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Research Article

Smart Composter for Experiential Learning in Sustainable Agriculture: System Design and Application for a Small-Scale Farm Setting

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ABSTRACT

Composting offers a practical pathway for recycling organic waste, yet maintaining favorable process conditions and translating composting into structured experiential learning remain challenging. This study designed and conducted a preliminary field evaluation of an automated, sensor-enabled composting system intended to process vegetative waste from a small-scale farm while supporting sustainability education. The prototype combined an aerated static-pile configuration with forced aeration, humidity-triggered irrigation, three vertically distributed temperature and relative-humidity sensors, oxygen and fill-level monitoring, a touchscreen interface, transparent viewing panels, multiple access points, and remote data logging. A 29-day trial was conducted in an unheated tunnel greenhouse using approximately 1 m^3 of vegetative waste and wood chips mixed at a reported 1:1 mass ratio. Sensor data were recorded at 10-minute intervals and analyzed descriptively to examine temporal patterns, vertical variation, system performance, and data completeness. Temperatures showed recurrent diurnal fluctuations and clear vertical stratification, reaching maximum values of 54.39°C, 45.83°C, and 35.67°C in the upper, middle, and lower zones, respectively. Lower-zone measurements were incomplete because of a connection failure, while middle-zone relative humidity remained near sensor saturation, limiting interpretation. The observed temperature increases, absence of malodor, and visible material changes were consistent with ongoing aerobic decomposition, although compost maturity and educational outcomes were not directly assessed. These findings demonstrate the feasibility of integrating monitoring, user interaction, visual access, and real-time data communication in a smart composter. Future work should validate sensor placement, quantify actuator performance, assess compost quality, and evaluate learning outcomes aligned with the United Nations Sustainable Development Goals.

KEYWORDS automation • compost • experiential learning • process control • static aeration • sustainable agriculture

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1. INTRODUCTION

Composting represents both a technical approach to organic waste management and a socio-cultural practice that contributes to sustainability within the broader food system. The global generation of municipal solid waste continues to increase, with organic waste constituting a substantial fraction of the total waste stream. When disposed of in landfills, organic materials undergo predominantly anaerobic decomposition and contribute significantly to greenhouse gas emissions, particularly methane [1]. Composting offers a relatively low-cost, decentralized, and circular waste-management strategy that diverts organic materials from landfills and transforms them into valuable soil amendments. The application of compost can improve soil structure, increase water-holding capacity, reduce soil erosion caused by wind and water, and facilitate nutrient cycling within agricultural systems [2]–[5]. Nevertheless, composting, like broader efforts to reduce food waste, should not be regarded solely as a technical process. Its successful implementation also depends on operational practices, environmental awareness, user participation, and institutional capacity.

The decomposition of organic matter ideally occurs under aerobic conditions, in which microorganisms use oxygen and water to metabolize organic substrates [6], [7]. Compared with anaerobic decomposition, aerobic composting generally facilitates more rapid stabilization of organic matter and reduces the production of undesirable environmental by-products, including methane, ammonia, and other malodorous volatile compounds. However, maintaining aerobic conditions throughout the composting matrix remains challenging. The predominance of aerobic or anaerobic decomposition is determined by interactions among several biotic and abiotic factors, including microbial community composition, feedstock type and quantity, particle size, moisture content, oxygen availability, structural porosity, and temperature [8], [9].

In addition to producing stabilized compost, aerobic and anaerobic decomposition processes generate several metabolic by-products, including water vapor, heat, carbon dioxide, methane, and other gases (Figure 1). The decomposition rate and the likelihood of producing a mature, nutrient-rich, and pathogen-free soil amendment are influenced by several interrelated parameters. These include moisture content, the carbon-to-nitrogen ratio of the feedstock, oxygen availability resulting from structural porosity, pH, and temperature [10], [11]. Moisture is essential for microbial metabolism and nutrient transport; however, excessive moisture may occupy pore spaces and restrict oxygen diffusion. Similarly, inadequate porosity may promote the formation of anaerobic zones, while inappropriate temperature and pH conditions may inhibit microbial activity and reduce pathogen inactivation. Effective composting, therefore, requires the systematic monitoring and management of multiple environmental variables throughout the decomposition process.

Figure 1. Basic composting process for a static pile (inputs and products of composting).

Numerous composting configurations have been developed, ranging from open heaps and turned windrows to in-vessel and aerated static pile systems [12]–[14]. Each method presents distinct advantages and operational limitations. Windrow composting is relatively simple to establish and can accommodate large volumes of organic material. However, it generally requires a substantial land area and frequent mechanical or manual turning to redistribute moisture, release excess heat, and maintain adequate aerobic conditions [8].

In-vessel composting systems, including rotating drums, offer greater control over environmental conditions by containing the composting materials within an enclosed structure. Mechanical rotation improves feedstock mixing and promotes greater homogeneity within the decomposing material, thereby reducing the formation of anaerobic zones that may delay decomposition and produce undesirable by-products [15]. Nevertheless, in-vessel systems are generally more complex and costly to construct, operate, and maintain, which may limit their applicability in resource-constrained or small-scale agricultural settings [16].

Aerated static pile systems provide an alternative approach that combines relatively simple construction with improved environmental control. These systems introduce air into the composting material through perforated pipes or similar aeration mechanisms. Compared with conventional windrows, aerated static piles can provide more uniform oxygen distribution, facilitate the removal of excess heat, reduce spatial requirements, and minimize the labor associated with frequent pile turning [13]. However, aerated static pile systems are not inherently self-regulating. Excessive aeration may accelerate moisture loss and cause over-drying, whereas insufficient airflow, feedstock compaction, or uneven material distribution may generate anaerobic zones. Consequently, the performance of an aerated static pile remains highly dependent on the continuous monitoring and adjustment of aeration, moisture, temperature, and material structure. The selection of an appropriate composting system must therefore consider feedstock characteristics and volume, site conditions, labor availability, operational objectives, and economic feasibility.

Recent developments in smart technologies have created new opportunities to improve the efficiency, consistency, and controllability of composting processes, particularly in small-scale and in-vessel applications [17]–[23]. Most smart composting systems employ microcontrollers, such as Arduino-based platforms, integrated with customized relay circuits and environmental sensors. These sensors are commonly used to monitor critical parameters, including temperature, moisture content, pH, relative humidity, and gas concentrations.

Digital control mechanisms can be programmed to maintain environmental parameters within predetermined ranges by activating water pumps, heating devices, mechanical mixers, or aeration fans. Data collected by the sensors may subsequently be transmitted through serial or wireless communication to local displays, digital dashboards, or remote databases for visualization and analysis. Some systems have incorporated machine-learning techniques to identify critical variables affecting decomposition efficiency, process stability, and compost maturity [17], [18], [23]. Other designs have focused primarily on remote monitoring and have included only limited automated control capabilities [19], [20], [22].

Although these prototype systems have demonstrated the potential of smart technologies to improve small-scale composting, most have been designed for enclosed or rotating in-vessel configurations. Their operation commonly relies on mechanical rotation, forced heating, active aeration, or a combination of these mechanisms to promote aerobic decomposition. Compared with other approaches, relatively little attention has been given to the development of smart systems based specifically on the aerated static pile principle. Furthermore, existing designs have generally emphasized technical monitoring and process optimization, while giving less consideration to educational accessibility, direct observation, and learner interaction. This represents an important technological and pedagogical gap, particularly for higher education institutions and educational farms seeking to integrate composting operations into experiential learning.

Composting is widely addressed in sustainable agriculture curricula as a fundamental strategy for managing organic waste, improving degraded soils, recovering nutrients, and reducing reliance on synthetic fertilizers [24]–[26]. Because organic decomposition is dynamic and influenced by continuously changing biological and environmental conditions, students require opportunities to observe the process directly and over time. However, most conventional composting systems are designed primarily for waste processing rather than educational engagement.

In traditional learning activities, students are often required to travel to the location of the composting unit and collect individual measurements using handheld instruments. Although this approach provides practical exposure, it captures only isolated conditions at specific points in time. Consequently, students and educators may be unable to observe temporal relationships among temperature, moisture, oxygen availability, microbial activity, and material decomposition. The use of intermittent measurements also restricts opportunities to identify process disturbances, evaluate system responses, and investigate the effects of environmental management decisions.

