A Dual-Function IoT and Machine-Learning Enabled Smart Composting System for Accelerated Compost Production and Quality Assessment

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Abstract: Declining soil fertility, rising fertilizer costs, and environmental degradation pose serious challenges to sustainable agriculture. Composting offers a low-cost and environmentally friendly alternative, but its adoption is limited due to long processing times, inconsistent quality, and lack of affordable monitoring tools. This report presents a dual-function smart composting system that both accelerates compost production and evaluates compost quality in real time. The system integrates low-cost IoT sensors (temperature, moisture, ammonia, and NPK), automated actuators, and a machine-learning-enabled dashboard. Experimental validation across five compost formulations over a 15-day monitoring period demonstrated sensor accuracy within ±10% of literature values. Results indicate a 20-25% reduction in composting time and a 40-50% reduction in production cost while maintaining compost quality. The system provides a composite Compost Quality Score (CQS) to enable objective, data-driven decisions. This work demonstrates the potential of IoT and machine learning to improve compost reliability, promote sustainable agriculture, and support circular waste management.

1. Introduction and Background Research

1.1 Soil Degradation and Agricultural Challenges

Agriculture remains the backbone of India's economy, employing over half of the population directly or indirectly. However, widespread soil degradation has emerged as a critical threat to long-term agricultural productivity. A key indicator of soil health, Soil Organic Carbon (SOC), is typically below 0.5% in Indian agricultural soils, compared to the recommended minimum of 1% for sustainable farming. Low SOC reduces water retention, weakens soil structure, and increases erosion, resulting in declining crop yields. To compensate, farmers increasingly rely on chemical fertilizers, which raises production costs and contributes to long-term environmental degradation. National surveys indicate that over 50% of Indian farmers are indebted, with fertilizer and pesticide costs being a major contributing factor.

1.2 Composting as a Sustainable Alternative

Organic composting is widely recognized as an effective method for restoring soil health, improving nutrient availability, and reducing dependence on chemical inputs. Compost enhances soil structure, increases microbial activity, and contributes to long-term SOC restoration. Studies indicate that compost application can reduce fertilizer expenses by approximately ₹4,000 per hectare and decrease pesticide use by up to 40% over multiple growing seasons. Despite these benefits, composting adoption remains low due to extended processing durations (typically 60–90 days), variability in nutrient content, odor generation, and lack of standardized quality assessment.

1.3 Technological Gaps in Compost Monitoring

Most traditional composting methods rely on manual observation and experience-based judgments, making quality assessment subjective and unreliable. Commercial compost monitoring solutions are often expensive and limited to single-parameter measurements, such as temperature alone. Recent advances in Internet of Things (IoT) technology, low-cost sensors, and embedded systems present an opportunity to overcome these challenges. By continuously monitoring key composting parameters-temperature, moisture, ammonia emissions, and nutrient content-IoT systems can provide objective, real-time insights into compost maturity and quality. When combined with machine learning, such systems can further generate actionable recommendations to improve compost outcomes.

2. Research Question and Objectives

2.1 Research Question

Can a low-cost, IoT-based smart composting system integrated with automated environmental control and machine-learning analysis reduce composting time while maintaining compost quality comparable to standard literature values?

2.2 Objectives

The objectives of this research are:

1. To validate the accuracy of low-cost temperature, moisture, ammonia, and NPK sensors for compost monitoring against established literature standards.
2. To design and develop a dual-function composting system capable of both monitoring compost quality and accelerating the composting process.
3. To quantify reductions in composting time and production cost achieved through automated control of composting parameters.
4. To develop a machine-learning enabled dashboard that evaluates compost quality and provides actionable improvement suggestions.
5. To assess the applicability of the system for household composting and farmer use.

3. Research Hypotheses

The study is guided by the following hypotheses:

- **H1:** Sensor readings for temperature, moisture, ammonia, and NPK will align with standard compost literature values within a ±10% deviation.
- **H2:** Automated environmental control will reduce composting time by approximately 20–25% compared to traditional composting methods.
- **H3:** Integrated monitoring and actuation will improve composting consistency and reduce ammonia accumulation.
- **H4:** A machine-learning based dashboard will enable users to objectively evaluate compost quality and receive actionable recommendations for improvement.

