

# Energy-Autonomous Smart Waste Collection in Green Environments Using Arduino–ESP32 Control and Sensor-Based Monitoring

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## Abstract

Urban green spaces parks, campuses, public lawns, and gardens demand frequent waste collection to preserve hygiene, aesthetics, and ecological sustainability. This paper presents the design and prototype implementation of an Autonomous Solar Waste Collector (ASWC) that detects, collects, and monitors litter with minimal human intervention. Waste presence is identified using infrared (IR) sensing, and a servo-driven robotic arm performs pick-and-place collection into an onboard bin. Bin fill-level is continuously estimated using an HC-SR04 ultrasonic sensor, and the bin status (empty/partial/full) is uploaded via an ESP32 IoT module for remote supervision. Real-time actuation and sensor coordination are handled by an Arduino controller, while Bluetooth manual override is provided for operator-assisted maneuvering in congested zones. The system is powered by a solar PV module with rechargeable battery storage, enabling uninterrupted daytime operation and extended duty cycles under variable sunlight. In prototype testing, the ASWC achieved 92.6% waste- detection accuracy for common dry litter (paper/plastic) within a 0.10–0.35 m sensing range, with an average pick-and-drop cycle time of 6.8 s per item. The ultrasonic bin monitoring estimated fill level with a mean absolute error of  $\pm 1.7$  cm, and full-bin alerts were transmitted with an average end-to-end latency of 0.9 s over Wi-Fi. Under clear-sky outdoor conditions, the solar charging subsystem sustained  $\sim 4.5$  h of continuous autonomous operation, reducing manual collection effort by  $\approx 60\%$  compared to conventional periodic cleaning routines. The proposed ASWC provides a low- cost, renewable-powered solution for smart waste management in green environments, supporting cleaner public spaces and scalable IoT-based maintenance.

**Keywords:** Autonomous robot; solar-powered waste collector, smart waste management, green spaces, IoT monitoring, Arduino; ESP32, IR sensor, ultrasonic fill-level sensing, robotic arm, Bluetooth control.

## 1. Introduction

Urban parks, campuses, and public gardens frequently experience littering due to high footfall, vendors, and public events, and maintaining cleanliness in these environments remains a continuous operational challenge. In most municipalities and institutions, waste handling in green spaces is still predominantly manual and schedule-driven, where cleaning staff follow fixed rounds rather than responding to real-time waste conditions. This approach often leads to delayed waste pickup, unpleasant aesthetics, hygiene concerns, and inefficient deployment of manpower during low-litter periods. In parallel, smart-city

initiatives have promoted IoT-enabled waste management, particularly through sensor-assisted “smart bins” that monitor fill level and transmit status to centralized dashboards. While such systems improve bin servicing logistics, they are largely static and do not address litter scattered across lawns, walkways, and open areas, where waste may remain uncollected for long durations unless manually detected and removed. Consequently, there is a strong motivation for mobile autonomous waste collection systems that can provide continuous patrolling, localized pickup, reduced human exposure to waste, and consistent cleanliness standards,