Similar limitations affect compost management on small-scale farms. The consistent production of mature and high-quality compost requires regular supervision and timely adjustment of environmental conditions. However, farm operators frequently face time constraints, limited labor availability, competing responsibilities, and inadequate access to continuous monitoring systems [26]. Because effective composting requires ongoing management of moisture, temperature, and oxygen availability, reliance on periodic manual observation may lead to delayed interventions and inconsistent compost quality [27]. Automated monitoring and control systems could therefore reduce routine labor requirements while simultaneously improving operational reliability and process transparency.

These technical, operational, and educational limitations indicate the need for a composting system that combines the relative simplicity of an aerated static pile with automated environmental monitoring, responsive control mechanisms, and interactive learning features. Such a system should not only support aerobic decomposition but also provide users with direct visual access to the composting material and continuous information regarding changes in environmental conditions. The integration of viewing panels, manual controls, sensors, actuators, and real-time data displays may enable the composting unit to function simultaneously as an organic waste-management system and an experiential learning platform.

This study aimed to develop and conduct a preliminary field evaluation of an automated, sensor-enabled composting vessel designed for both operational and educational applications in a small-scale agricultural setting. In contrast to smart composting systems that primarily rely on rotating in-vessel mechanisms, the proposed system applies the aerated static pile principle while integrating continuous environmental monitoring, automated aeration and moisture control, physical viewing features, user-operated controls, and real-time data visualization.

The specific objectives of this study were to: (1) develop a composting vessel capable of supporting the aerobic decomposition of vegetative farm waste in a small-scale agricultural setting; (2) integrate automated monitoring and environmental control mechanisms capable of providing continuous information on critical composting conditions; (3) incorporate interactive features, including viewing panels, user controls, and real-time data displays, to facilitate direct observation and systematic exploration of the decomposition process; (4) generate continuous environmental data to support systems-based investigations of composting dynamics; and (5) pilot-test the system under field conditions to evaluate its operational feasibility and identify priorities for future technical refinement and educational assessment. Through the integration of aerated static pile composting, environmental sensing, automated process control, and interactive data visualization, this study establishes an initial framework for the development of composting systems that are operationally appropriate for small-scale agricultural contexts and pedagogically relevant to sustainability and agricultural education.

2. LITERATURE REVIEW

2.1. Waste Management, Sustainability Education and Societal Impacts

Rittel and Webber [6] classify food and organic waste management as a "wicked problem" because it involves interconnected environmental, social, cultural, and institutional factors that resist simple or linear solutions. Lake et al. [28] further argue that narrowly focused techno-scientific interventions or educational campaigns cannot adequately address complex problems such as food waste. Effective waste management, therefore, requires integrated approaches that combine technological innovation, institutional support, behavioral change, community participation, and sustainability education.

Educational scholarship also situates contemporary environmental challenges within a broader 'meaning crisis,' in which students struggle to understand their roles in rapidly changing ecological and social systems [29]. However, behavioral participation alone may not lead to transformative learning when educators fail to connect practical activities to relevant scientific concepts. In early childhood education, Marchal-Gaillard [30] found that children developed a deeper understanding of organic matter decomposition when educators explicitly connected experiential activities with scientific knowledge. Similarly, research in higher education shows that participation in campus composting programs correlates with stronger environmental attitudes, greater composting knowledge, and a stronger internal environmental locus of control [31]. These findings indicate that composting initiatives can shape learners' knowledge, environmental identity, and sense of responsibility when educators engage them meaningfully in the learning process.

Recent research also shows that students' emotional responses to the climate crisis increasingly influence environmental and climate education. These responses include climate anxiety, grief, fear, and psychological distress. Studies have found that many young people and university students express considerable concern about climate change, while some experience negative effects on their daily functioning and mental well-being [29]. Climate-related emotions may lead to disengagement or eco-paralysis when students feel powerless to address the scale and complexity of environmental problems. However, educators can also channel these emotions into pro-environmental behavior, collective action, and sustained environmental engagement when they provide appropriate support.

Sustainability education, therefore, performs a broader role than simply communicating scientific information. It must also help students process climate-related emotions and develop confidence in their capacity to contribute to environmental solutions. Williams and Grain [29] propose a "praxis of critical hope," through which educators integrate emotional engagement, systems thinking, and practical pathways for action. This approach enables students to acknowledge the seriousness of the climate crisis while maintaining hope, agency, and long-term engagement.

Broader educational scholarship also situates contemporary environmental challenges within a broader "meaning crisis," in which students struggle to understand their roles in rapidly changing ecological and social systems [32]. Complex environmental problems may appear distant or abstract when students cannot connect them with their personal experiences, communities, or local environments. Sustainability education can address this challenge by emphasizing experiential learning, community engagement, and the direct observation of environmental systems.

Interactive and place-based learning activities can strengthen students' sense of belonging, purpose, and connection to their communities and environments. By making ecological processes visible, tangible, and locally relevant, educators can help students transform abstract environmental concerns into situated understanding and meaningful participation. Composting provides one practical example because it allows learners to observe material transformation, nutrient cycling, microbial activity, and waste reduction within a familiar setting.

Collectively, the literature indicates that well-designed sustainability learning environments should integrate scientific knowledge, experiential activities, emotional support, systems thinking, and opportunities for practical action. Interactive, place-based, and systems-oriented approaches can reduce climate-related distress while strengthening students' environmental knowledge, agency, identity, engagement, and persistence [29], [32].

2.2. Composting & Process Control for Aerated Systems

Previous studies have identified the environmental conditions that support aerobic composting (Table 1) and have developed various techniques to optimize the process. Researchers have particularly focused on maintaining sufficient oxygen throughout decomposition because oxygen availability directly influences microbial activity, temperature development, and organic matter stabilization.

Michel et al. [13] conducted an integrative review of aerated static pile (ASP) and comparable aerated composting systems. They found that the recommended aeration rate varies according to the type and dry weight of the primary feedstock. For example, they recommended the highest aeration rate of 0.62 L/min·kg for vegetative and fruit waste and the lowest rate of 0.20 L/min·kg for a mixture of sewage sludge and corn stalks. Their review also identified several aeration strategies, ranging from continuous to intermittent operation. Some systems incorporated temperature-based overrides that adjusted the blower schedule when the compost temperature exceeded or fell below predetermined limits, suggesting a disruption of aerobic decomposition.

Then et al. [7] examined the effects of forced aeration rates and aeration methods on fruit and vegetable waste in a laboratory-scale composting system. The researchers compared intermittent and continuous aeration by measuring temperature, moisture loss, and pH over seven days. Their findings showed that intermittent aeration at rates between 0.20 and 0.30 L/min·kg produced the highest level of aerobic decomposition, as indicated by temperature development and moisture retention. However, this aeration range represents approximately half of the rate that Michel et al. [13] recommended for similar feedstocks. This discrepancy suggests that researchers should also consider aeration system design, system scale, external environmental conditions, sensor type, and sensor placement when determining an appropriate aeration rate. Moreover, Michel et al. [13] primarily reviewed industrial-scale applications, which may require different process-control strategies from those used in household or educational farm settings.

Table 1. Recommended operating ranges for key variables in aerobic composting (Source: Smidt et al. [10]).

Parameter	Reasonable	Preferred
Moisture Content	40 – 65%	50 – 60%
C: N Ratio	20:1 – 60:1	25:1 – 40:1
Oxygen concentration within the interior pore space	>5%	>10%
Temperature	45 – 70°C	50 – 65°C
pH	5.5 – 9.0	6.5 – 8.0

Researchers have increasingly applied smart technologies to improve composting process control, particularly in small-scale, non-industrial in-vessel systems. Bhoir et al. [21] developed a prototype for household organic waste using an Arduino Uno and multiple sensors. The system detected newly added material and regulated conditions within the composting chamber through irrigation, ventilation, and rotation. It also incorporated a dashboard that displayed compost temperature, moisture, pH, and carbon-to-nitrogen ratio throughout a 12-week composting period. The system successfully maintained the favorable composting conditions presented in Table 1 and produced a stabilized final product.

