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REMOTE MONITORING TECHNIQUES FOR COMPOSTING MACHINES WITH COMBINED TEMPERATURE AND MOISTURE SENSORS: OPTIMIZING ENVIRONMENTAL SUSTAINABILITY

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Abstract:
Composting, as an eco-friendly waste management solution, has gained prominence in recent years. Composting machines are essential in this process, transforming organic waste into valuable compost on large volumes. To ensure the efficiency and sustainability of composting operations, intelligent monitoring techniques have emerged as vital tools. By harnessing these intelligent monitoring techniques, composting machines can maintain the ideal balance of temperature and moisture, fostering faster decomposition and high-quality compost production. This paper explores the integration of intelligent monitoring technologies, specifically focusing on temperature and moisture sensors, to enhance composting machines' performance.

Keywords: **composting machines, monitoring techniques, combined moisture and temperature sensors, remote monitoring, environmental sustainability, empirical modelling**

I. INTRODUCTION

Composting is a key solution in sustainable waste management, significantly reducing the environmental impact of organic waste. To enhance efficiency and sustainability, intelligent monitoring techniques - particularly combined temperature and moisture sensors – can transform the composting industry.

Traditional methods rely on manual monitoring, which can be imprecise and labor-intensive. Advanced sensors now provide real-time, accurate data, enabling composting operators to maintain optimal microbial conditions for faster decomposition, reduced greenhouse gas emissions, and higher-quality compost.

This paper explores the integration of temperature and moisture sensors in composting machines, demonstrating their role in maintaining ideal thermophilic conditions, optimizing moisture levels, and preventing process disruptions. Through case studies and practical applications, we showcase how these innovations enhance efficiency, reduce waste, and minimize environmental impact, paving the way for the future of sustainable waste management.

II. COMPOSTING PROCESS AND ESSENTIAL PARAMETERS

Composting is a biological process where microorganisms break down organic matter into a stable, nutrient-rich soil amendment. A key factor in its efficiency is the carbon-to-nitrogen (C: N) ratio, which regulates microbial activity, decomposition rate, and compost quality. Maintaining an optimal C:N ratio of 25–30:1 ensures efficient decomposition, prevents nutrient loss, and minimizes odors.

1. **Carbon (C)**
   Energy Source: Found in dried leaves, straw, and sawdust, carbon fuels microbial metabolism and heat production. Excess carbon can slow decomposition by drying out the compost.

2. **Nitrogen (N)**
   Microbial Growth: Present in grass clippings, vegetable scraps, and manure, nitrogen supports microbial reproduction. Too much nitrogen can cause ammonia release and strong odours. Aeration and moisture control help maintain balance.

Beyond the C:N ratio, temperature and moisture significantly impact decomposition speed, microbial activity, and compost quality. Proper management of these factors enhances efficiency, elevates composting temperatures, eliminates pathogens and weed seeds, and produces high-quality compost.

3. **Temperature Regulation**

- Accelerating Decomposition: Microorganisms generate heat as they break down organic material. Maintaining 135°F to 160°F (57°C to 71°C) ensures rapid decomposition, pathogen elimination, and weed seed destruction.
- Monitoring Progress: Temperature changes indicate microbial activity. A premature drop may require turning, moisture adjustment, or nitrogen supplementation, while excessive heat can harm beneficial microbes. Regular monitoring maintains efficiency.

4. **Moisture Management**

- Hydration for Microbial Activity: Optimal moisture levels (40-60%) support decomposition. Too much moisture leads to anaerobic conditions and odors, while too little slows microbial activity.
- Balancing Moisture: Compost should feel like a damp sponge - moist but not dripping. Adding dry materials absorbs excess water, while moistening dry piles prevents dehydration.
- Aeration & Efficiency: Proper moisture prevents compaction and ensures oxygen flow, aiding in efficient decomposition. Without aeration, anaerobic conditions cause odors and slow breakdowns.

Temperature and moisture are interdependent, influencing microbial activity, decomposition speed, and compost quality. Regular monitoring and adjustments ensure a sustainable and effective composting process.

