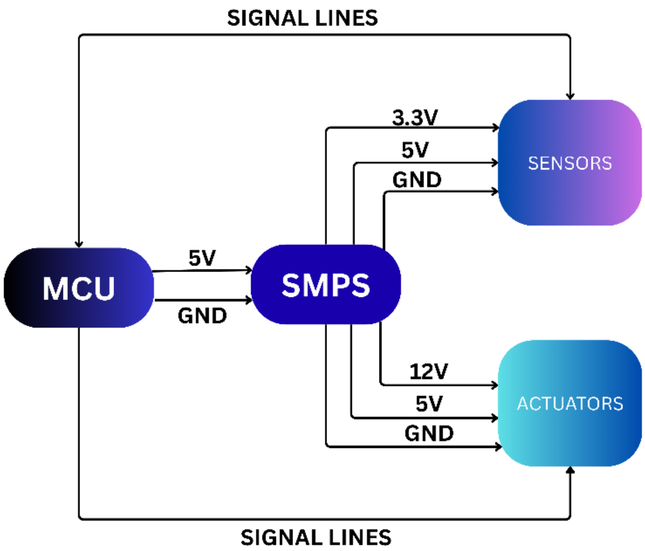

Figure 2.45 SMPS and MCU Connection Plan with Components

Wires were colour-coded to enhance readability and maintainability. Wires for the power supply were marked red for VCC and black for GND. Signal wires were marked with yellow, blue and green cables so that they would be distinguishable from power wires, and hence it was easy to identify during debugging and installation. 3-pin and 4-pin connectors were utilised in connecting sensor signal wires to the prototype PCB, where the ESP32-S3 microcontroller is mounted to enable easy detachment and mounting.

2.8.2 Ideal Placement of Sensors to Take Measurements

Sensors were placed within every composting chamber for the highest measurement accuracy of environmental conditions. Optimal placement was conducted considering the individual function of each sensor:

Soil Moisture Sensor: Placed at the bottom of each chamber to directly detect the moisture of the compost pile, to accurately measure the moisture content essential for decomposition.

Figure 2.46 Soil Moisture and DS18b20 Places inside chamber

Figure 2.46 shows the placement of Soil Moisture and DS18b20 inside the chamber, ensuring proper sensing and water resistance.

DS18B20 Temperature Probe: Placed beside the soil moisture sensor at the bottom of each chamber for sensing the internal temperature inside the compost pile to facilitate proper monitoring of decomposition. Level Sensor: Placed at the top of each chamber for sensing the fill level of the compost material to facilitate proper control of material transfer between the chambers.

DHT22 Sensor: Situated at the upper rim of each chamber to detect ambient humidity and temperature, recording complete details of the environmental condition of the chamber.

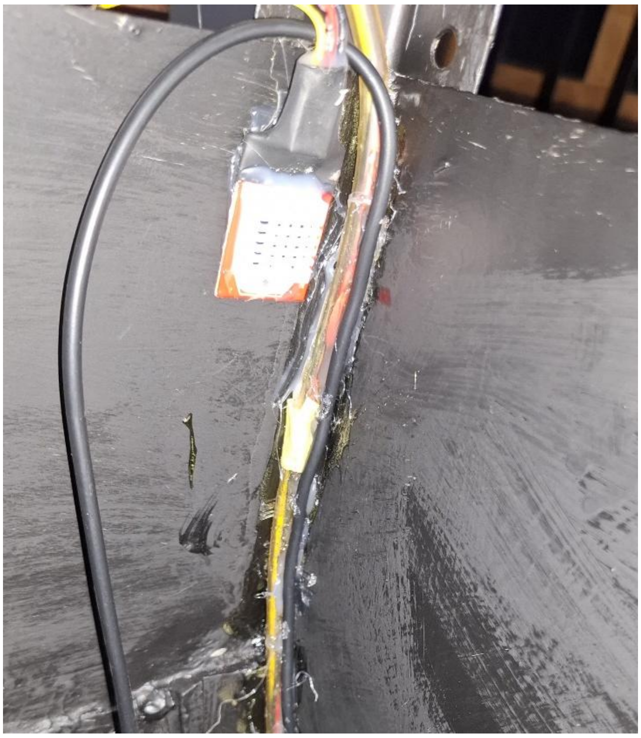

Figure 2.47 DHT22 Placed inside the Chamber

Figure 2.47 shows that the strategic location, where the DHT 22 sensor is placed, provides vigorous and representative sensor readings for proper control and optimisation of the composting process.

