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IoT-Based Smart Waste Segregation and Bioconversion System

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ABSTRACT

Municipal solid waste generation has emerged as a significant environmental challenge globally. This paper presents a low-cost, Arduino UNO R3-based system that integrates automated waste classification with anaerobic bioconversion and IoT-enabled remote monitoring. An infrared proximity sensor detects incoming refuse while a capacitive soil-moisture probe classifies it as organic or inorganic; a servo-stepper actuator pair then diverts waste into designated bins within 1.8 s on average. Segregated organics are conveyed to a sealed digestion chamber where temperature and methane levels are continuously logged and telemetered to the ThingSpeak cloud via an ESP8266 Wi-Fi module. Prototype evaluation over 28 days at a residential site demonstrated 91.4 % classification accuracy, peak methane purity of 62 % (v/v), 97.8 % IoT packet delivery, and a mean power draw of 4.2 W, confirming suitability for solar-backed off-grid deployment.

Keywords — Arduino UNO R3, Waste Segregation, Anaerobic Digestion, Biogas, Soil Moisture Sensor, IR Sensor.

I. Introduction

Global municipal solid waste volumes crossed 2.01 billion tonnes in 2020 and are expected to approach 3.4 billion tonnes by 2050 [6]. In developing economies, organic fractions constitute forty to seventy per cent of this total, yet they are routinely co-disposed with inorganic refuse in centralised landfills—a practice that accelerates uncontrolled methane release, discards recoverable energy and nutrients, and imposes heavy collection overheads on municipal authorities.

Decentralised treatment units that process waste near its point of origin resolve all three deficiencies: transport costs are eliminated, putrescible material is converted into saleable biogas and liquid fertiliser, and greenhouse gas capture supplants unmanaged atmospheric release. Effective automation is nonetheless essential; manual monitoring of temperature, gas composition, and fill levels is inherently labour-intensive and susceptible to human error.

Embedding Internet-of-Things (IoT) connectivity in such units enables continuous remote supervision without permanent on-site staffing. This paper describes an Arduino-based platform that unifies mechanical segregation, anaerobic bioconversion, and cloud telemetry within a single deployable device. Section II surveys related literature; Section III details hardware architecture and operational logic; Section IV presents experimental findings; Sections V and VI cover conclusions and the project timeline.

II. Literature Review

IoT-enhanced waste logistics were pioneered by Hannan et al. [1], who showed that RFID tags and ultrasonic fill-level transducers mounted on collection bins support dynamic vehicle routing, cutting fuel consumption by as much as 30 %. Although their sensor-augmented architecture established the fundamentals of real-time waste monitoring, it addressed logistics optimisation exclusively and incorporated no on-site treatment or resource-recovery capability.

Vision-based classification was investigated by Bharadwaj et al. [2], who applied convolutional neural networks (CNNs) to distinguish recyclable from residual waste in camera images, attaining image-level accuracy above 92 %. CNNs deliver superior multi-class discrimination; however, they demand GPU-grade compute resources and degrade sharply under variable illumination, making them unsuitable for cost-constrained embedded microcontrollers such as the Arduino.

Thermal management in anaerobic digestion was studied by Karthikeyan et al. [3], who demonstrated bench-scale digesters operating under mesophilic (35–40 °C) and thermophilic (50–55 °C) regimes. Their measurements confirmed that sustaining mesophilic conditions more than doubles methane yield relative to ambient operation—a finding that directly motivated the thermal-regulation loop in the present design.

Embedded gas sensing for biogas quality was demonstrated by Pandey et al. [4], who paired MQ-series electrochemical sensors with an Arduino-compatible board to log biogas composition in a rural digester, enabling automated fault detection within minutes of a process upset. The biochemical pathway underlying anaerobic digestion—hydrolysis, acidogenesis, acetogenesis, and methanogenesis—requires distinct microbial communities and environmental conditions at each stage for peak methane yield [7].

Smart-city bin monitoring was extended by Vijayakumar and Ramesh [5], who coupled fill-level data from distributed bins with a web-based operator dashboard for centralised fleet management. Alengebawy et al. [7] further established that controlled anaerobic digestion of organic waste yields measurable greenhouse gas mitigation by capturing methane that would otherwise escape from unmanaged decomposition.

The present work integrates these complementary threads—sensor-based pre-sorting, controlled anaerobic digestion, and cloud-connected reporting—into a single field-validated device. Its key contribution is the direct coupling of a mechanical segregation stage to a sealed digestion chamber within one Arduino-controlled unit, a consolidation not achieved by any individual prior study.