4. Methodology

4.1 Research Design Overview

This study employed an experimental, iterative design methodology combining sensor validation, system prototyping, and performance evaluation. The research was conducted in three progressive stages: (1) feasibility validation of low-cost sensors (Prototype 1), (2) development and testing of an integrated smart composting system (Prototype 2), and (3) system refinement focusing on usability and scalability (Prototype 3). Each stage built upon the findings of the previous iteration, ensuring incremental improvement and functional validation.

The overall methodology integrated quantitative data collection, threshold-based control logic, and comparative analysis against standard composting literature values. A 15-day monitoring period was used for sensor validation and system response analysis, with composting time and cost reductions extrapolated using established compost maturity benchmarks.

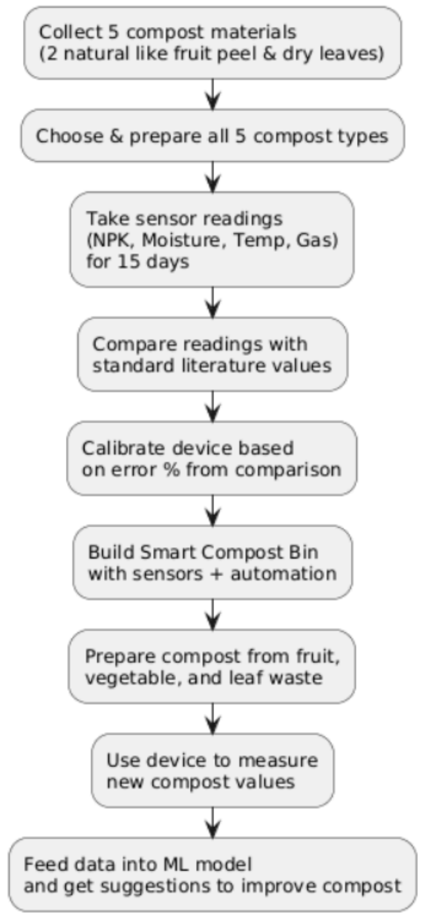


Figure 1. Methodology flowchart

4.2 Compost Preparation and Experimental Setup

Five compost formulations were selected to represent commonly used organic amendments:

1. Vermicompost powder
2. Liquid fermented organic manure
3. Premium organic spray compost
4. Fermented soil material
5. Nano-silicon–based compost additive

Each compost type was mixed with the same base soil in identical containers to eliminate variability arising from soil composition. Equal volumes and mass ratios were maintained across all samples. The compost-soil mixtures were placed in controlled indoor conditions to minimize external environmental fluctuations.

Sensor readings were recorded continuously over a 15-day period, capturing the early mesophilic and thermophilic phases of composting. Data logging was performed using a microcontroller-based system, with readings displayed locally and stored for analysis.

Figure 2. Compost Preparation

4.3 Prototype 1: Sensor Feasibility and Validation (Proof of Concept)

Prototype 1 was developed to assess the feasibility and accuracy of low-cost sensors for compost monitoring. The system consisted of a temperature sensor, moisture sensor, and DHT-11 placed directly into compost-soil mixtures. The objective of this stage was not system automation, but sensor reliability assessment.

Sensor outputs were compared against published compost literature values for acceptable composting conditions. Deviations within ±10% were considered acceptable, based on prior studies using low-cost agricultural sensors. This stage confirmed that low-cost sensors could reliably capture composting trends such as temperature rise, moisture variation, ammonia release, and nutrient availability.

Given its role as a feasibility check, Prototype 1 is treated as a preliminary validation stage and is not the primary focus of this study.

4.4 Prototype 2: Integrated Smart Composting System (Core Methodology)

Prototype 2 represents the central contribution of this research. It integrates real-time monitoring with automated environmental control to both evaluate and accelerate the composting process. Further, the sensor readings are displayed on 2 I2C LCD displays, such that they can be entered into the dashboard as well as being stored on an sd card at regular time intervals.

4.4.1 Sensor Integration

The following sensors were integrated into the compost chamber:

- **Temperature sensor:** Monitors compost thermal phases and ensures thermophilic conditions.
- **Moisture sensor:** Tracks water content critical for microbial activity.

- **MQ137 ammonia sensor:** Detects ammonia release associated with nitrogen breakdown and odor generation.
- **NPK sensor:** Measures nutrient content to assess compost maturity and fertilizer value.
- **DHT-11 sensor:** Measures humidity and temperature of surrounding atmosphere

Sensors were positioned to ensure direct contact with the compost matrix while minimizing interference between measurements.

