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Research Article

A Hybrid Smart Bin Approach to Urban Waste Ecology: Enhancing Public Health and Reducing Ecological Risk via Sustainable Energy and Ozone Sanitation

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Abstract
The objective of this study was to develop and evaluate a hybrid smart-bin system integrating solar power, ozone disinfection, and Internet of Things (IoT)-based monitoring to improve urban waste management at the source. The compact, scalable prototype was designed to operate autonomously using solar energy while reducing waste volume and microbial contamination. Performance tests demonstrated a waste-volume reduction factor of 3.15 compared with conventional waste handling. Following a six-hour solar-powered charging cycle, the system remained operational for 168 h, enabling approximately one week of operation without grid electricity. A 10-min ozone treatment reduced the microbial count to 1.25 ± 0.22 log CFU/mL, representing an approximately six-log reduction relative to untreated waste. These findings highlight the system's potential to reduce waste-collection frequency and landfill demand while improving resource efficiency and minimizing exposure to pathogens, leachate, unpleasant odors, and disease vectors. However, potential reductions in transport-related carbon emissions require further verification through a life-cycle assessment (LCA). A multi-year techno-economic assessment incorporating operating and battery-replacement costs indicated that the projected cash flows were insufficient to recover the initial capital investment of 300,000 THB within a 10-year evaluation period at a 10% discount rate, yielding a base-case net present value (NPV) of approximately −139,000 THB. A positive financial return was achieved only under optimistic assumptions of zero maintenance costs and a service life exceeding 20 years. Therefore, the current justification for deployment rests primarily on the system's observed volume-reduction and microbial-reduction performance and its potential public-health benefits. Achieving economic feasibility will require lower capital costs, higher annual net benefits, or a combination of both.

Keywords: Energy Economics, Hybrid Smart Bin, Internet of Things, Ozone Disinfection, Solar Energy

1 Introduction

From the beginning of the pandemic, the handling of waste with potentially COVID-19-laden contaminants was considered a critical issue. That's because waste from people who are sick or considered at risk could potentially be used to spread the virus [1]. This significant problem must be properly handled to ensure health hazards for the public and medical personnel are avoided. In the risk assessment for health care workers and patients, waste contaminated with COVID-19 was identified as an immediate pathogen threat rather than waste management as traditionally practiced. If improperly disposed of, outbreaks could be triggered within a business or among the general population [2].

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Management of short- and long-term impacts of COVID waste on public health is indispensable. This means that safe, effective, and orderly procedures must be introduced and followed so that the risk to public health is minimized [3]. Multistakeholder collaboration is required for such an issue to be properly and effectively resolved. In hospitals, the management of acquired pathogens and waste was encountered as another major challenge. Because infectious patients were treated in these facilities, there were higher chances of pathogenic spread through waste disposal among workers and service users [4]. Thus, equal attention should be paid to waste and pathogen management in healthcare facilities. By creating this two-pronged approach, the spread of healthcare-associated infections can be controlled, and a safe environment for the medical staff and the public is assured [5].

The dissemination of disease was decisively checked by a series of elaborations of waste management, among which the disinfection of dangerous materials was considered essential. Heat sterilization, chemical sanitizers, or even futuristic technologies are in use or being developed at many hospitals and medical centers to allow the total eradication of pathogens. Through the use of these sophisticated modalities, the infectious potential of agents is neutralised prior to the final disposal of agents [6]. Total adherence to set guidelines and regulations is necessary and can be ensured through the use of dedicated infectious waste bags along with compatible containment systems. Through these structured protocols, appropriate waste handling is ensured, and exposure risks for both disposal personnel and the surrounding ecosystem are successfully minimised [7]. To prevent the transmission of outbreaks and safeguard healthcare delivery, pathogen control and waste management within hospital and healthcare units were deemed strictly necessary. Comprehensive policies and guidelines should be implemented and enforced so that an environment of safety is created for all personnel within healthcare settings. Consequently, the outcomes of provided medical care can be improved, and disease transmission within both the workplace and the community can be significantly reduced. These challenges can only be properly addressed when collaboration is established among all involved parties [8]. Although infectious waste management in organized healthcare systems was addressed adequately, the COVID-19 pandemic revealed the importance of pathogen control in general urban waste on a decentralized and immediate basis. A comparable, but less concentrated, public health threat was generated by contaminated material from homes and public areas, which was usually classified as urban solid waste. Hence, in this study, a hybrid smart bin was proposed that not only reduced the volume of the general municipal solid waste effectively but also performed a pre-collection microbial disinfection (log-reduction) on-site via ozone. This combined functionality is intended to reduce infection risk associated with routine, general municipal solid waste ahead of collection. The target waste stream and validation performed in this study are scoped to general, non-infectious municipal solid waste; the system has not been validated for infectious or healthcare-associated waste, and no such suitability is claimed here.