2.8.3 Motor Control and Power Supply

There are two motors used in the composting system and are provided with a 220V AC power supply and operated utilising the ESP32-S3 microcontroller through relay modules to prevent mis operation, along with safety reasons.

2.8.3.1 Compost Turning Motor

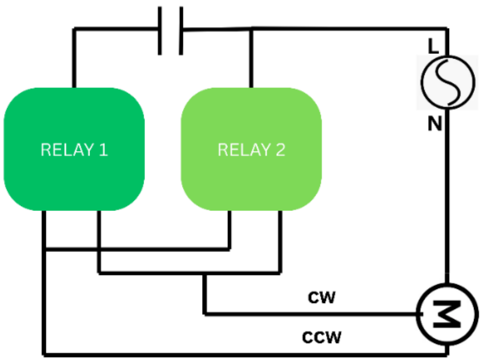

Figure 2.48 Motor Bi-Directional Control Unit

It is powered by a 220V AC series motor that powers a compost turning mechanism capable of introducing aeration and moving material between chambers. The motor is controlled by two dual-channel relays, which are illustrated in Figure 2.48**.**

The first dual-channel relay alternates the live and neutral wires of the 220V AC power supply on and off for protection during work and complete disconnection of power supply when the motor is shut down. The second two-channel relay inverts the motor direction to create forward and reverse rotation for the optimum compost transfer and aeration needs. Both relays are mounted on the ESP32-S3 microcontroller for controlling accurately as per system requirement or user instruction.

2.8.3.2 Grinding Motor

An additional 220V AC motor is also fitted within the kitchen trash collection bin for grinding big trash into small pieces. This extends aerobic digestion by allowing air to permeate the trash, hence reducing composting time costs. The grinding motor is powered through an electromagnetic relay, also interfaced with the ESP32-S3 microcontroller. Through this, automatic grinding machine triggering is programmable whenever high amounts of trash are sensed, hence guaranteeing effective processing.

2.8.4 Integration of Microcontroller and Power Supply

All the motors, sensors, and actuators are attached to the SMPS of various voltage levels (12V, 3.3V, and 5V) to supply the power needed by each device. The ESP32-S3 microcontroller is the control unit that computes the sensor information and offers instructions to the relays to activate the motors. Sensor and actuator signal wires are connected to the prototype PCB so that the interaction with the microcontroller is orderly and organised. In this type of design, integrating the electrical components for monitoring and controlling the composting system in real-time is straightforward.

2.9 Final Assembly and Thermal Insulation

Following wiring, painting, and the installation of mechanical and electrical components, measures were taken to prevent heat loss from composting chambers to the external environment, thereby conserving the maximum amount of heat available for composting. Twice the thickness of aluminium foil-coated heat-resistant foam was utilised to cover all chambers for efficient thermal insulation. This material was selected as it has extremely high heat flow resistance, which lessens heat dissipation and assists in keeping the required level of temperature in every chamber.

Figure 2.49 After placing sensors and the Shaft with arms inside the chamber

Figure 2.49 shows a picture of the sensors and shaft with the turning arms placed in the chamber.