Aquino et al. [17] developed a comparable smart system for processing banana agricultural waste. Their system used internal air temperature and humidity measurements to regulate the composting process. The researchers applied decision-tree machine-learning analysis and a two-sample t-test to identify variables that significantly influenced composting performance. The system produced mature compost at more than twice the rate reported in the benchmark results, demonstrating the potential of data-driven process control to accelerate organic matter stabilization.

Other researchers have incorporated intelligent computational approaches into customized in-vessel composting systems. Illahi et al. [18] applied fuzzy logic, while Prayoga et al. [23] used regression tree modeling to control composting conditions. Both systems showed a greater ability to maintain aerobic conditions than conventional household in-vessel composting systems. Elalami et al. [19], Jo et al. [20], and Anggraini et al. [22] also developed Internet of Things (IoT)-enabled systems that allowed users to monitor composting processes remotely. However, among these studies, only Elalami et al. [19] incorporated smart functions that actively controlled the composting process rather than limiting the technology to environmental monitoring.

Despite recent advances in composting process control, most previous studies have concentrated either on industrial applications or on in-vessel aerated systems that use mechanical stirring, supplementary heating, or both to maintain aerobic conditions. These studies have rarely examined how the external environment influences compost temperature, moisture, and other process dynamics. Existing designs have also prioritized decomposition efficiency and process acceleration rather than the development of composting systems that support experiential sustainability education.

To address these limitations, the present study applied an engineering design-based approach and conducted a preliminary field-performance evaluation of an automated, in-vessel aerated composting system for processing vegetative waste on a small-scale farm. The design incorporates a hybrid operating mode that allows users to control selected processes, continuously records environmental data from multiple locations, and provides sensory and visual access to the composting chamber. These features enable the system to support organic waste processing while also functioning as an experiential and transformative learning tool for systems-based sustainability education.

3. MATERIALS AND METHODS

3.1. Study Site

The study was conducted at the Sustainable Agriculture Project (SAP), a 4-acre university-supported farm at Grand Valley State University in Allendale, Michigan, USA. Established in 2008, the SAP promotes ecologically sustainable, socially responsible, and economically viable agriculture through experiential learning and community engagement [33]. The site experiences warm, humid summers and cold, snowy winters. Its composting activities previously relied on low-input static piles with limited control of aeration, moisture, and carbon-to-nitrogen ratio, resulting in slow decomposition and low compost production. These conditions made the SAP suitable for evaluating an improved composting system. The prototype was installed in a 3.7 m × 6.0 m unheated tunnel greenhouse with manually operated sidewalls to assess system performance and the contribution of solar radiation to heat generation under variable climatic conditions.

3.2. Design of Physical System

Table 2 summarizes the specifications of the Smart Composter prototype, including the chamber geometry and effective volume, structural and food-safe materials, aeration and irrigation subsystems, sensor types and locations, and the primary control, data-logging, and communication components. Figures 2 and 3 present labelled views of the overall system and the placement of the aeration columns and sensors.

The research team designed the composting unit by adapting the principles of in-vessel single-bin and aerated static pile systems while maintaining its educational function [9], [10], [34]. The final design employed a static aerated configuration rather than a rotating or frequently turned system. This configuration preserved the spatial structure of the decomposing material while allowing the blowers to provide forced aeration. It also enabled users to observe time-dependent changes, including material layering, moisture and condensation patterns, visible biological activity, and vertical stratification through the transparent viewing panels.

The composter included one hinged loading door at the top and four hinged unloading doors on opposite sides of the lower section. The enclosed, untreated pinewood structure prevented rodent access, while adjustable dampers on the upper panel maintained ventilation within the chamber.

The aeration subsystem consisted of two 6.5-horsepower blowers, each capable of producing 180 cubic feet per minute (CFM) of airflow. The research team mounted the blowers at the bottom of the unit and connected them to vertical stainless-steel tubes, as shown in Figure 3. The tubes contained openings beneath conical flanges that distributed air into the composting material. This arrangement provided the required forced airflow for aerated static pile systems.

The monitoring subsystem used AHT20 I2C sensors to measure temperature and relative humidity at three vertical positions. The research team installed the sensors along the stainless-steel tubes at heights of 10, 40, and 70 cm above the bottom plate. Custom-designed three-dimensional printed polyethylene terephthalate glycol-modified (PETG) holders enclosed and secured each sensor. The researchers selected these sensors because they could withstand the warm and humid aerobic conditions expected during composting. They selected PETG because manufacturers classify it as food-safe and because it offers greater resistance to degradation in humid environments than commonly used filaments such as polylactic acid (PLA).

An externally filled high-density polyethylene (HDPE) barrel supplied water to the irrigation subsystem. A pump transferred water from the barrel through a polyvinyl chloride (PVC) tube, and drilled openings at the top of the unit distributed the water across the composting material. To maintain food-safe internal surfaces, the research team lined the chamber walls with HDPE and constructed the bottom plate from stainless steel.

The system also incorporated a SEN0208 weatherproof ultrasonic sensor and an I2C electrochemical oxygen sensor. The ultrasonic sensor monitored the compost fill level, while the oxygen sensor measured the oxygen concentration within the chamber. These sensors allowed the control system to monitor both the quantity of material and the internal conditions required for aerobic decomposition.

The research team attached transparent polycarbonate panels to three of the four exterior walls to provide visual access to the decomposition process. These panels allowed users to observe physical and biological changes without opening the composting chamber. To improve environmental resistance while supporting sustainable construction, the team sealed all wooden components with a mixture of 100% tung oil and pine oil containing zinc. They then coated the surfaces with food-safe milk paint.

Table 2. Mechanical, hydraulic, sensing, control, and connectivity specifications of the Smart Composter prototype.

Subsystem/component	Model/material	Key specifications	Operation/notes
Composting enclosure	Framed wood enclosure; food-safe interior surfaces	Exterior dimensions: 1.37 × 1.47 × 1.02 m; Interior dimensions: 0.91 × 1.18 × 1.32 m; usable volume: 1.41 m^3	Manual loading/unloading; placed in a tunnel greenhouse.

Subsystem/component	Model/material	Key specifications	Operation/notes
Access & visibility	Loading door + unloading doors; PC viewing panels + treated plywood	Full-width loading door; unloading doors on both sides; three large viewing windows.	Enables safe loading/removal and public-facing observation.
Food-safe interior & base	HDPE lining + stainless-steel floor	HDPE barrier covers exposed plywood; stainless floor for durability/ cleanability.	Supports food-safe design intent; improved cleanability.
Ventilation & drainage	Roof dampers; floor drain holes	Roof: 4 × 9.5 cm holes for adjustable dampers; floor: 8 × 0.64 cm drain holes + perimeter drainage slits	Dampers are manually adjustable and prevent water accumulation.
Forced aeration subsystem	2x stainless aeration columns w/ diffusion cones + mounted blowers	Two equally spaced assemblies; cones promote radial distribution; blowers: 6.5 HP, 180 CFM each (shop-vac style).	Blowers on/off via controller/ relay; manual flow adjuster reduces upper-hole flow if needed.
Irrigation subsystem	208 L HDPE drum; 1.9 cm Schedule 40 PVC manifold; T33 diaphragm pump (115 Vac)	Reservoir adjacent to unit; roof-mounted drilled outlets; insulated lines for freeze protection.	Pump switched by controller (relay); triggered by humidity threshold and/or manual mode.
Environmental sensing (internal)	3x AHT20 I2C temperature/RH sensors + PETG mounts	Sensors positioned at 10, 40, and 70 cm; PETG clamshell mounts with vents; -40°C - 80°C (± 0.3°C; 0.01°C resolution); 0 – 100% RH (± 2%RH; 0.024% RH resolution).	Sensors read by the controller; values displayed/logged; supports stratification interpretation and control inputs.
Additional sensing	I2C electrochemical O_2 sensor; SEN0208 ultrasonic fill sensor	O_2: offboard air-tap approach; fill level: internal mounting.	Logged/displayed; not used in control loop (research/education indicator).
Controller + UI	Arduino GIGA R1 Wi-Fi + touchscreen LCD + pushbuttons.	Live sensor readings + warnings + actuator status; password-protected settings.	Controls pump/blowers via relay driver; user-configurable thresholds/intervals; manual override.
Data logging + connectivity (deployment)	Arduino → Raspberry Pi Zero 2 W (serial) → Wi-Fi → server.	Sends sensor readings + event timestamps; public read-only web visualization.	Wi-Fi via campus network or hotspot; supports remote monitoring & public display.
Site requirements	120 Vac supply + Wi-Fi	120 Vac (±5 Vac) with 20-A NEMA 5-20R; Wi-Fi 2.4 GHz (~15 m).	Supports continuous operation within the tunnel greenhouse.