III. THE NEED:

The need for a composting machine equipped with combined moisture and temperature sensors becomes even more apparent when considering the intricacies of composting. These sensors act as essential guardians of the composting process, providing real-time data that allows composters to make informed decisions. The symbiotic relationship between temperature and moisture is crucial for fostering microbial activity, which is essential for effective decomposition. A composting machine with integrated sensors not only automates the monitoring process but also enables prompt adjustments, maintaining the delicate equilibrium required for optimal composting. This technology improves efficiency and empowers composters to proactively address potential issues, ensuring that the composting process remains both productive and environmentally sustainable. As we navigate the challenges of waste management and environmental conservation, these advanced composting machines play a pivotal role in promoting responsible and efficient composting practices.

IV. SYSTEM OVERVIEW OF COMPOSTING MACHINE EQUIPPED WITH DEVELOPED COMBINED MOISTURE AND TEMPERATURE SENSOR AND EDGE CONTROLLER AND MODEM:

Figure 1 shows a typical arrangement of composting machine installed with combined moisture and temperature sensor.

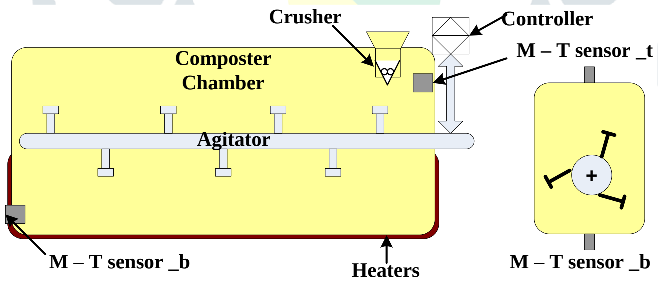


FIGURE 1: Finalized Sensor locations; M-T Sensor at sides of drum, top (t) and bottom (b)

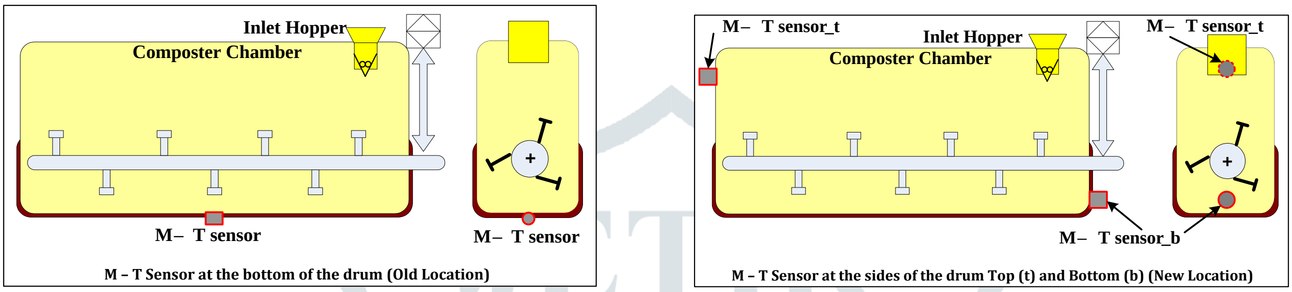
The composting machine installed with combined moisture and temperature sensor basically consists of 6 main parts:

1. Crusher / Shredder: To cut down the input wet waste material into small pieces to increase the surface area microbes must work and improve the degradation process.
2. Biomass degradation chamber / digesting vessel / drum: A drum like container to carry out the complete composting process.
3. Heaters: To remove excess moisture from the biomass inside the drum. The heaters could be either band type heaters or blanket heaters.
4. Agitator / mixer: To mix the input material with leftovers of previous batch and bio enzymes. It also helps to distribute heat applied by heaters and moisture evenly through the chamber.
5. Controller: To program a process cycle by setting process parameters.
6. M-T Sensor: Combined moisture and temperature sensors for in situ measurement for deciding control actions.

Composting converts organic waste into nutrient-rich compost, enhancing soil health and reducing environmental impact. Moisture and temperature are key factors influencing microbial activity and decomposition rates.