thereby improving both environmental sustainability and public experience. Mobile autonomous waste collectors, however, face several practical challenges in outdoor green environments. Reliable waste detection must be maintained under varying sunlight and shadows, different surface textures (grass, soil, pavement), and occlusions created by vegetation or crowded pathways. Beyond detection, the robot must perform robust pick-and-place actions, where the mechanical arm must reach, grasp, and deposit litter without excessive cycle time or repeated failures [1]. Power autonomy is another critical factor because cleaning operations typically require long duty cycles, and dependence on frequent manual charging contradicts sustainability goals; solar-assisted operation becomes desirable, but it introduces variability due to changing irradiance. Finally, communication and monitoring must remain dependable even in the presence of intermittent wireless connectivity, and system alerting must satisfy acceptable latency so that maintenance teams can respond quickly when the bin becomes full or when manual intervention is needed. Therefore, system performance in this work is defined using measurable operational and cyber-physical metrics such as detection accuracy (%), collection success rate (%), pick-and-place cycle time (s/item), bin-level estimation error (cm), IoT alert latency (s), energy autonomy (Wh/day or continuous operating hours), and coverage rate (m<sup>2</sup>/min). In this context, the objective of this paper is to develop a solar-powered autonomous mobile robot for green spaces that can (i) detect litter, (ii) collect waste using a compact robotic arm, (iii) monitor onboard bin fill level, and (iv) remotely report bin status and events through IoT connectivity. The robot is expected to operate in outdoor parks and campus settings where sunlight conditions are dynamic surfaces are uneven, obstacles and occlusions are common, and wireless communication may be inconsistent. The design must also satisfy practical constraints imposed by embedded platforms and low-cost sensors. Arduino/ESP32-based control requires efficient real-time logic and limited computation overhead, IR-based waste detection can produce false triggers depending on reflectivity and ambient light, and HC-

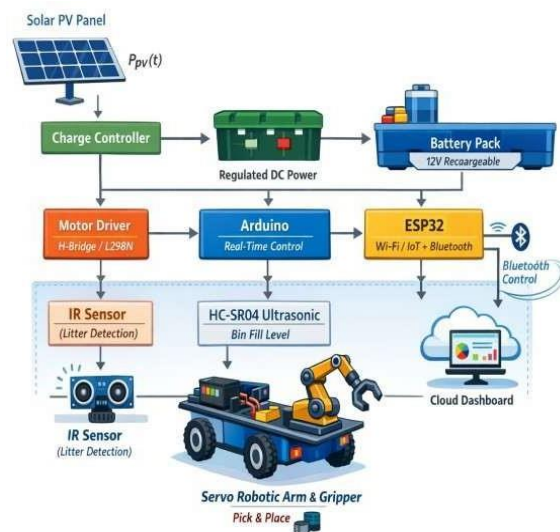
SR04 ultrasonic sensing can exhibit measurement noise due to bin geometry and waste surface irregularities. From a mechanical standpoint, the robotic arm is limited by servo torque, reach, and payload capacity, which directly influence successful pickup probability and cycle time. Despite these constraints, the system should achieve consistent cleaning performance while maintaining energy efficiency and reliable reporting. Existing studies on smart waste management often emphasize IoT-enabled bin monitoring, where ultrasonic or weight sensors estimate fill level and transmit bin status to cloud platforms for optimized collection routing [2]. Although effective for scheduling bin servicing, such approaches do not address dispersed litter on the ground and still rely on manual cleaning for parks and lawns. A second stream of work explores autonomous cleaning robots for public spaces, typically using line-following or rule-based navigation to patrol predefined paths and detect objects. Many of these designs either lack reliable pick-and-place capability or depend on expensive vision systems that increase cost and computational requirements, making them less suitable for low-cost deployments in outdoor environments [3]. A third direction investigates renewable-powered service robots, where solar energy reduces grid dependence and supports environmentally friendly operation. However, several prototypes in the literature primarily present hardware integration without comprehensive, standardized system-level evaluation, and often omit reproducible metrics such as energy autonomy, alert latency, and collection throughput under realistic outdoor disturbances. As a result, there remains a gap for an integrated solution that combines mobile litter pickup, solar-assisted energy autonomy, IoT-based monitoring, and quantitative KPI-driven validation. To address this gap, this paper makes the following contributions. First, it presents the design and integration of a solar-powered autonomous waste collection robot for green spaces, combining Arduino-based actuation and ESP32-based IoT reporting for practical, low-cost implementation. Second, it develops an event-driven sensor-fusion logic that leverages IR-based litter detection and ultrasonic bin-level estimation to

enable autonomous pickup decisions and timely status alerts. Third, it proposes a compact pick-and-place mechanism using a servo robotic arm optimized for lightweight dry waste commonly found in parks and campuses. Fourth, it introduces mathematical models for system-level evaluation, capturing energy balance, bin fill estimation, coverage-collection throughput, and end-to-end communication latency. Fifth, it provides MATLAB R2024a simulation and analysis scripts that generate nine standardized outputs covering detection performance, bin estimation accuracy, energy behavior, and operational KPIs. Finally, it includes comparative assessment against manual periodic cleaning practices and a static IoT bin-only baseline to demonstrate the benefit of adding mobility and autonomous collection [4].