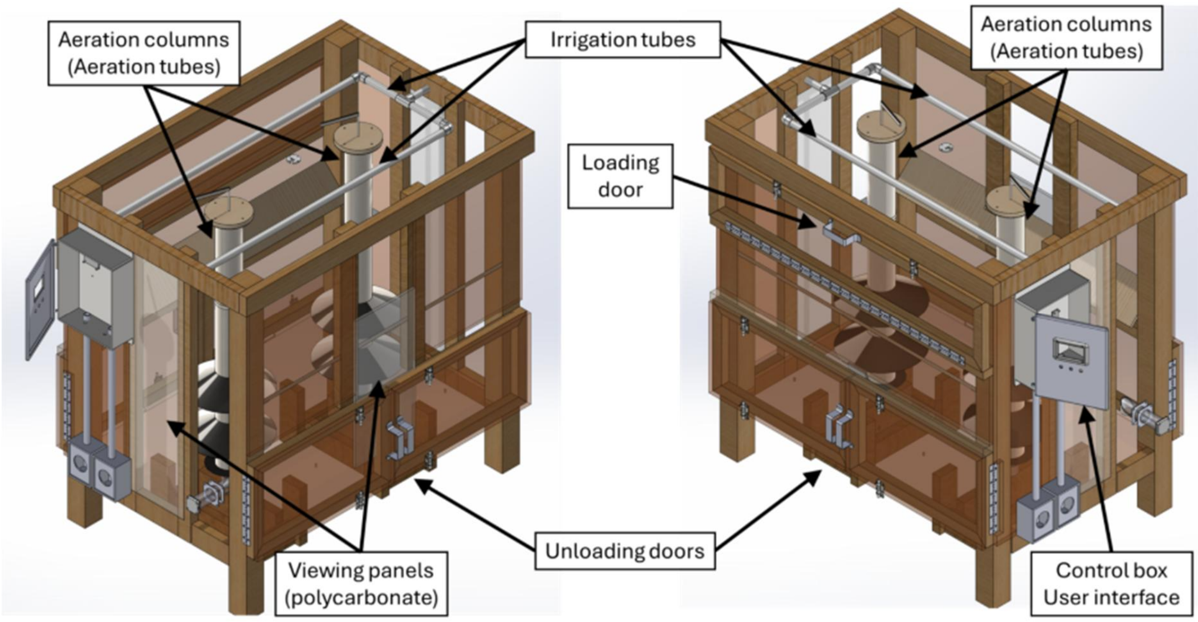

Figure 2. The design of the smart composter physical system shows the main user-access features (loading and unloading doors), aeration columns/tubes, irrigation tubes, the control box/user interface, and polycarbonate (PC) viewing panels.

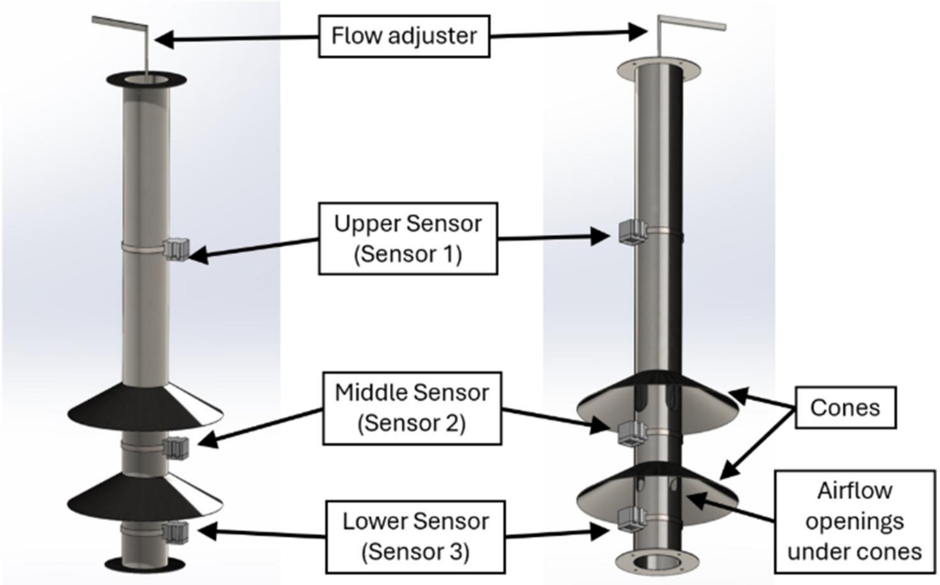

Figure 3. Design of an aeration column used for forced aeration within the composter. (Left) Assembly view highlighting flow adjustment and sensor mounting; (Right) Rotated view of the conical diffuser showing outlet slots that promote radial air distribution.

3.3. Design of the Control System and Interactive Display

The research team designed the Smart Composter's control system to regulate two primary operational variables: aeration and irrigation. Table 3 presents the control logic and operating parameters, including the Auto and Manual modes, user-adjustable temperature and relative humidity thresholds, baseline aeration cycles, humidity-triggered irrigation, and a high-temperature override with a predefined cooldown sequence. Figure 4 illustrates the configuration and operational flow of the control system.

Users configured the system through a password-protected touchscreen menu. The interface allowed authorized users to adjust the duration and frequency of aeration, thereby supporting experimental trials under different operating conditions. Users could also modify the temperature and relative humidity thresholds that controlled the automated aeration and irrigation processes.

When users selected Manual mode, the controller suspended all automatic sensor-based operations. Users then activated the blowers and irrigation pump directly through the touchscreen buttons, regardless of the sensor readings. This mode allowed educators to demonstrate the aeration and irrigation functions to learners and enabled users to test each subsystem independently.

When users returned the system to Auto mode, the controller disabled manual commands and resumed the sensor- and timer-based control rules listed in Table 3. The controller activated the blowers according to the programmed aeration schedule and started the irrigation pump when the relative humidity fell below the user-defined threshold. When the measured temperature exceeded the specified limit, the controller initiated the high-temperature override and applied the predefined cooldown sequence before returning to normal operation.

Table 3. Automated and manual control logic and parameter settings implemented during the 29-day field trial.

Control element	Auto mode (sensor/timer-based)	Manual mode (user override)	Trial settings/notes
Mode selection/ priority	Runs only when Auto is selected	Users directly actuate the pumps/blowers.	Manual overrides Auto while selected
Sensor inputs used	Temperature and RH from upper/middle/lower sensors used for decisions (per Table 3 rules)	Sensor values displayed; do not restrict user actions	Control logic references the three sensors (display + logging)
Irrigation rule	If RH < RH_set, pump ON for a fixed duration	Pump ON/OFF via Pump/Water button	RH_set = 45%; pump ON = 30 s
Aeration baseline cycle	Blowers run periodically on a timer	Each blower is ON/OFF via buttons	Aeration ON = 10 s every 60 min
High-temperature (T) override + cooldown	If T > T_set, blowers activate; then apply cooldown before the next cycle	Not applicable (user controls blower)	Cooldown = 1/3 of interval

Control element	Auto mode (sensor/timer-based)	Manual mode (user override)	Trial settings/notes
User settings/ configuration	Thresholds and runtimes can be adjusted via a password-protected settings menu.	Same settings menu; manual actions still possible.	Adjustable: RH_set, T_set, aeration interval/ON-time, pump ON-time, security PIN.