Empirical models, built from in situ measurements, provide real-time insights by tracking moisture and temperature directly within the composting process. These mathematical models help optimize efficiency by identifying patterns and relationships essential for successful composting. Key components considered for building the model include:

1. Experimental Design
   The type of composting materials used, initial conditions, capacity of composting drum and sensor locations are controlled variables. These factors influence how the empirical model is developed. Temperature and moisture of biomass inside the drum are measured variables. Garden and kitchen (food) waste is used as carbon and nitrogen ingredients for biomass. During trials on actual machine, it was crucial to decide the location of the sensor mounting. For initial trials of the sensor on actual machines, the assumption was that only one sensor at the centre in the bottom of the drum ,as shown in Figure 2(a) will be enough for deciding the heater control strategy, however it was later observed that measuring moisture and temperature at the mentioned location is not sufficient, because depending upon the tonnage capacity of machine the length of the drum varies. In such conditions two (or more depending upon the length of drum) sensors shall be placed at the correct location. Currently the trials are carried out for 100kg machines and concluded that two sensors are good enough for 100kg machine. The finalized locations for the sensors in 100 kg machine are as shown in Figure 2 (b).



(a) (b)

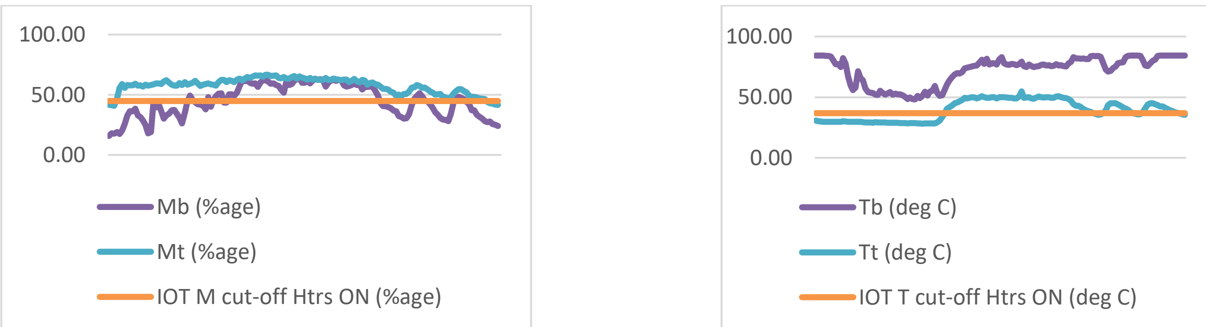
FIGURE 2: Sensor locations for 100kg machine; (a) M-T Sensor at bottom of the drum (Old Location), (b) M-T Sensor at sides of drum, top (t) and bottom (b) (New Location)

2. Data Collection
   Combined temperature and moisture sensors are strategically placed within the composting drum for in situ measurement of moisture and temperature. Data is collected regularly, capturing the dynamic changes in these parameters. Arrangement of two sensors, one at top and second at bottom for 100KG capacity machine was used to acquire actual data. Table 1 below represents the obtained data as a sample.

TABLE 1: Actual data acquired by developed sensor on actual machine.