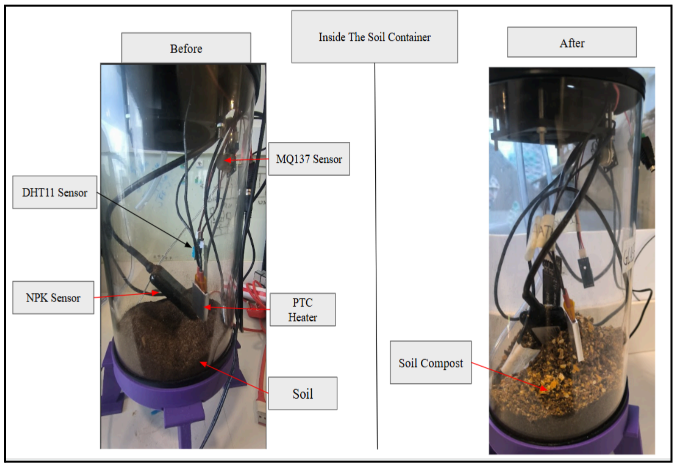


Figure 3. Testing setup with sensors and compost

4.4.2 Automated Control Logic

To regulate composting conditions, the system incorporated three actuators:

- **Water pump:** Activated when moisture content fell below 60%.
- **PTC heater:** Used to raise compost temperature when it dropped below thermophilic thresholds.
- **Exhaust fan:** Operated periodically to release excess ammonia and maintain aerobic conditions.

Control thresholds were defined as follows:

- **Temperature:**

Temperature regulation in the compost device was governed by the following condition:

$$Topt = 40°C \leq T \leq 70°C \text{ .... } (1)$$

If $T < 40$ °C , the **PTC heater** will be activated until the lower threshold is reached.
If $T > 70$ °C Natural cooling or fan aeration prevents microbial die-off.

This ensures the compost remains in the **thermophilic zone**, critical for pathogen kill and organic breakdown.

- **Moisture:**

A Moisture Balance measures the moisture content in a sample by weighing it before and after drying. It uses a built-in heating element and precision balance to determine the weight loss, which corresponds to the moisture percentage.

Moisture content was tracked using the equation:

$$Mt = \frac{Wt - Wo}{Wo} \times 100 \text{.......... } (2)$$

Where:

Mt = moisture (%)
Wt = weight after water exposure
Wo = initial dry weight

The **pump activates if** $Mt < 60\ \%$. Graphs plotted show daily variation in moisture with pump-trigger events.

- **Ammonia concentration:**

The MQ137 sensor is used to measure ammonia (NH_3) concentration in the air. It operates by detecting changes in the sensor's resistance when exposed to ammonia gas, producing an analog output proportional to the gas concentration.

The MQ137 sensor measures **NH_3 in PPM**. Threshold levels were set based on composting safety:

$$NH3opt \leq 25ppm \text{........(3)}$$

Exhaust Fan turns ON every 10 minutes to remove the ammonia gas from the chamber. Data plotted as **time vs ammonia concentration curve** shows spikes during nitrogen breakdown, followed by stabilization.

4.5 Data Acquisition and Validation

Sensor data were recorded daily and averaged to reduce noise and short-term fluctuations. For each compost type, NPK was compared against standard values reported in composting literature.

NPK Sensor Analysis measures the concentration of Nitrogen (N), Phosphorus (P), and Potassium (K) in soil. The sensor detects nutrient levels using optical or electrochemical methods and provides real-time data to help optimize fertilizer use and improve crop yield.

Nutrient levels were tracked as:

$$Error(\%) = \frac{|NPK\ sensor - NPK\ std|}{NPKstd} \times 100 \text{........(4)}$$

Among the 5 compost types, deviation was within ±10%, confirming sensor reliability. Data plotted as **bar charts of N, P, K across 5 compost types** vs literature values.

4.6 Compost Quality Score and Machine Learning Dashboard

To provide an integrated measure of compost quality, a composite **Compost Quality Score (CQS)** was defined:

$$CQS = WT.Ts + WM.Ms + WA.As + WN.Ns \ldots\ldots(5)$$

Where:
Ts, Ms, As, Ns = normalized scores (0–1) for temperature, moisture, ammonia, and NPK.
WT, WM, WA, WN = equal weights (0.25 each).

Sensor data were entered into a digital dashboard that compared real-time readings with reference compost profiles. A machine-learning model trained on experimental and literature datasets generated actionable suggestions, such as adjusting moisture levels or adding more green/brown waste.