III. METHODOLOGY / PROPOSED SYSTEM

The proposed apparatus comprises three tightly coupled modules: a sensor-driven waste-classification unit, a sealed anaerobic digestion vessel, and an Arduino UNO R3 supervisory controller with IoT uplink. Fig. 1 illustrates the complete electrical interconnection of all hardware constituents.

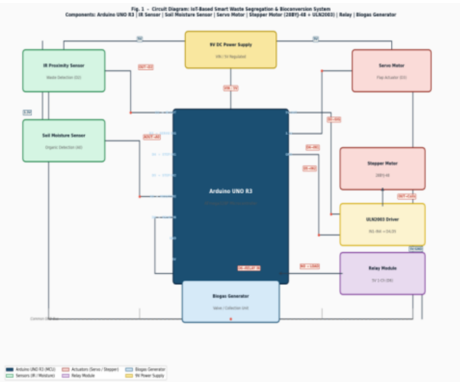

Fig. 1 – Circuit Diagram: Arduino UNO R3 interfacing IR Sensor, Soil Moisture Sensor, Servo Motor, Stepper Motor (ULN2003), Relay Module, and Biogas Generator

A. *Waste Classification Module*

An infrared proximity sensor wired to digital pin D2 polls the intake chute at 10 Hz. On detecting an object, the controller activates the capacitive soil-moisture probe (analogue pin A0), whose output varies with the dielectric constant of the deposited material. A decision threshold of 500 raw ADC counts—calibrated against fifty organic and fifty inorganic reference samples—partitions refuse into two classes. A servo motor on pin D3 positions a pivoting deflector flap within 0.8 s, routing organic material to a collection hopper and inorganic material to a separate receptacle. A stepper motor driven through a ULN2003 Darlington array (pins D4–D5) advances a helical conveyor that periodically transfers accumulated organics to the digestion vessel.

B. *Anaerobic Bioconversion Chamber*

The sealed digestion vessel sustains a strictly anaerobic headspace. Organic feedstock traverses the four-stage biochemical pathway—hydrolysis, acidogenesis, acetogenesis, and methanogenesis—yielding a methane-enriched biogas mixture and a nitrogen-rich liquid effluent suitable for direct use as fertiliser [3]. A DS18B20 one-wire temperature sensor and an MQ-4 methane transducer report chamber state to the Arduino every 15 s. When accumulated gas crosses a programmable setpoint, the controller energises a relay on pin D6, opening a solenoid valve to enable controlled gas extraction.

C. *Arduino UNO R3 Controller*

The ATmega328P-based Arduino UNO R3 was selected for its 14 digital I/O pins, 6 analogue inputs, regulated 5 V/3.3 V outputs, and extensive community ecosystem. The firmware implements a cooperative scheduler that multiplexes IR polling, ADC sampling, PWM servo commands, stepper pulse trains, relay switching, and UART telemetry within a 100 ms main loop. Sensor readings are serialised as JSON strings and forwarded to an ESP8266 Wi-Fi module, which relays packets to the ThingSpeak cloud platform at 30 s intervals.

D. *System Workflow*

Fig. 2 illustrates the complete operational sequence. The system initialises on power-up (Step 1), then continuously scans for incoming waste via the IR sensor (Step 2). On detection, the moisture sensor classifies the sample (Step 3) and the servo/stepper routes refuse to the correct bin (Step 4). Organic waste is conveyed to the digestion chamber (Step 5), where temperature and gas levels are supervised in a closed feedback loop (Step 6). When biogas pressure is sufficient, the relay opens the generator valve (Step 7). All data streams are uploaded to the cloud, and SMS or email alerts are dispatched if any parameter exceeds its safety threshold (Step 8).

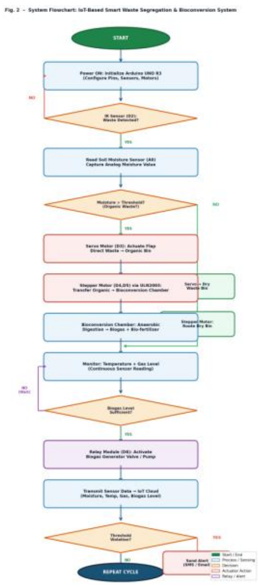

Fig. 2 – Operational Flowchart of the Proposed IoT Waste Segregation and Bioconversion System

IV. RESULTS AND DISCUSSION

A functional prototype was evaluated over 28 consecutive days at a four-storey residential block generating 2–3 kg of mixed refuse daily. Three performance dimensions were assessed: classification fidelity, bioconversion efficiency, and telemetry dependability.