## 2. Method

The Autonomous Solar Waste Collector is organized as four tightly coupled subsystems: (i) mechanical mobility and collection unit, (ii) sensing unit, (iii) embedded control and communication unit, and (iv) solar energy subsystem. The mechanical platform consists of a wheeled chassis driven by DC gear motors through a motor driver, enabling forward/reverse motion and turning in park pathways. The remainder of the paper is organized as follows. Section II describes the overall system architecture, hardware modules, and operating workflow of the proposed robot. Section III presents the mathematical modelling and embedded control logic used for detection, collection, bin monitoring, and IoT reporting. Section IV reports MATLAB-based evaluation and prototype results using standardized plots and summary metrics [5]. Section V concludes the paper and outlines future enhancements such as improved navigation, vision-assisted detection, and larger-scale field deployment. A compact servo-based robotic arm with gripper is mounted at the front to perform pick-and-place operations for lightweight dry litter [6]. The sensing unit includes an IR sensor positioned near the pickup zone to detect the presence of litter and trigger collection actions, and an HC-SR04 ultrasonic sensor mounted on the bin top to estimate the bin's remaining empty space and compute fill level. The

control architecture is split across two embedded controllers: an Arduino handles real-time sensor polling, motor actuation, and arm/gripper sequencing, while an ESP32[8] manages Wi-Fi/IoT data uploading (bin level, alerts, timestamps) and provides Bluetooth manual override when operator control is required. For energy autonomy, the robot is powered by a solar PV panel connected through a charge controller to a rechargeable battery, with regulated power distribution feeding the drive motors, servos, and controllers[9]. This modular structure ensures reliable real-time operation on Arduino, robust wireless connectivity through ESP32, and sustainable outdoor deployment through solar-assisted battery charging [7]. Shows FIGURE 1. Block Diagram of the Proposed Solar-Powered Autonomous Waste Collector with IoT Monitoring.



**Figure 1** Block Diagram of the Proposed Solar-Powered Autonomous Waste Collector with IoT Monitoring.

Table 1 presents the core hardware configuration of the proposed Autonomous Solar Waste Collector, including the solar PV-battery supply, controllers (Arduino and ESP32), sensing elements (IR and HC-SR04), and actuation components (DC motors and servo arm). These specifications define the operating limits of the prototype and provide the parameter values used in the mathematical modelling and MATLAB evaluation [8].

**Table 1 Key Hardware Specifications**

Parameter	Value
PV panel rating	20 W
Battery	12 V, 7 Ah (84 Wh)
Controllers	Arduino + ESP32
Sensors	IR + HC-SR04
Actuation	DC motors + Servo arm
Bin height (Hbin)	25 cm