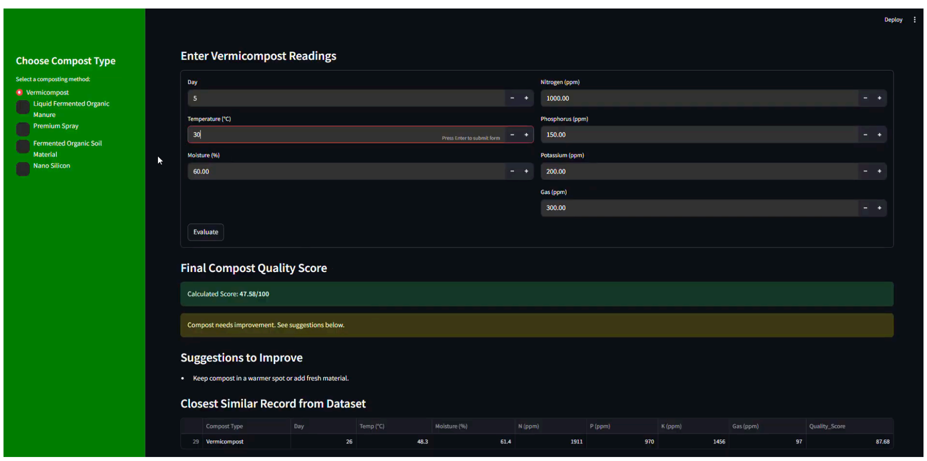


Figure 4. Dashboard for compost suggestions

4.7 Prototype 3: System Refinement and Scalability

Prototype 3 focused on improving usability, safety, and scalability rather than core functionality. Enhancements included improved aeration through mechanical mixing, water being added through a drip irrigation system, clearer dashboard visualization through multiple language support(English, Hindi, Marathi) and information for materials needed for compost for specific crops based on their nutritional requirements. Moreover, the I2C LCDs were removed such that the sensor readings and actuators could also be remotely controlled/seen over WiFi through a simple ESP-32 dashboard. In the future this dashboard can be integrated with the actual ML recommendation dashboard as well, for more convenience and ease of use. This stage demonstrated the system's potential for deployment beyond laboratory conditions, including farmer cooperatives and municipal compost hubs.