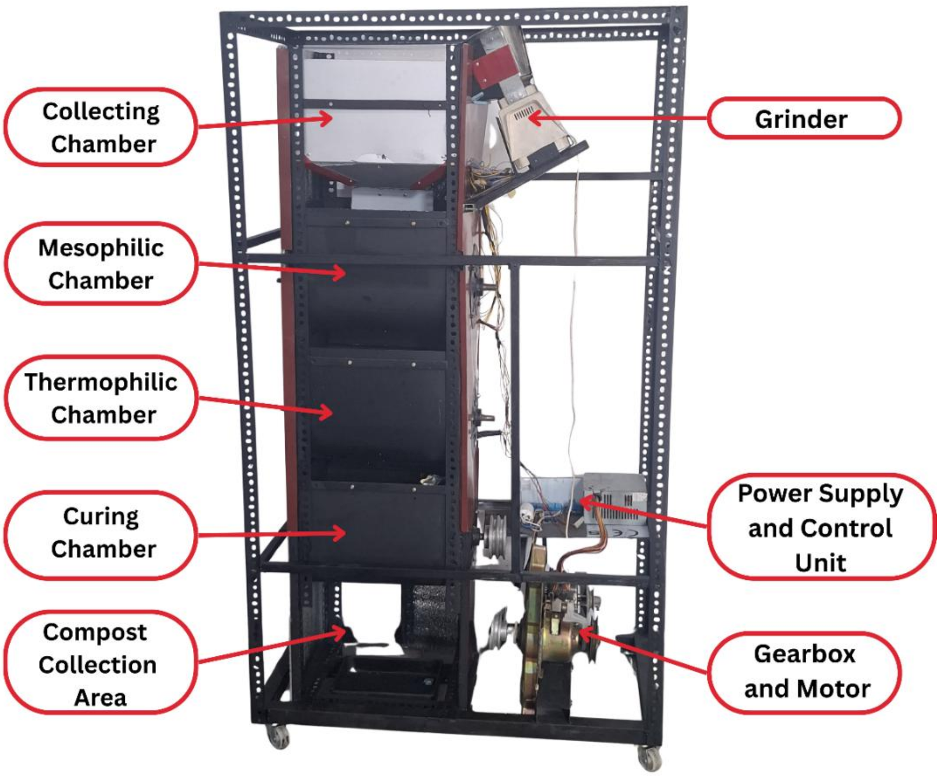

Figure 2.50 Front View - After Assembled

Figure 2.50 shows the front view of the machine after assembling all the mechanical and electrical parts without the outer casing and mentions the major components and units of the machine in the image.

Figure 2.51 shows the machine's isometric view with the dimensions of the machine.

Figure 2.52 shows the backside and the other side view of the machine.

Figure 2.51 Machine with Dimensions

Figure 2.52 Backside other side view of machine

After insulation, the entire insulated chamber frame and machine frame were then covered with thin sheets of aluminium. This outer cover adds to the system structure stiffness as well as providing it with a shiny, cosmetic appearance. The employment of thermal insulation and the use of aluminium sheeting provides the composting machine with functional performance as well as a cosmetic appearance.

CHAPTER 3: Results and discussion

This chapter describes the rigorous testing procedures conducted to provide validity of functionality, accuracy, and reliability of the sensors and actuators that are integrated into the composting system. The test phase was geared towards component-level verification, sensor calibration, actuator functionality, and system integration. All tests were conducted using custom test codes to allow precise testing and calibration where needed. The results were analysed for the system to be operationally viable, with the data being smoothly integrated into the Firebase real-time database and the mobile application for interaction with the users.

3.1 Sensor Testing and Calibration

In order to determine accuracy in the environmental readings in the composting chambers, each sensor was separately tested and, where necessary, calibrated. Soil moisture sensor, DS18B20 temperature probe, DHT22 temperature and humidity sensor, and ultrasonic level sensor testing and calibration are explained in the subsequent subsections.

3.1.1 Soil Moisture Sensor Calibration

Soil moisture sensors were calibrated to get accurate readings of compost pile moisture content. Calibration was carried out under two conditions: dry soil and wet soil. To replicate the wet soil condition, a glass of water was used to fully enclose the sensor environment to replicate high moisture levels. For the dry soil condition, the sensor was exposed to open air, replicating low moisture.

	Sensor 1	Sensor 2	Sensor 3
Dry Value	2960	3499	2968
Wet Value	1231	1747	1260

Table 3.1 Calibrated Values - Soil Moisture Sensor

A total of three soil moisture sensors underwent testing, and multiple readings were recorded for each condition to account for variability. The average of the readings was calculated for the dry as well as the wet conditions, and the values were used to calculate calibration constants. Table 3.1 illustrates the average values of Dry and Wet values of all the sensors. These constants were then incorporated into the main data collection code to collect stable and correct soil moisture values from all the chambers.