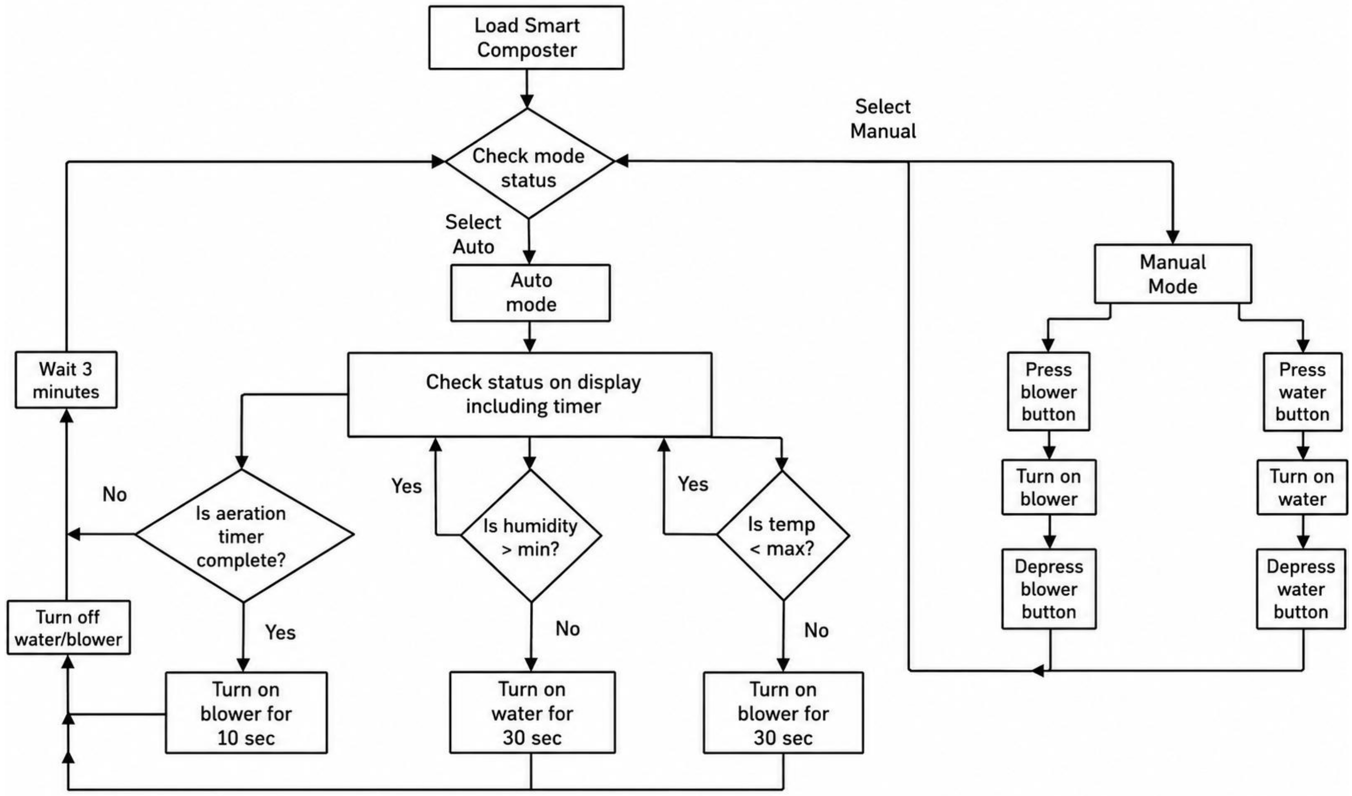

Figure 4. Process flow chart for the Smart Composter with example pre-set rules for reference.

Figure 5 presents an overview of the interactive control system. The research team connected the Arduino Giga liquid-crystal display (LCD) touchscreen to an Arduino Giga microcontroller. It equipped the system with push buttons that control the two blowers and the irrigation pump. The LCD displayed real-time temperature and relative humidity data from three environmental sensors located in the upper zone (Sensor 1), middle zone (Sensor 2), and lower zone (Sensor 3). It also presents system warnings and the operational status of the water pump and blower fans. In Manual mode, users can activate the aeration and irrigation systems directly through the corresponding push buttons. The touchscreen interface allows users to navigate between screens, adjust the temperature and relative humidity thresholds for each composting zone, change the security personal identification number (PIN), and configure the operating durations of the blowers and irrigation pump. Section 3.5 describes the data collection and storage procedures in greater detail.

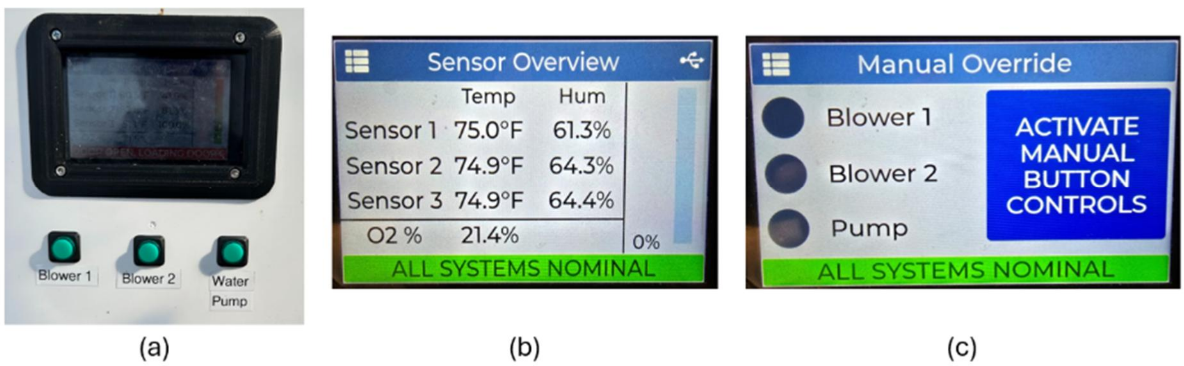

Figure 5. Control system representing the (a) LCD/push buttons, (b) sensor overview and (c) interactive screen to activate manual mode. (Note: Fahrenheit (°F) was used based on preference from the SAP)

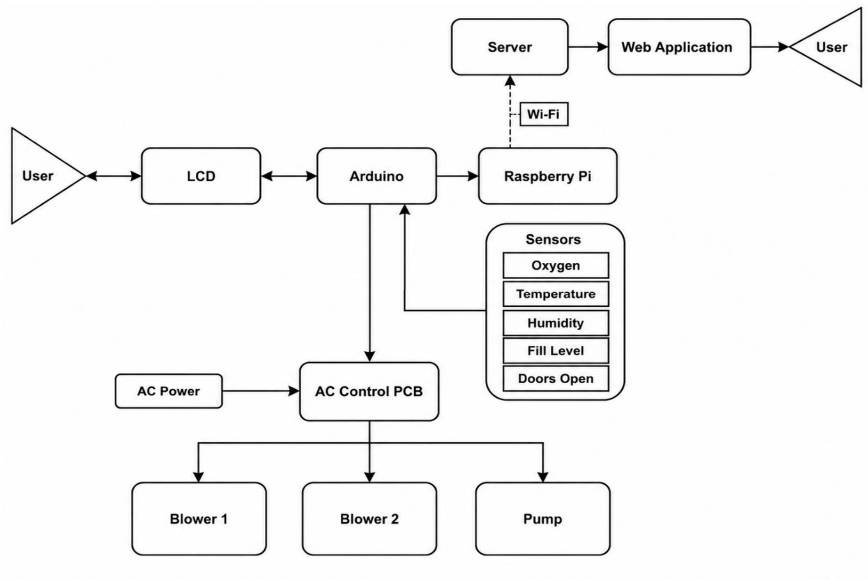

Figure 6. Smart Composter Block Diagram

3.4. Sensor Selection and Placement

The research team documented sensor placement and conducted basic validity checks against manufacturer specifications before initiating the trial to support reproducibility and the accurate interpretation of sensor data. The system used AHT20 I2C sensors to measure temperature and relative humidity at three vertical positions within the composting chamber: the upper, middle, and lower zones. The team mounted these sensors along the aeration columns (Figures 2 and 3) to capture vertical gradients in temperature and relative humidity throughout the composting material.

