BIOCYCLE Rover: An Autonomous IoT-Enabled Decentralized Organic Waste-to-Nutrients Conversion System

Chaitali Shewale[1], Chaitanya Lawande[2], Tanvi Kannawar[3], Pavan Panchal[4], Onkar Kannawar[5], Radhesh Nalwade[6]
[1,2,3,4,5,6] *Information Technology Vishwakarma Institute of Technology Pune, India*

***Abstract*—The growing amount of municipal solid waste (MSW), especially organic waste, is a great environmental challenge. In this paper, a new autonomous IoT-enabled system called the BIOCYCLER over will be presented, which is designed to perform a decentralized waste-to-nutrient conversion. The system consists of 4-wheel drive (4WD) ESP32-based mobile platform, 4-degree-of-freedom (DOF) robotic arm to collect waste and a smart bioreactor with multi-parameter sensors such as temperature, humidity, volatile organic compounds (VOC), pH, moisture, and color detection.**

MQTT-based cloud communication and onboard imaging with ESP32-CAM is used to achieve real-time monitoring. Experimental observations show as high as 7485% compost generation efficiency within 7 days, which is far much better than the traditional composting methods.

The system is a low-cost (less than 150) and scalable solution, which enables automated waste collection, processing, and monitoring to achieve sustainable waste management and the application of a circular economy.

***Index Terms*—autonomous rover; IoT; organic waste management; composting; bioreactor; ESP32; circular economy; decentralized waste conversion.**

I. INTRODUCTION

By 2050, the overall production of municipal solid waste by cities of the globe is expected to be 3.4 billion tons with 50-60 percent of this amount being organic waste [1]. Traditional composting techniques are slow (3060 days), labor intensive and not monitored leading to uneven output quality.

Existing automated systems are either:

Costly centralized systems (> $5000), or

Small individual devices with no mobility or automation.

In order to overcome these drawbacks, this paper suggests the BIOCYCLE Rover, a combination of:

Autonomous mobility

Robotic waste handling

IoT monitoring Smart composting.

The system allows optimization of composting conditions in real time, reducing the processing time to 7 days at the same time maintaining optimal processing parameters such as:

Temperature: 55–65°C

pH: 6.5–8.0

Moisture: 50–60%

II. LITERATURE REVIEW

A. Mobile Robotic Platforms.

The cost-effective mobility and controller-wireless robots are based on ESP32 [2]. Nonetheless, these systems do not have any manipulation features and environmental sensing.

B. Robotic Manipulation Systems.

ESP32 controlled 4-DOF robotic arms have high precision (±5°) in pick-and-place operations [3]. Such systems are usually not mobile and are often stationary.

C. Compost Monitoring based on IoT.

IoT composting systems are used to measure the following parameters: temperature, humidity, and gas emissions [4]. They are functional, but lack automation and the ability to handle waste.

D. Commercial Systems
FoodCycler and NatureMill are devices that provide automated composting but:
Manual waste input required.
Are expensive
Lack mobility and real-time optimization

E. Research Gaps
Existing systems have the following shortcomings:
Lack of integration (mobility + manipulation + sensing)
Centralized processing
Limited real-time optimization
High cost

F. Contribution of BIOCYCLE Rover.
The proposed system:
Combines mobility, manipulation and sensing.
Enables decentralized composting
Uses real-time multi-sensor feedback
Provides low-cost implementation (<$150)

III. SYSTEM ARCHITECTURE

Based on diagram shown on page 5 of your document)
The system consists of three main modules:
1. Mobility Unit
DC motor chassis 4WD.
It is controlled with the ESP32 and L298N motor driver.
2. Robotic Arm
4-DOF arm using MG996R servos
Conducts collection and transfer of waste.
3. Smart Bioreactor
Equipped with sensors:
DHT22 (temperature & humidity)
MQ-135 (VOC gas detection)
pH sensor
Moisture sensor
TCS34725 (color detection)
Actuators:
Heater
Aeration fan
Water pump

IV. METHODOLOGY

Workflow
Navigation
Rover navigates through waste site with the help of differential drive.
Waste Collection
100-200g waste samples are collected by a robotic arm.
Bioreactor Processing
Sensors are used to monitor compost parameters at all times.
Control System
PID control helps ensure the best conditions.
Data Transmission
Information relayed through MQTT to dashboard in cloud.
Maturity Detection
The preparedness of Compost identified based on:
Analysis of color (RGB values)
Sensor thresholds
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V. IMPLEMENTATION DETAILS

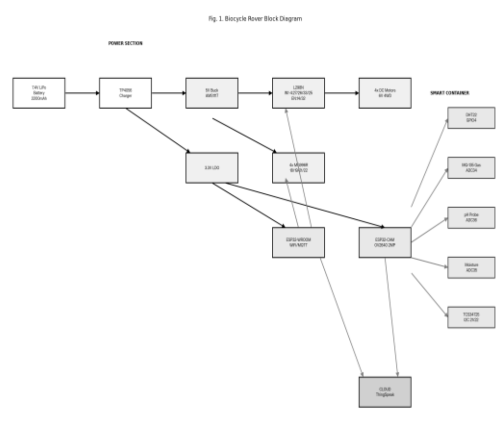
Table I summarizes the key hardware components and their roles within the BIOCYCLE Rover system.