3.1.2 Calibration of the DS18B20 Temperature Probe

The DS18B20 temperature probes that were used to log the internal compost pile temperature were calibrated for accuracy. Two of the DS18B20 probes were set against each other and their temperatures measured against ambient room temperature. Both sensors provided nearly the same reading, and they were also the same as the reference temperature, indicating that they were very accurate and reliable. Thus, there was no need to calibrate the DS18B20 sensors, and they were utilised in the system as is.

3.1.3 Testing of DHT22 Temperature and Humidity Sensor

Ambient temperature and humidity measurement within the composting chambers using DHT22 sensors were also tested experimentally. Readouts from different DHT22 sensors were compared with each other and determined to be in agreement with each other and with factory-calibrated benchmarks. They were not required to be further calibrated due to their pre-calibration accuracy at the factory level and were utilised as is in the system for reliable environmental monitoring.

3.1.4 Calibration of Ultrasonic Level Sensors

Ultrasonic level sensors were utilised to measure the fill level of compost material in both chambers. Sensors were calibrated upon installation in the chambers. The reading of the sensor was taken at two reference points: an empty chamber (which was equated to 0% fill level) and a full chamber (which was equated to 100% fill level). These coincident distance measurements were used to create a linear calibration scale of 0% to 100% fill level. Each of the ultrasonic sensors was calibrated individually using this process in order to give accurate and consistent level measurement for each of the chambers.

3.2 Actuator Calibration and Testing

Actuators, or servo motors used in opening and closing the chambers, were controlled to perfection and smoothly by trial and error. Recalibration of the servo motors was purely a matter of finding the right opening and closing angles for every servo motor, since varying motors had differences at their breaking points.

3.2.1 Servo Motor Calibration

Another test code was run to determine the proper angles to open and close the doors of each chamber. The code ran through positions of servo motors to find the required angles, and they were added to the control code. Parameters were calibrated so that each servo motor could open and close doors of the chambers ideally for easy compost pile transfer from one chamber to another. The calibration was performed for each one of the chambers to correct any mechanical deviation.

3.3 System Integration Testing

After the module test, end-to-end testing of the complete composting system was done to verify integrated functionality. The system was tested for end-to-end communication between the ESP32-S3 microcontroller, Firebase real-time database, and Flutter-based mobile application. The following were tested:

3.3.1 Real-Time Data Acquisition and Upload

It was set to record the sensor readings each second in the MicroSD Card connected to the ESP32-S3. Using the MicroSD Card module connected via SPI bus, it also updates the current sensor data reading into the Firebase real-time database with the timestamp at fixed intervals of 2 minutes. Sensor readings (temperature, humidity, fill level, and soil moisture) were sent to the database during testing, and the latest data were accessed in real-time on the mobile app. Periodicity and timeliness of data uploading were tested and gave constant data storage and retrieval.

3.3.2 Control of Mobile Application

Even actuator remote control was done using the Firebase real-time database via the mobile app. Commands from the mobile app, i.e., activating servo motors or toggling states of actuators, were transmitted successfully to the ESP32-S3 microcontroller. The system responded following a delay of a few seconds, which translates to almost real-time control. The actuators' state changes were simulated correctly on the physical system as well as on the mobile app user interface, confirming the software and hardware systems' interface.

3.4 Mobile App and Functionality Development

The mobile application of the composting system was developed on the Flutter platform, and the UI was initially created based on Figma for optimal user usability and visual appearance. The app directly communicates with a Firebase real-time database to ensure real-time monitoring, setup, and control of the composting system. The app has three primary interfaces that each serve a unique purpose in the management of the composting process.