The team selected the sensors based on their operating ranges and accuracy specifications (Table 2). During the initial laboratory setup, the researchers verified sensor communication, display output, and data logging from all three monitoring locations. They fabricated the mounting brackets from 3D-printed polyethylene terephthalate glycol-modified (PETG) because this material offers food-safe properties and humidity resistance. The team also incorporated printed slots into the sensor covers to expose the sensors to airflow while protecting the electronic components from direct contact with the composting material. The control system evaluated readings from all three sensor locations and activated the blowers or irrigation pump whenever a sensor value crossed the corresponding user-defined threshold.

3.5. Data Collection Procedure and Data Pipeline

The research team configured the system to record sensor data at 10-minute intervals throughout the trial. The Arduino microcontroller collected readings from the internal sensors and transmitted timestamped records to the Raspberry Pi through serial communication. The Raspberry Pi then transferred the data via Wi-Fi to a server for storage and visualization, as illustrated in Figure 6.

The system initially stored the data locally on the Raspberry Pi in a tabular format and subsequently uploaded the records to a MongoDB document-oriented database for long-term storage and analysis. The research team performed basic data quality control by verifying the plausibility of recorded values and identifying missing or potentially unreliable sensor channels. The researchers retained unavailable observations as missing values rather than replacing or estimating them and calculated the percentage of missing data for each monitoring channel.

4. RESULTS

4.1. System Operation

A team of senior-level engineering students constructed the Smart Composter in a university laboratory and subsequently relocated it to the Sustainable Agriculture Project (SAP). The team installed the unit inside a tunnel greenhouse and rolled up the greenhouse sides to a height of approximately 0.75 m to maintain ventilation during operation. Figure 7 presents the main features of the completed system, while Figure 8 illustrates the initial loading process. The research team conducted a 29-day trial from mid-September to mid-October to evaluate the system's overall functionality under conditions simulating routine operations at the SAP.

The team mixed farm-generated vegetative waste, consisting of spent greens and overripe vegetables measuring 5 to 30 cm, with locally produced wood chips measuring 2 to 15 cm. The researchers combined both materials in 19 L buckets at a 1:1 weight ratio, resulting in an estimated carbon-to-nitrogen ratio of approximately

30:1 and an initial moisture content of approximately 50%. They continued loading the materials until the chamber reached approximately two-thirds of its total capacity, equivalent to about 1 m³. Before starting the trial, the team tested the irrigation and aeration systems in both Auto and Manual modes and confirmed that both operated properly. The researchers then programmed the aeration system to run for 10 seconds every 60 minutes.

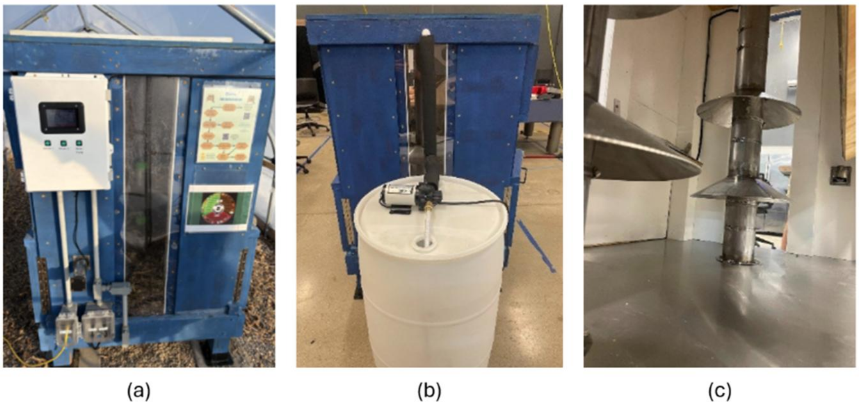

Figure 7. The fully assembled Smart Composter with (a) controller and viewing window, (b) external water delivery system, and (c) aeration assembly

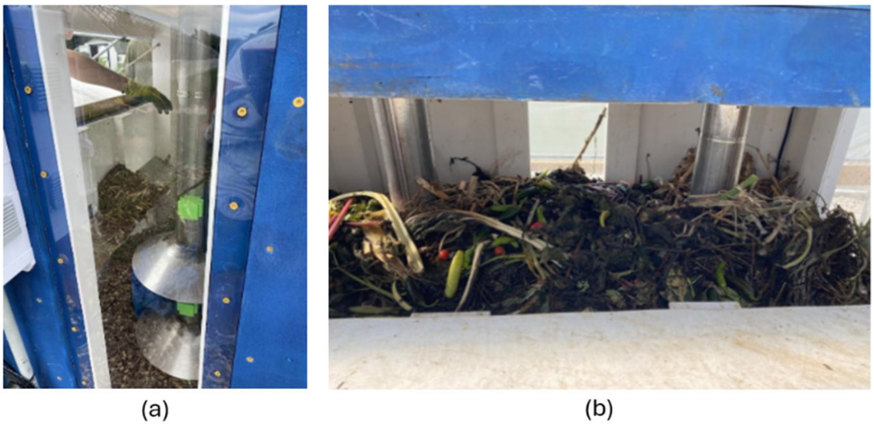

Figure 8. The Smart Composter in operation with (a) loading and (b) freshly loaded material

4.2. Datalogging and Smart Responses

The Smart Composter recorded data at 10-minute intervals throughout the 29-day operating period (Figure 9). Temperature sensors in the upper, middle, and lower zones showed a consistent diurnal pattern, with temperatures rising during the day and declining overnight. The upper and middle zones generally experienced greater daytime increases than the lower zone, while the upper sensor recorded the maximum temperature of 54.39°C. Figure 10 presents Days 11–15 to illustrate the recurring daily cycle and vertical temperature gradients. A faulty connection interrupted lower-zone temperature and humidity measurements during Days 24–28, resulting in missing data for that period.

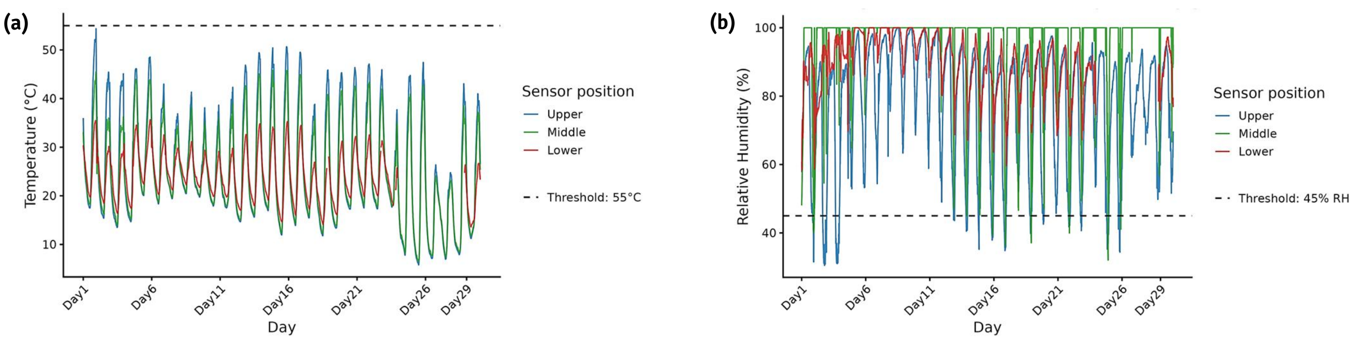

Figure 9. (a) Temperature (°C) and (b) relative humidity (%) measured at upper, middle, and lower sensor locations during the 29-day operating period of the smart composter.