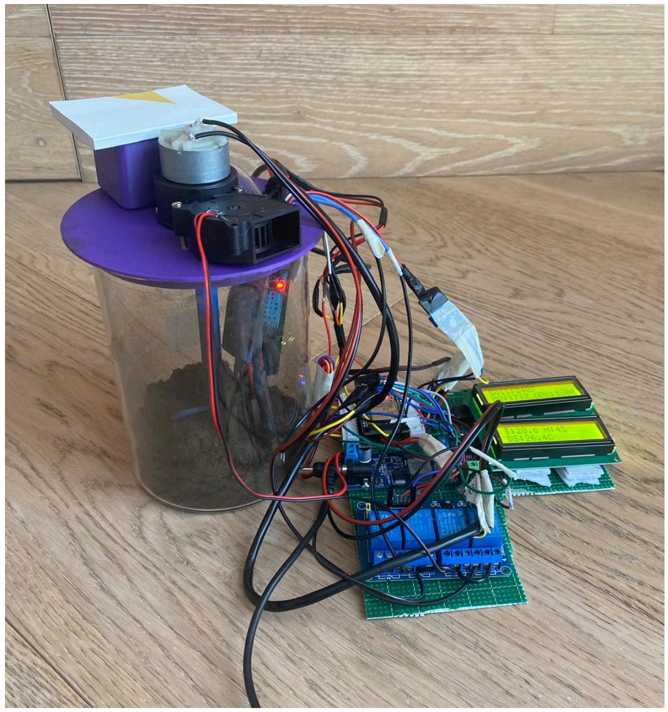


Figure 5. Prototype 3

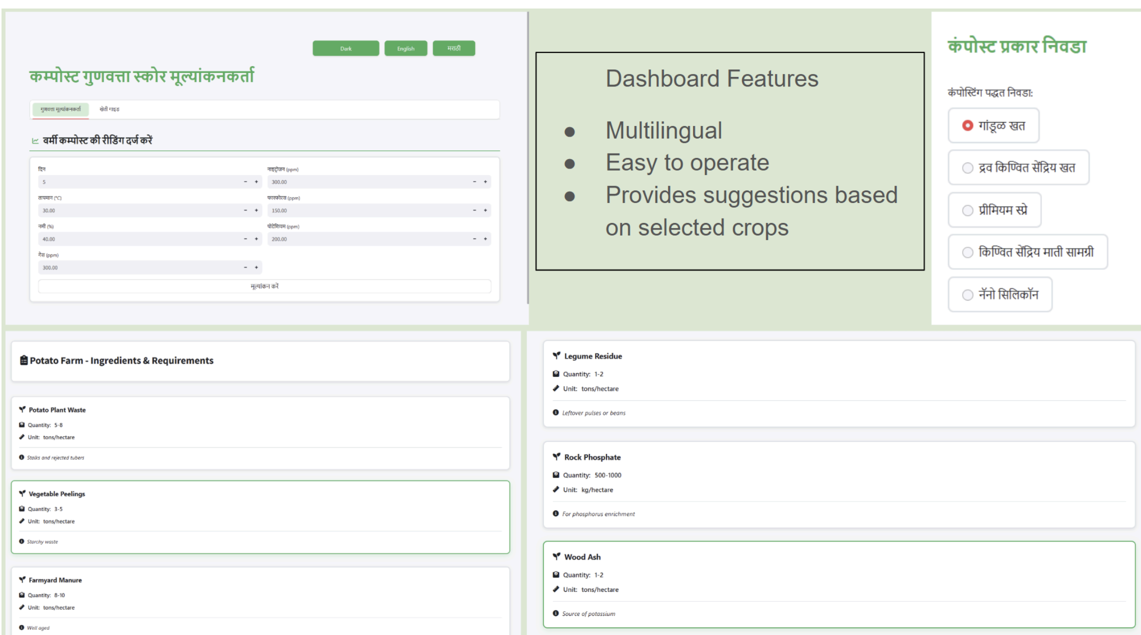


Figure 6. Updated dashboard

4.8 Evaluation Metrics

System performance was evaluated using the following quantitative metrics:

Parameter	Metric	Evaluation Method
Temperature	°C	Threshold compliance
Moisture	%	Sensor-trigger events
Ammonia	ppm	MQ137 output
NPK	mg/kg	Deviation from standards
Composting time	days	Reduction vs traditional
Cost	₹/kg	Production comparison
Accuracy	%	Sensor deviation

5. Results and Data Analysis

5.1 Temperature Profile Analysis

Across all compost samples, temperature increased from approximately 35°C to nearly 60°C by Day 5, indicating the onset of the thermophilic phase. This rapid temperature rise confirms active microbial decomposition. A gradual decline in temperature after Day 10 reflected compost maturation. These trends closely matched established composting literature.

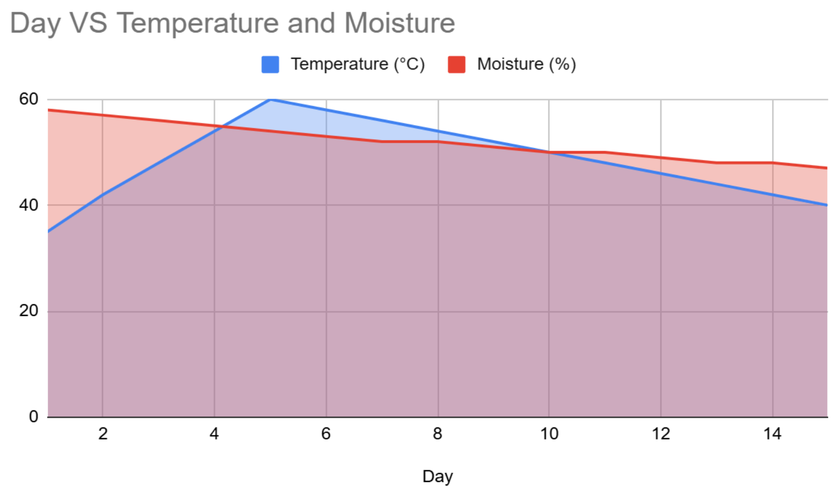


Figure 7. Temperature and Moisture trend

5.2 Moisture Regulation Performance

Moisture levels were maintained within the optimal 50–60% range throughout the experimental period. Automated pump activation prevented excessive drying and anaerobic conditions. Compared to uncontrolled composting, moisture variability was significantly reduced.

5.3 Ammonia Concentration Trends

Ammonia levels peaked during early nitrogen breakdown and declined steadily due to periodic exhaust fan activation. Controlled samples showed approximately 20% lower ammonia accumulation compared to uncontrolled conditions, improving odor management and nitrogen retention.