3.4.1 Monitoring Interface

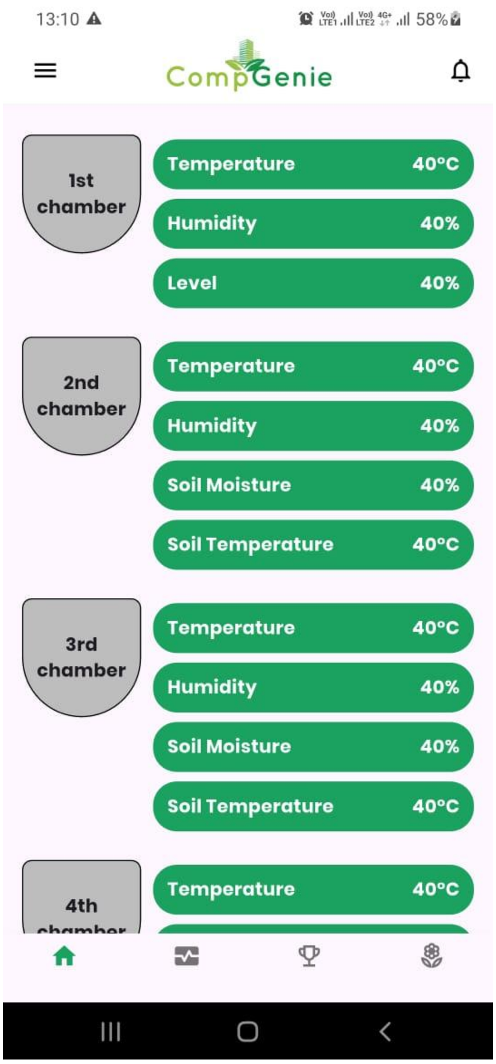

Figure 3.1 Monitoring Screen

Figure 3.1 shows the UI of the Monitoring Screen, reserved for online monitoring, which includes real-time sensor readings of all the composting chambers. They are environmental parameters such as temperature, soil moisture content, and trash fill levels in the chambers. The interface provides real-time feedback to the users regarding the system operation status, thus facilitating efficient monitoring of the composting process.

3.4.2 Threshold Configuration Interface

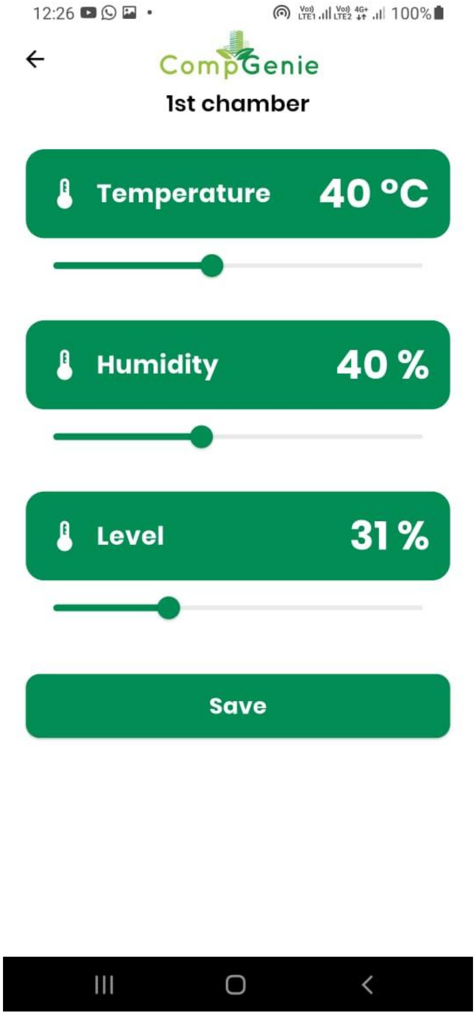

Figure 3.2 Threshold Screen

Figure 3.2 shows the second interface, which allows users to input threshold values of the main environmental parameters, for example, temperature, soil moisture content, and levels of waste in all chambers. Such an ability allows for the potential of customising the composting environment for maximum performance. Users are able to adjust such limits to allow for conducive conditions for decomposition, which are saved and synced through the use of the Firebase real-time database.