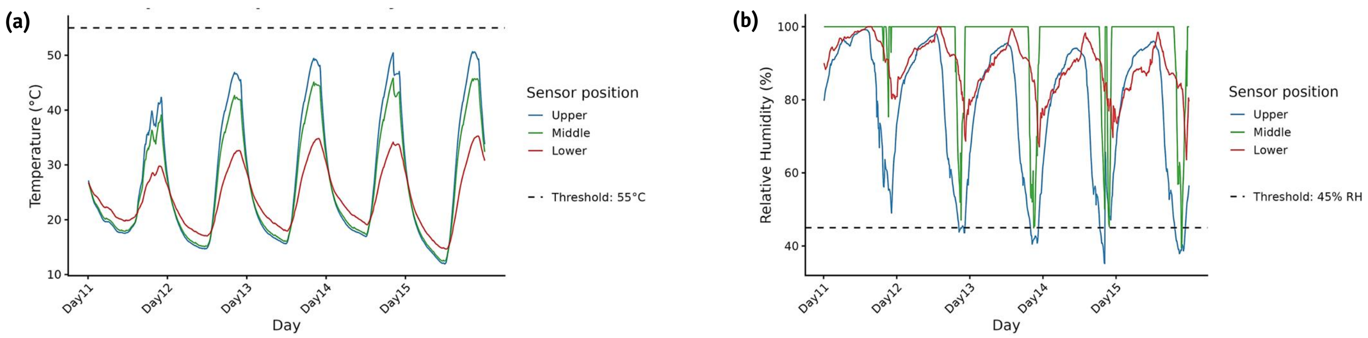

Figure 10. Representative 5-day window (Days 11–15) showing diurnal (a) temperature (°C) and (b) relative humidity (%) trends at upper, middle, and lower sensor locations in the smart composter.

Table 4. Descriptive statistics and data completeness for temperature (°C) and relative humidity (%) recorded at three vertical sensor locations during the 29-day field trial.

Variable	Sensor	N total	N valid	N Missing	N Missing (%)	Mean	Median	Std Dev.	Min.	Max.
Temperature (°C)	Upper	4121	4121	0	0	25.44	22.39	10.98	5.78	54.39
Temperature (°C)	Middle	4121	4121	0	0	24.29	22.28	9.21	6.44	45.83
Temperature (°C)	Lower	4121	3385	736	17.86	24.08	23.72	4.89	13.61	35.67
Relative Humidity (%)	Upper	4121	4121	0	0	77.80	84.28	17.56	30.47	100
Relative Humidity (%)	Middle	4121	4121	0	0	96.26	100	11.20	32.03	100
Relative Humidity (%)	Lower	4121	3385	736	17.86	89.79	91.19	8.08	58.23	100

Relative humidity showed an inverse relationship with temperature, declining during the daytime and recovering overnight (Figures 9 and 10). Relative humidity ranged from 30.47% to 100% in the upper zone and from 32.03% to 100% in the middle zone. However, the middle-zone humidity channel remained close to 100 percent for most of the monitoring period. In the lower zone, relative humidity ranged from 58.23% to 100%. Oxygen concentrations remained close to ambient levels at approximately 20–21%, while the fill-level sensor produced relatively stable readings of 91–95%. Channel-specific summary statistics and missing-data percentages are presented in Table 4. Regarding sensor-based control of the irrigation and aeration systems, relative humidity decreased below the 45% activation threshold on 14 days, indicating that the programmed irrigation rule would have triggered pump operation on those days.

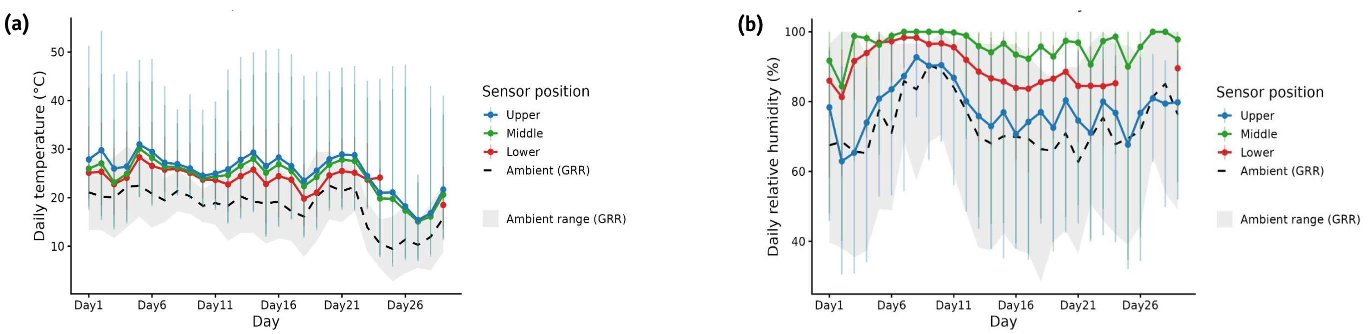

Figure 11. Daily average, minimum, and maximum values showing for (a) temperature (°C), and (b) relative humidity (%) in the three recording zones (upper, middle and lower) as well as the published local weather values (shown as ambient).

4.3. Sensor Value Comparison to Published Daily Local Values

To assess the potential effect of the external environment on the conditions within the composter, the daily average, high and low values for each of the three sensor zones were plotted against the closest local ambient values (Grand Rapids (GRR)) published by the Iowa Environmental Mesonet Database [35]. Figure 11 shows that the temperature cycling for the three zones was comparable to ambient values; however, all zones maintained higher averages with maximum values as much as 20°C above the average. In addition, the minimum temperatures were consistently higher than the ambient temperature. In terms of relative humidity, the ambient values most closely reflected the daily averages for the upper zone and included a broad range that nearly reflected the minimum/maximum values for the three zones.

4.4. Compost Observations

The decomposing vegetative waste/wood chip mixture was observed through the viewing panels daily over the 29-day trial period. Although decomposition appeared minimal during the first few days, unexpected observations began to emerge. Through the viewing panels, a variety of insects and spiders could be seen crawling along the inside walls of the composter and within the decomposing matter. In addition, condensation appeared on the inner walls periodically throughout the day, especially during sunrise and sunset. In the final days of the trial period, the loading doors were opened and samples were taken. Although not deliberately added, numerous earthworms, nematodes, and pill bugs emerged.

Figure 12. Representative composting material collected after 29 days.

A sample of the final product (Figure 12) was brownish in color, damp, and somewhat friable, although there remained some fragments of wood chips. Throughout the 29 days, no foul odor indicative of anaerobic decomposition was detected. These observations indicate that decomposition occurred within the compost chamber; however, further quantitative analysis would be necessary to verify compost maturity and quality.

5. DISCUSSION

5.1. Formative Evaluation of the Smart Composter

This study developed a programmable and automated aerated static pile (ASP)-type composter to support the aerobic decomposition of vegetative waste at a university farm and provide an experiential learning tool for sustainable waste management. Effective aerobic composting typically increases the temperature of the composting material to approximately 45–70°C. During the formative evaluation, the continuous monitoring system recorded temperatures within this range on several occasions in the upper and middle zones. However, the system did not sustain these temperatures throughout the trial. The lower zone reached a maximum temperature of only 36°C.

The placement of the sensors along the stainless-steel tubes may have prevented them from accurately capturing the internal temperature of the decomposing material. Nevertheless, qualitative observations indicated that some aerobic decomposition occurred. The compost did not produce foul odors, and the final product showed visible signs of decomposition. Figures 9 and 10 also show vertical temperature stratification across the three monitoring zones. Positively aerated ASP systems commonly exhibit this pattern, particularly when ambient air is cooler than the composting mass [13]. Previous studies also identified convection and air diffusivity as important mechanisms that influence the spatial distribution of temperature within composting materials [36]–[38]. Future trials should therefore consider sensor depth, orientation, and location when evaluating the thermal performance of the system.

The feedstock particle size may also have limited the development of sustained thermophilic conditions. The researchers selected the loading method to reflect the practical conditions that farm workers, educators, and students are likely to encounter. However, the feedstock included particles ranging from approximately 2 to 30 cm. Larger particles may have reduced the surface area available for microbial activity and restricted the rate of decomposition. Peng et al. [39] demonstrated that reducing feedstock particles to less than 5 cm can improve aerobic decomposition. Future studies should therefore reduce the particle size and conduct a more detailed quantitative analysis of the feedstock. Such an analysis should include particle-size distribution, moisture content, carbon-to-nitrogen ratio, and material composition to support process optimization.