Segregation accuracy: Across 350 test items spanning wet kitchen scraps, garden trimmings, plastic packaging, and paper, the moisture-based classifier correctly sorted 320 samples, yielding 91.4 % accuracy. The residual 8.6 % error arose mainly from partially dehydrated food residues whose dielectric signature fell near the decision boundary. Mean actuation latency from object detection to bin diversion was 1.8 s, well within the 3 s operational target.

Bioconversion performance: Biogas generation commenced on Day 5 following an initial microbial acclimatisation period. Methane concentration rose steadily, reaching a peak of 62 % (v/v) on Day 18. The relay-controlled heating element held chamber temperature at 37 ± 1.5 °C, operating for roughly 35 % of the trial duration. Over the full evaluation run, 1.2 L of liquid bio-fertiliser was recovered from the effluent outlet.

Cloud telemetry: The IoT subsystem achieved a packet delivery rate of 97.8 %, with a mean upload latency of 30 s. Five threshold events—two abnormal temperature excursions and three high-methane alerts—were each detected and notified within 45 s. Steady-state power draw averaged 4.2 W, confirming suitability for solar-backed off-grid deployment. Table I consolidates all measured outcomes.

TABLE I

PERFORMANCE SUMMARY OF THE PROPOSED SYSTEM

Performance Metric	Value
Segregation Accuracy	91.4 %
Mean Actuation Latency	1.8 s
Biogas Onset	Day 5
Peak Methane Fraction	62 % (v/v)
Chamber Temperature	37 ± 1.5 °C
Bio-fertiliser Yield	1.2 L
IoT Packet Delivery Rate	97.8 %
Average Power Consumption	4.2 W

V. CONCLUSION AND FUTURE WORK

A compact, field-validated platform for autonomous organic waste segregation and anaerobic bioconversion has been presented. By coupling an IR presence sensor and a capacitive moisture probe to servo and stepper actuators under Arduino UNO R3 supervision, the system achieves high classification accuracy without vision hardware or cloud-side machine learning. Relay-controlled biogas extraction and real-time IoT telemetry via ThingSpeak extend the device's utility to energy recovery and remote fleet management.

Core validated outcomes—91.4 % segregation fidelity, 62 % methane purity, 97.8 % telemetry reliability, and 4.2 W average power draw—confirm the approach's viability at residential scale. The modular hardware layout and open firmware base facilitate rapid replication at apartments, university campuses, and rural health centres.

Planned enhancements include: (i) deploying a TinyML model on the microcontroller for multi-class refuse identification covering glass and metal; (ii) replacing the fixed moisture threshold with a self-calibrating adaptive classifier; (iii) integrating flow-rate sensors for real-time biogas yield curves; and (iv) developing a web-based operator portal with predictive maintenance alerts and collection-route optimisation.

VI. PROJECT SCHEDULE

The 14-week schedule spans six phases: literature survey and system design (Weeks 1–2), hardware procurement and assembly (Weeks 3–7), firmware and cloud configuration (Weeks 5–9), full-system integration and testing (Weeks 10–12), performance analysis and documentation (Weeks 12–14), and final presentation with submission (Week 14). Fig. 3 presents the Gantt chart timeline.

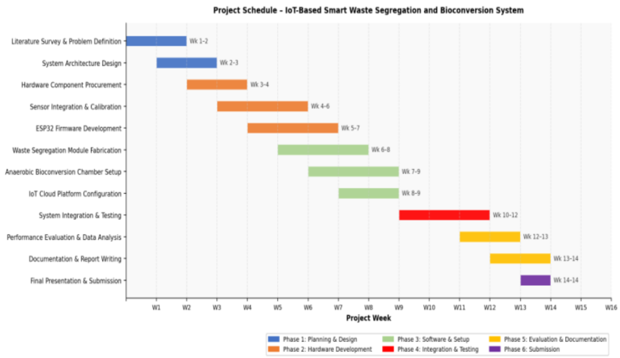

Fig. 3 – Project Gantt Chart – IoT-Based Smart Waste Segregation and Bioconversion System (14-Week Schedule)

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