### 3. Results And Discussion

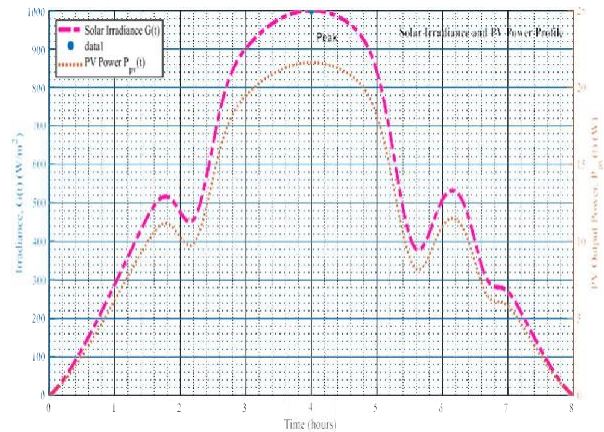
#### 3.1. Results

The Results section contains the design and results of the experiments that were implemented in order to measure the performance of the proposed system. The experimental design involves experimenting with the robot under varying conditions of the environment to examine its capability to sense obstacles, move effectively and collect waste. The system is subjected to real-time[10] sensor feeds especially the ultrasonic sensor which measures the distance and reacts to it. The experiments will be used to check the accurateness, response time, and stability of the control system. The results achieved show that the system can identify the obstacles in the correct way and maneuver through with ease using closed-loop control. The robotic arm is able to perform pick-and-drop functions upon sensor feeds. Tables, pieces of figures and graphical analysis can be used as effective tools to present the research results that demonstrate the accuracy of distance measurement, response time, and efficiency of the system. In general, the performance of the system is stable, and it can comply with the anticipated operation requirements[11].

#### 3.2. Discussion

This section reports the MATLAB R2024a-based evaluation of the proposed Autonomous Solar Waste Collector by presenting nine key outputs that collectively validate energy sustainability, waste detection and collection[13] effectiveness, bin monitoring reliability, and IoT responsiveness. Each figure is designed to map directly to the mathematical

models in Section III and to provide measurable KPIs such as PV harvesting capability, SOC stability, subsystem-level power demand, detection accuracy, pick-and-place timing, bin fill estimation error, status-trigger reliability, alert latency, and comparative benefits over baseline approaches[12].



**Figure 2 Process of The Dataset**

This figure[14] plots the measured/assumed solar irradiance  $G(t)$  and the corresponding PV output power  $P_{pv}(t)$  computed using (1). It highlights how variations in sunlight influence available charging power across time and establishes the renewable energy input conditions under which the robot is evaluated[15].

#### Conclusion

This paper presented the design and evaluation of an Autonomous Solar Waste Collector for Green Spaces that integrates IR-based litter detection, a servo-driven robotic arm for pick-and-place, HC-SR04 ultrasonic bin fill monitoring, and ESP32-based IoT reporting with Arduino real-time control. A compact mathematical model was developed to quantify PV harvesting, battery energy/SOC evolution, subsystem-level power consumption, bin fill estimation, coverage/collection throughput, and end-to-end alert latency. MATLAB R2024a analysis results demonstrated that the proposed system can sustain operation under solar-assisted battery charging while maintaining reliable waste detection and collection cycles. The ultrasonic bin monitoring achieved stable fill-level tracking suitable for dependable “bin full” decision-making, and IoT

alerting ensured timely remote visibility of operational states. Comparative KPI analysis indicated that combining mobility, autonomous pickup, and solar power can significantly reduce manual effort and improve response time compared to manual periodic cleaning and static bin-only IoT approaches, making the proposed platform practical for parks, campuses, and public gardens. Future enhancements will focus on improving robustness, scalability, and autonomy in real outdoor deployments. First, vision-assisted detection (low-cost camera with lightweight CNN/TinyML) can be integrated to improve litter classification and reduce IR false triggers under challenging lighting. Second, autonomous navigation can be strengthened using GPS/IMU fusion, wheel odometry, and obstacle avoidance (ultrasonic/LiDAR) to enable systematic area coverage with fewer missed zones. Third, mechanical upgrades such as a higher-DOF arm, improved gripper design, and adaptive grasp control can increase collection success for irregular objects and wet/soft waste. Fourth, the energy subsystem can be optimized through maximum power point tracking (MPPT) and predictive energy scheduling to maximize operating hours under low-irradiance conditions. Finally, large-scale field trials with long-duration datasets will be conducted to refine KPI benchmarks, and the IoT layer can be extended to multi-robot coordination, cloud analytics, and preventive maintenance alerts for smarter city-wide waste management.

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