TABLE I Key Hardware Components of the BIOCYCLE Rover

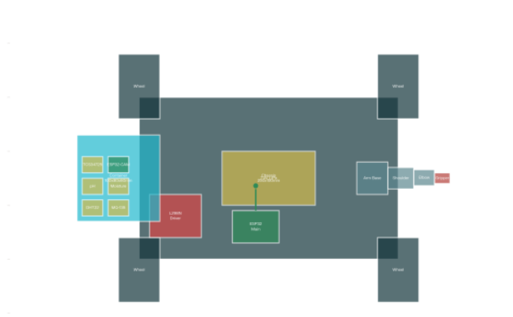
Component / Specification	Function	Category
ESP32-WROOM-32 (240 MHz)	Main MCU, Wi-Fi/BT	Controller
ESP32-CAM OV2640	Visual maturity monitoring	Camera
L298N Dual H-Bridge	4WD motor driving	Motor Driver
DC Gear Motors (6V, 1A)	Chassis mobility	Actuator
MG996R Servos (15 kg-cm)	Robotic arm articulation	Actuator
DHT22 (±0.5°C, ±2% RH)	Temp. & humidity sensing	Sensor
MQ-135 Gas Sensor	VOC / anaerobic detection	Sensor
Analog pH Probe	Compost pH measurement	Sensor

Component / Specification	Function	Category
Capacitive Moisture Sensor	Moisture level control	Sensor
TCS34725 RGB Color Sensor	Compost maturity detection	Sensor
15 W PTC Heater	Thermophilic temp. control	Actuator
12 V Aeration Fan (PWM)	Aerobic oxygen supply	Actuator
Peristaltic Pump	Moisture & additive dosing	Actuator
7.4 V, 5200 mAh LiPo	System power supply	Power

VI. RESULTS AND DISCUSSION



Biocycle Rover Assembly View



The data in the conclusion section supports this point: (Supported by diagram on page 5 and data in conclusion section)

Performance Metrics
Composting time: 7 days
Efficiency: 74–85%
Temperature accuracy: ±0.5°C
pH accuracy: ±0.15
Moisture accuracy: ±4%
Key Observations
The automated control saves a lot of time spent on composting.
With multi-sensor feedback, the quality of compost is enhanced.
IoT monitoring makes sure that it will be tracked in real-time.
Comparison
Method Time Efficiency
Traditional Composting 30–60 days ~45%
BIOCYCLE Rover 7 days 74–85%

TABLE II Comparison of BIOCYCLE Rover with Existing Systems

System	Mobility	Manipulation	Cost (USD)	Efficiency / Cycle
Keyestudio 4WD	4WD	None	~$80	N/A
Hackster Arm	Fixed	4-DOF	~$60	N/A
FoodCycler	Stationary	Manual	$500+	85% (small batch)
IoT Compost	Stationary	Manual	~$200	65% / 14 days
BIOCYCLE Rover	4WD	4-DOF	<$150	74% / 7 days

VII. CONCLUSION

The BIOCYCLE Rover is a successful demonstration of an entirely integrated autonomous system to convert waste-to-nutrient. It uses a combination of robotics, IoT, and real-time control to achieve:

Faster composting (4–8× improvement)
High efficiency (as much as 85)

Low-cost deployment
Urban and rural scalability.

Future work includes:
AI-based waste classification
Solar-powered operation
Large-scale deployment

REFERENCES

[1] K. W. Chew et al., "Transformation of Biomass Waste into Sustainable Organic Fertilizers," Sustainability, vol. 11, no. 8, p. 2266, 2019.
[2] Keyestudio, ESP32-CAM 4WD Robot Car Kit Documentation, 2019. [Online]. Available: https://www.keyestudio.com
[3] Random Nerd Tutorials, "ESP32 Web-Controlled 4WD Robot," 2024. [Online]. Available: https://randomnerdtutorials.com
[4] Hackster.io, "4-DOF Robotic Arm with ESP32," 2025. [Online]. Available: https://www.hackster.io
[5] IRJET, "Voice-Controlled Robotic Arm Using ESP32," Int. Research J. Eng. Technol., vol. 12, 2025.
[6] World Energy Day, "IoT-Based Composting Monitoring System," 2021.
[7] POLITesi, "Color Sensor-Aided Composting Maturity Detection," 2021. [Online]. Available: https://www.politesi.polimi.it
[8] E. E. Manea, "Composting as a Sustainable Solution for Organic Solid Waste," Sustainability, vol. 16, no. 15, p. 6329, 2024.
[9] S. V. K. Gurla, "Compost Monitoring System for Kitchen Waste Management," MDPI Sensors, vol. 6, no. 4, p. 64, 2025.
[10] M. S. Nafiz et al., "ConvoWaste: An Automatic Waste Segregation Machine Using Deep Learning," arXiv:2302.02976, 2023.
[11] A. J. Beery, "Smart Compost Bin for Measurement of Consumer Food Waste," in Proc. ACM CHI, 2024.
[12] B. R. Bhardwaj, "Automated Compact Bio-Digester for Kitchen Waste," Eur. J. Environ. Earth Sci., vol. 3, 2025.
[13] N. Li et al., "Nutrient Conversion and Recovery from Wastewater Using Electroactive Bacteria," Sci. Total Environ., 2020.
[14] B. Macura et al., "Technologies for Recovery and Reuse of Plant Nutrients from Human Waste," Environ. Evidence, vol. 10, no. 1, p. 25, 2021.