The selected aeration rate may have further influenced the composting process. During the trial, the control system activated the aeration mechanism for 10 seconds every hour. Previous studies showed that oxygen concentrations in ASP systems begin to decline immediately between aeration cycles, particularly during the initial and most biologically active stage of decomposition [13]. The aeration schedule may therefore have supplied insufficient oxygen to support continuous microbial activity and sustained thermophilic conditions. Future trials should evaluate different aeration durations and frequencies and regulate airflow based on real-time measurements of temperature, moisture, oxygen concentration, and other relevant process variables.

External environmental conditions also influenced the thermal behavior of the composting chamber. As shown in Figure 11, the average daily temperatures recorded by the compost sensors generally tracked changes in ambient temperature. However, the average and maximum compost temperatures remained approximately 10–20°C higher than the corresponding ambient values. This difference suggests that microbial activity generated heat within the composting mass. At the same time, solar radiation entering through the tunnel greenhouse and daily fluctuations in environmental temperature likely contributed to the chamber's temperature variations. The interaction between biological heat generation and external heat transfer, therefore, shaped the thermal performance of the system.

The prototype used automation and environmental monitoring to support a systems-oriented investigation of composting dynamics. Continuous temperature and relative humidity measurements revealed clear differences among the upper, middle, and lower zones of the composting mass. The monitoring system also identified an inverse relationship between temperature and relative humidity. The Clausius–Clapeyron relationship explains this pattern because warmer air can hold more water vapor, resulting in lower relative humidity while the absolute moisture content remains relatively stable.

Relative humidity became an operationally important variable when its value fell below the user-defined threshold of 45%. Each time the sensor detected a value below this threshold, the control system activated the irrigation cycle. Excessive drying commonly limits microbial activity and decomposition efficiency in ASP systems [13]. Each irrigation cycle supplied approximately one liter of water, which may have helped restore moisture within the composting material. Aguino et al. [17] also demonstrated the importance of moisture during composting. Their machine-learning analysis of banana agricultural waste identified soil moisture as a critical process variable, possibly related to relative humidity within the chamber.

The patterns recorded throughout the trial demonstrate that composting functions as a responsive and time-dependent process. Biological activity, feedstock characteristics, operational settings, and external environmental conditions jointly influenced the performance of the system. Through automation and continuous monitoring, the Smart Composter can provide farmers, educators, and students with a more comprehensive understanding of the spatial and temporal dynamics of composting.

Several technical limitations affected the stability and reliability of the monitoring system. Sensor placement may have reduced the accuracy of the measurements, while condensation or sensor saturation may have affected the middle-zone relative humidity sensor. Connectivity problems also caused periods of missing data from the lower-zone sensor. In future trials, researchers should rotate the three zonal sensors toward the interior of the aeration tubes to better reflect internal composting conditions. Researchers should also redesign the polyethylene terephthalate glycol-modified (PETG) sensor enclosures to reduce condensation accumulation, which may have contributed to the malfunction of the middle-zone humidity sensor.

Future studies should extend the duration of the composting trial and periodically collect compost samples for physicochemical and biological analyses. Researchers should also improve the data-logging interface to record and display the exact times when the control system activates irrigation or aeration in response to user-defined thresholds. The system should incorporate additional sensors to measure gases produced during decomposition, including carbon dioxide, methane, and ammonia. Researchers should also monitor temperature and humidity within the tunnel greenhouse to distinguish microbial heat generation from external environmental effects. These modifications could strengthen the monitoring and control functions of the Smart Composter and provide additional opportunities for research, teaching, and experiential learning.

5.2. Educational Design Affordances

Beyond its technical functions, the Smart Composter can support sustainability education by providing a tangible and systems-based learning environment. Its transparent panels and access doors allow users to directly observe the relationship among inputs, processes, and outputs. Users can observe organic waste, water, and oxygen as inputs; microbial decomposition and heat generation as processes; and stabilized compost as the principal output. These observations can help learners understand essential ecological concepts, including nutrient cycling, energy flow, decomposition, and material transformation.

Although the researchers did not activate the manual operating mode during the 29-day trial, this feature allows users to control irrigation and aeration within the composting chamber. Learners can modify operational conditions and observe how these changes affect temperature, moisture, and decomposition. Such interaction can strengthen experiential learning, as direct engagement with natural processes can enhance understanding and participation in educational settings [40].

The Smart Composter also incorporates features that align with the Next Generation Science Standards (NGSS) and the United Nations Sustainable Development Goals (SDGs). These features support systems thinking, crosscutting concepts, scientific inquiry, and science and engineering practices [41]–[43]. Educators can therefore integrate the system into K–12 curricula in environmental science, life science, agricultural science, and sustainability education. Research has shown that learners often connect new observations with their previous knowledge and experiences. Hands-on composting activities may consequently help learners recall and understand sustainability concepts more effectively than classroom instruction alone [44].

The system can also facilitate collaborative learning. Participants can compare observations, discuss changes in composting conditions, reflect on their own waste-management practices, and collectively interpret real-time environmental data. Through these activities, learners can strengthen the social dimensions of sustainability education by engaging in shared observation, discussion, reflection, and problem-solving.

At the post-secondary level, the Smart Composter provides an interdisciplinary learning platform that connects engineering design, environmental science, agriculture, data analysis, and sustainability. The project demonstrates how project-based learning can address complex environmental challenges while developing technical competencies, critical thinking, and systems-thinking skills. As both an engineering capstone project and an educational exhibit, the Smart Composter allows learners to examine the relationships among feedstock composition, particle size, moisture balance, temperature, aeration, environmental conditions, and system scale.

The trial also highlighted the role of external environmental conditions in controlling heat and mass transfer within the composting system. Many composting studies focus primarily on biological and operational variables, but the present study demonstrates that the surrounding environment can also influence system performance. The Smart Composter, therefore, enables learners and researchers to investigate not only microbial decomposition but also the engineering and environmental mechanisms that regulate composting dynamics.

The real-time monitoring and data-logging functions make the system particularly suitable for technical research and data-driven learning. Learners can analyze temporal trends, identify relationships among environmental variables, evaluate the effects of operational decisions, and formulate evidence-based recommendations for improving composting performance. At the same time, the system provides a dynamic, interactive, and contextually relevant example of sustainable waste management. By showing how users can transform organic waste into a useful soil amendment, the Smart Composter can support climate-change education and help reduce climate anxiety through practical and solution-oriented sustainability activities [29], [45].

6. CONCLUSION

This study demonstrates the potential of a smart composting system to serve both as a technical solution for organic waste management and as a public-facing educational tool in a small-scale agricultural setting. The system successfully integrated sensor-based monitoring, automated process controls, and user interaction features to support composting operations with reduced labor requirements while making the decomposition process more visible and accessible. Data collected during the 29-day trial showed consistent diurnal temperature patterns, vertical stratification within the composting mass, and stable oxygen levels, confirming the feasibility of real-time monitoring for operational management and educational interpretation. From an implementation perspective, the findings highlight the importance of designing sustainability infrastructure that is not only functional but also pedagogically intentional. The Smart Composter, therefore, offers a practical model for institutions seeking to combine experiential learning with campus sustainability initiatives.

Future research should extend the monitoring period, improve sensor reliability, expand data logging and visualization capabilities, and incorporate additional sensors to measure gaseous by-products and environmental conditions specific to the tunnel greenhouse. Quantitative analysis of the final compost product is also needed to evaluate its quality and maturity. In addition, the educational impact of the system should be assessed through clearly defined learning outcomes and formal evaluation instruments aligned with the Next Generation Science Standards and the United Nations Sustainable Development Goals. Overall, the Smart Composter functions as a bridge between sustainable practice and sustainability education by transforming organic waste from an overlooked by-product into a visible and interactive system that promotes learning, engagement, and broader participation in circular food systems.

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CONFLICTS OF INTEREST

The authors declare that no conflicts of interest are associated with this study. All aspects of the research were conducted with the utmost integrity and transparency.

DATA AVAILABILITY

The datasets utilized and analyzed during this research are available from the corresponding author upon reasonable request.

ETHICAL STATEMENTS

Not applicable. This study did not involve any human participants or animals, and no personal or sensitive data were collected, used, or analyzed at any stage of the research.

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