3.4.3 Actuator Control Interface

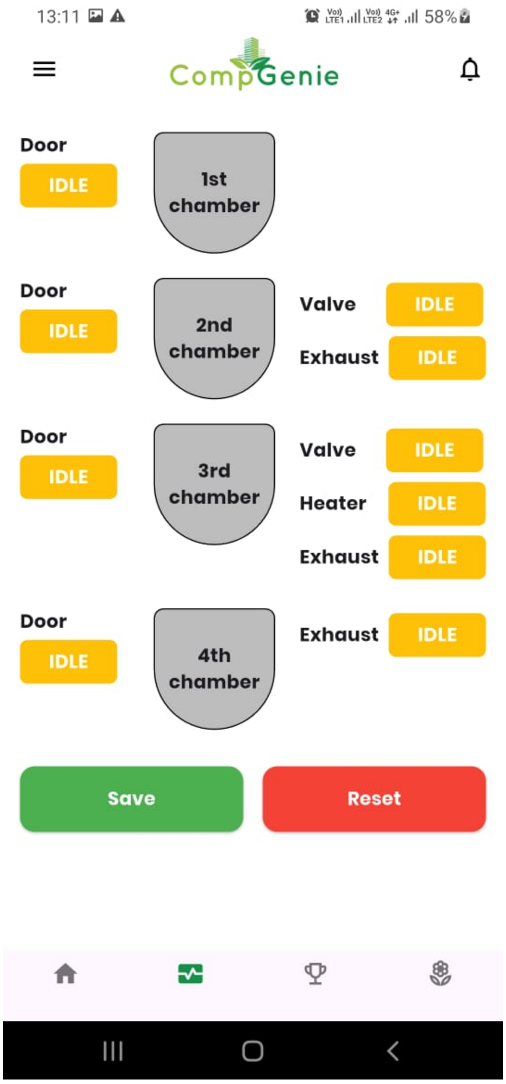

Figure 3.3 Actuator Control Screen

Figure 3.3 shows the third interface, which is the remote control of the actuators of the system. Through the interface, the user can commandeer actuator states such as on/off motors, on/off heaters, and on/off water valves to regulate the composting process. The interface posts updates to the Firebase real-time database, where actuator control parameter updates are saved. The ESP32-S3 microcontroller will constantly scan the database for such changes and update the actuator status automatically within seconds, thus providing timely and accurate response to the user input.

3.4.4 Firebase Real-Time Database Integration

The mobile app uses Firebase real-time database to facilitate effective communication of data between the composting system and the user. The data from sensors is uploaded to the database in real time, thus making the monitoring interface display real-time values. Consequently, any adjustment of actuator control parameters established via the mobile app also immediately shows up in the database. The updates are captured by the ESP32-S3 microcontroller, the control system, and applied to enact the respective change in actuators for synchronised cooperation between the physical system and the mobile app.

This blended approach, the union of a stunningly designed UI with collaborative sharing of real-time data, provides users complete monitoring and control ability, contributing to usability and productivity of the composting system.

3.5 Database Structure and Integration

Figure 3.4 Firebase Realtime DB Structure

Figure 3.4 shows that the database structure of the composting system is designed in such a way that it enables proper linking of the composting machine, mobile app, and data acquisition system. It plays a dual role: facilitating real-time communication between the ESP32-S3 microcontroller and mobile app and storing sensor data in the composting chambers for future use. This is data storage that enables optimisation of control mechanisms as a function of correlating sensor readings to end-compost product and allowing iterative tuning of operating parameters by testing against changing threshold levels.

Firebase real-time database was used due to its excellent integration features and ease of use. Its synchronisation in real time offers real-time updates for all devices connected, hence making it appropriate for this app. The Firebase platform makes it easy to integrate with the ESP32-S3 microcontroller through the Arduino Integrated Development Environment (IDE), making development easy. Similarly, Firebase support through the Flutter framework offers easy integration with the mobile app without requiring additional backend hosting infrastructure.

3.5.1 Data Collection and Storage

Sensor measurements like temperature, humidity, and waste quantities in every composting bin are sampled in real time by the ESP32-S3 microcontroller and uploaded to the Firebase real-time database. Centralised storage ensures real-time access to environmental parameters and long-term analysis, allowing for the optimisation of the efficiency of the composting process. Archiving sensor readings allows the system to compare diverse control parameters to facilitate data-driven modification to optimise compost quality.

3.5.2 Device-Mobile Application Communication

Firebase real-time database serves as an interface to facilitate communication between the composting device and the mobile application. ESP32-S3 microcontroller constantly searches for updates to the actuator control parameters in the database in order to achieve real-time synchronisation of commands sent through the mobile application. Sensor data on Firebase is, on the other hand, easily retrieved using the mobile app's monitoring interface, providing users with immediate, real-time feedback of the system status. This two-way communication gives a free user interface and hardware interaction.