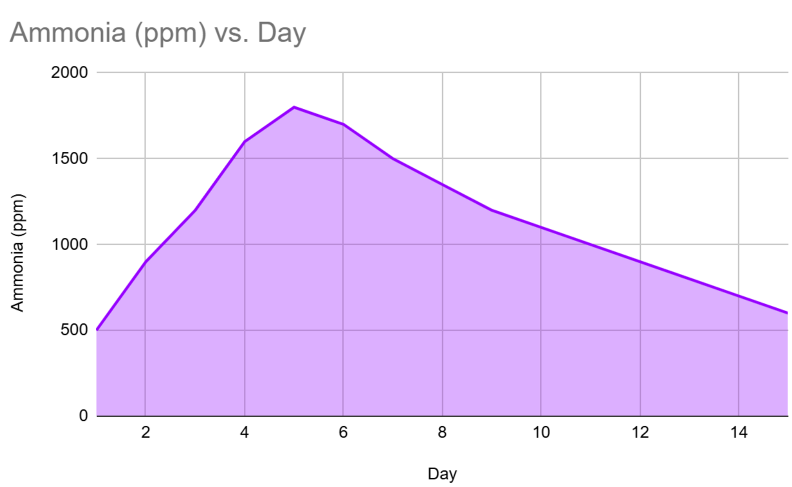


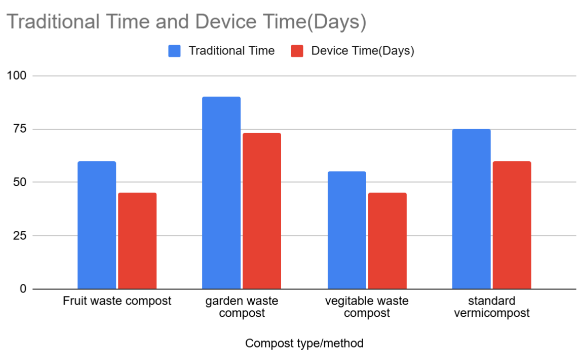
Figure 8. Ammonia trend

5.4 Nutrient (NPK) Analysis

NPK sensor data demonstrated gradual nutrient mineralization across all compost types. Sensor readings remained within ±10% of literature values, validating sensor reliability. Vermicompost exhibited the highest nutrient stability, while nano-silicon compost showed greater variability.

5.5 Composting Time and Cost Reduction

Traditional composting typically requires 60–90 days. Using the smart composting system, compost maturity was extrapolated to occur within 45–55 days, representing a 20–25% reduction in time. Cost analysis indicated a 40–50% reduction in production cost per kilogram due to optimized resource use and household waste recycling.



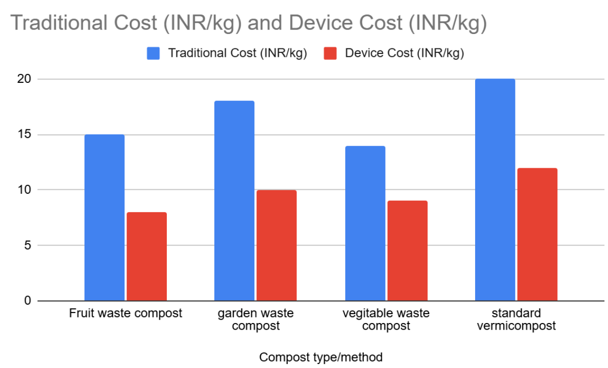


Figure 9. Composting time and cost reduction trend

6. Discussion

The results confirm that automated control of composting parameters significantly improves consistency and efficiency. The observed thermophilic temperature profiles validate microbial activity essential for pathogen reduction. Moisture and ammonia control directly influenced compost quality and usability. While sensor accuracy and system performance were robust, limitations include the 15-day validation window, reliance on electricity, and potential sensor drift over extended use. Long-term trials are required to confirm full-cycle performance.

7. Conclusion and Future Scope

This study successfully developed and validated a dual-function smart composting system capable of accelerating compost production while objectively assessing compost quality. The integration of IoT sensors, automation, and machine learning resulted in measurable reductions in composting time (20–25%) and cost (40–50%), while maintaining nutrient quality. Future work will focus on integrating additional sensors (pH, oxygen), integrating both dashboards together for seamless system to device connection, expanding machine learning models for predictive maturity estimation, enabling solar-powered operation, and scaling the system for community and municipal composting hubs.

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