Time stamp	drum T (V)	drum T (deg C)	Mb (V)	Mb (%age)	Tb (V)	Tb (deg C)	Mt (V)	Mt (%age)	Tt (V)	Tt (deg C)	Set T (deg C)	Cut Off T (deg C)	IOT T cut-off Htrs ON (deg C)	IOT M cut-off Htrs ON (%ag
Wed Sep 11 15:15:41	1.45	42.78	2.03	15.98	4.02	84.42	1.13	41.77	1.47	30.87	85.00	80.00	36.75	45.00
Wed Sep 11 15:23:42	1.44	42.48	1.96	17.99	4.02	84.42	1.14	41.48	1.44	30.24	85.00	80.00	36.75	45.00
Wed Sep 11 15:31:44	1.39	41.01	1.97	17.70	4.02	84.42	1.16	40.91	1.43	30.03	85.00	80.00	36.75	45.00
Wed Sep 11 15:39:46	1.41	41.60	1.92	19.13	4.02	84.42	0.95	46.93	1.41	29.61	85.00	80.00	36.75	45.00
Wed Sep 11 15:47:48	1.43	42.19	1.98	17.41	4.01	84.21	0.64	55.81	1.41	29.61	85.00	80.00	36.75	45.00
Wed Sep 11 15:55:49	1.42	41.89	1.88	20.28	4.00	84.00	0.53	58.96	1.42	29.82	85.00	80.00	36.75	45.00
Wed Sep 11 16:03:51	1.41	41.60	1.69	25.72	3.98	83.58	0.64	55.81	1.42	29.82	85.00	80.00	36.75	45.00
Wed Sep 11 16:03:51	1.40	41.30	1.45	32.60	3.84	80.64	0.56	58.10	1.42	29.82	85.00	80.00	36.75	45.00
Wed Sep 11 16:11:53	1.39	41.01	1.32	36.32	3.68	77.28	0.57	57.81	1.42	29.82	85.00	80.00	36.75	45.00
Wed Sep 11 16:19:54	1.39	41.01	1.32	36.32	3.68	77.28	0.57	57.81	1.42	29.82	85.00	80.00	36.75	45.00
Wed Sep 11 16:27:56	1.39	41.01	1.24	38.62	3.57	74.97	0.52	59.25	1.42	29.82	85.00	80.00	36.75	45.00
Wed Sep 11 16:35:58	1.40	41.30	1.44	32.89	3.92	82.32	0.58	57.53	1.44	30.24	85.00	80.00	36.75	45.00
Wed Sep 11 16:44:00	1.40	41.30	1.49	31.45	3.70	77.70	0.57	57.81	1.43	30.03	85.00	80.00	36.75	45.00
Wed Sep 11 16:52:01	1.39	41.01	1.59	28.59	3.19	66.99	0.60	56.95	1.42	29.82	85.00	80.00	36.75	45.00

The nature of moisture and temperature variation in the live measurements on an actual machine can be seen below Figure 3 (a) and 3 (b) respectively.



(a) Moisture (b) Temperature

FIGURE 3: In process sensor performance on actual machine; (a) Moisture (b) Temperature

3. Process Adjustments
   Based on the observations, heater and agitator cycles are adjusted accordingly. It is observed that at the process start instance, moisture content is high and drops as the time lapses as measured by top sensor however at the process start instance, moisture content is low and increases as the time passes as measured by bottom sensor. After some time when the material is mixed both the sensors stabilize within a range and as the process approaches to an end it decreases further.

   Similarly, the temperature is low initially as the heaters are OFF at the time of loading. At the time instance when top sensor senses high moisture and bottom sensor also starts detecting increase in moisture; heaters are turned ON resulting in rise in temperature. Heaters are switched OFF when moisture starts decreasing and temperature reaches heater OFF threshold. The trend of switching the heaters ON or OFF continues till the moisture reaches to the optimum level at desired temperatures. Parameters like aeration cycle and agitation cycle also need to be adjusted based on the change in moisture to ensure aerobic decomposition of biomass.

V. RESULTS:

As shown in Table 1 and Figure 3, moisture and temperature values stabilize at optimal setpoints throughout the cycle. The integration of temperature and moisture sensors, enhanced by remote monitoring, marks a significant advancement in organic waste management.

This paper highlights how real-time sensor data enables precise control of microbial conditions, ensuring efficient decomposition. Beyond operational benefits, remote monitoring minimizes environmental impact, reducing greenhouse gas emissions and diverting waste from landfills. Efficient composting management produces high-quality compost, conserves resources, and supports sustainable agriculture and horticulture.

VI. CONCLUSION:

The integration of remote monitoring with combined temperature and moisture sensors has transformed composting, marking the beginning of further innovation. Future research can explore advanced sensor technology, AI-driven predictive modelling, and diverse composting methods to enhance efficiency.

This paper highlights significant progress in composting technology and calls on researchers, engineers, and practitioners to push innovation forward. By embracing intelligent monitoring, we can transform organic waste into a valuable resource, driving a greener, more sustainable future.

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