3.5.3 User Authentication

For protecting access to the mobile app, Firebase authentication functionality is utilised. Figure 3.5 shows the Firebase authentication panel, which provides a secure and scalable solution for user authentication, supporting secure login and authorisation without additional backend code. The Firebase authentication system ensures that only authorised users have access to sensor readings, adjust thresholds, or control actuators, thus securing the composting system.

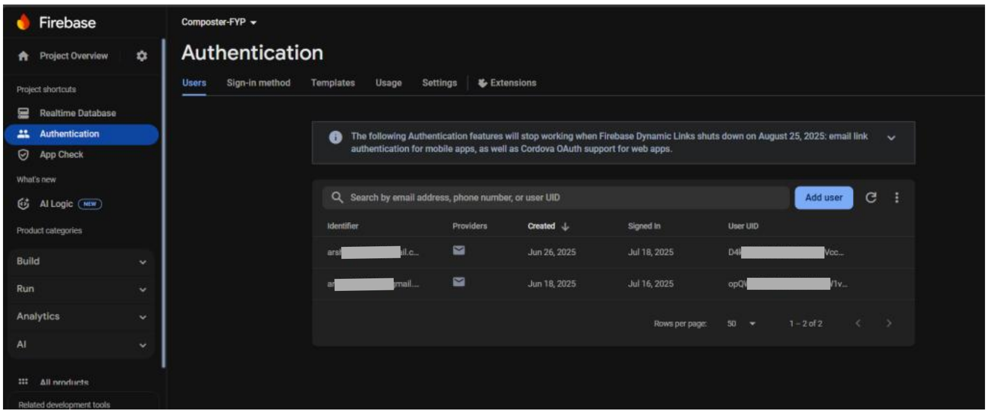

Figure 3.5 Firebase Authentication Panel

Operating with Firebase as a database manager and authenticator reduces backend complexity to a minimum, making it easy to develop and maintain, and delivering robust, real-time capability for the composting system.

3.6 General System Performance

The entire composting system was subjected to simulated conditions for performance evaluation. The automatic control systems, like actuator response to sensor readings and material transportation from one chamber to another, all functioned as expected. The climatic control systems (heaters and water valves), the turning drive, and the servo motors all collaborated with the sensor feedback to provide the optimal composting conditions. The smartphone application provided evident real-time monitoring and control, demonstrating the reliability and usability of the system.

3.7 Results and Observations

The testing phase verified that the actuators and sensors remained within functional limits, and calibration provided accurate readings to the ultrasonic level and soil moisture sensors. The DS18B20 and DHT22 sensors were factory accurate and not recalibrated. The servo motors were successfully calibrated to provide accurate door control, enabling smooth compost transfer within chambers. The ESP32-S3 microcontroller was in good working order, utilising a Firebase real-time database, SD Card integration, and a mobile app. Uploads were performed every 2 minutes at regular time intervals, and actuator commands were transmitted with minimal latency from

Firebase. Overall system performance was as per design spec and automated well, and environmental monitoring was precise, along with a remote control feature which could be used with ease. For the testing of the entire system, we have reduced the time delays and tested the system's workability, and it worked as expected, as in the workflow diagrams

CHAPTER 4: Conclusion and Recommendations

4.1 Conclusion

The project successfully conceived, designed, and deployed an IoT-enabled automated home composting system for Sri Lankan urban residences to cope with the formidable challenge of biodegradable municipal solid waste (MSW) management. The system features a three-chambered modular structure for mesophilic, thermophilic, and curing processes with sensors (temperature, humidity, moisture, and fill level) and actuators (motors, heaters, and water valves) regulated by an ESP32-S3 microcontroller. Real-time monitoring and control are accomplished by a real-time Firebase database and an application based on Flutter, minimising human action and useability.

During the testing phase, functionality of the system was set up with sensors delivering precise environmental information and actuators to control optimal levels of composting. The three-chamber system allowed efficient decomposition to lead to high-quality compost to be employed in home gardening and small-farm operations. By mechanising important operations like mixing, heating, and keeping moist, the system circumvents the disadvantages of conventional composting, i.e., labour, odours, and space. With its low-cost, compact, and modular nature, the system is especially suited to the urban environment of developing nations like Sri Lanka, where waste management plants are normally not available.

The project is a valuable addition to sustainable waste management by minimising landfill reliance, reducing greenhouse gas emissions, and promoting the circular economy through the recycling of organic waste. It aligns with international sustainability targets by encouraging green behaviour among metropolitan consumers, minimising chemical fertiliser reliance, and ensuring healthier communities in the soil. Success in implementing IoT technology is proof enough that intelligent, self-governing technologies can work successfully against major environmental problems on a mass scale at the domestic level.

4.2 Future Development Suggestions

To improve the system's performance, scalability, and efficiency further, the following are proposed for future development:

AI and Machine Learning Integration: The integration of artificial intelligence (AI) and machine learning (ML) algorithms would be useful in generating predictive changes to composting parameters using waste composition and sensor data. This would maximise decomposition efficiency and make the system sensitive to different waste inputs, as Azis et al. (2022) suggested. For this purpose, we are logging continuous monitoring data into an SD Card for future ML model training and achieving optimal results with minimal resource usage.

4.2.1 Solar Power Integration

Increasing sustainability, incorporating solar panels as a power source, can limit the system's dependence on grid power and make it environment-friendly and cost-effective, particularly for areas with recurrent power outages.

4.2.2 Better Odour Control

Although the existing activated carbon filters are effective at odour control, studying newer filter systems, i.e., biofilters or photocatalytic oxidation, can reduce odour emissions even further, increasing user satisfaction in urbanised cities.

4.2.3 Waste Sorting System

Incorporating an automated sorting system for sorting biodegradable and non-biodegradable waste at the input level would enhance efficiency and minimise risk of contamination for high-quality compost.

4.2.4 Large-Scale Institutional Scaling

Institutional scale-up of the system for institutional applications, i.e., schools, community clubs, or small businesses, would require scaling up chamber capacity and incorporating multi-unit synchronisation for centralised management of waste.

4.2.5 User. Education and Outreach

Public outreach programs and educational materials would enhance adoption rates by making the public more aware of the advantages of home composting as well as how to use and maintain the system properly.

4.2.6 Cost Optimisation

Cost material and manufacturing process optimisation would reduce the cost of the system even further, making it even more affordable for low-income households in developing countries.

4.2.7 Special-Purpose Unit Optimisation

The composting unit comprises a set of specially designed units, such as the PWM-based heat control system, moisture control system, motor control units (turning and grinding motors), turning mechanism, and exhaust system with activated carbon filters. In future optimisation, research and development are suggested

4.2.7.1 PWM-Based Temperature Control System

The current application of a pulse-width modulation (PWM) controller to the heating coils enables precise temperature control. Future developments must focus on minimising the PWM algorithms for increased energy efficiency and response time, enabling fast and stable temperature control in the thermophilic chamber. Experimental testing on different PWM frequencies and duty cycles can further enhance the thermal performance of the system.

4.2.7.2 Moisture Control System

The moisture control system that regulates water sprinkling for optimal levels of moisture would be improved with more advanced sensor integration and feedback algorithms. More precise moisture sensors or predictive models using waste composition could optimise moisture control, conserve water usage while supporting ideal composting conditions.

4.2.7.3 Motor Control Systems

Motor control systems for grinding and turning are critical to the operation of the system. Future improvement could include the utilisation of adaptive control algorithms that would be able to optimise the motor speed and torque as a function of composition and waste volume. In addition, the incorporation of fault detection mechanisms can be utilised to enhance the reliability and life of motors.

4.2.7.4 Turning Mechanism

The turning mechanism utilised to aerate the compost pile could be optimised for increased cleanliness and energy efficiency of aeration. Sensor-activated or variablespeed turning or sequences of turning can be considered for ensuring uniform aeration with lower power utilisation.

4.2.7.5 Exhaust System with Activated Carbon Filters

Ongoing research within the exhaust system can be focused on optimum airflow dynamics and filter efficiency. Research into new material or new design, such as hybrid biofilter-activated carbon systems, is applicable to odour control optimisation and maintenance interval frequency.

These advances would leverage the strengths of the existing system, mitigate its weaknesses and push its applications. With ongoing innovation in automation, sustainability, and ease of use for the end user, the suggested composting system can be a global pioneer in scalable, intelligent waste disposal technology, solving environmental sustainability and circular economy.

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