Thailand's registered population was approximately 66 million at the end of 2022. As a result of increasing population density, the country is now experiencing escalating demand for public utilities, infrastructure, and city services to serve the people [9]. The COVID-19 pandemic, which the World Health Organization treated as a public health emergency of international concern until May 2023, further increased waste generation. Together with sustained consumption, this has produced a large and growing volume of waste. As a result, all communities, cultures, and countries now have to confront this ever-increasing amount of waste. Additionally, the capacity of solid waste management at the municipal level is overstretched, making it imperative to identify sustainable long-term solutions to reduce the environmental consequences [10].

Meanwhile, in 2018, China’s ban on waste imports came into force, and an excess volume of waste was diverted to Thailand. However, this influx was allowed to go unmanaged, as waste management systems were inadequate, resulting in rising pollution, landfills bursting at the seams, and waste pickers being exploited. One channel for shifting the pathway of the recycling industry in Thailand is via the use of mobile platforms. These platforms can reduce intermediaries and transport costs, increase government tax collections, and enhance the revenues and livelihoods of waste pickers. Such a system can contribute to the realization of the Sustainable Development Goals (SDGs) 1 (No Poverty), 8 (Decent Work and Economic Growth), and 12 (Responsible Consumption and Production). So, a more sustainable, efficient, and equitable solid waste management system can be developed [11].

Prior work has separately reported IoT-enabled smart bins for fill-level monitoring and routing [12]–[14], solar-powered waste-handling units, and ozone- or UV-based disinfection systems for waste and agricultural settings [15]. What has not, to the authors' knowledge, been reported is the combination of all three elements — solar-autonomous power, on-site mechanical compaction, and on-site ozone-based microbial reduction — within a single, field-tested, IoT-monitored unit intended for source-level treatment of general municipal solid waste. The present study addresses this gap by developing and field-testing such an integrated system and by reporting, alongside its operational performance, an explicit multi-year techno-economic assessment and a streamlined operation-phase environmental screening, rather than treating cost and environmental performance as secondary claims.

It is worth noting that several alternative technologies exist for managing the organic fraction of municipal solid waste, and that the hybrid smart bin addresses a different stage and function of the waste chain than these. Anaerobic digestion and composting are biological treatment routes that convert source-separated organic waste into biogas/digestate or stabilised compost over days to weeks, and are best suited to centralised or community-scale organic-waste streams rather than mixed general waste at the point of collection. Bioethanol and biodiesel production from lignocellulosic or fat/oil feedstocks, including circular-economy-integrated production routes reported for the Southeast Asian region [16], likewise target valorisation of specific, pre-sorted waste fractions into fuel products, typically requiring dedicated processing facilities; other biomass-waste valorisation routes convert similar lignocellulosic fractions (e.g., sugarcane bagasse) into value-added materials such as carboxymethyl cellulose rather than fuel [17]. In contrast, the hybrid smart bin proposed here operates at the point of waste generation and performs two distinct, immediate functions — mechanical volume reduction and on-site microbial load reduction of mixed general waste — prior to collection, rather than converting waste into a recovered product. The two approaches are complementary rather than competing: source-level compaction and disinfection can reduce collection frequency and transport burden ahead of any downstream anaerobic digestion, composting, or biofuel-conversion step applied to the collected material.

The objective of this work was to conceptualize and realize the hybrid smart bin, which can contribute to diminishing operational expenses, including labor and fuel, by way of in-situ disinfection of waste and its intensive storage. In the proposed scheme, IoT management, solar energy, and ozone-based disinfection are combined to improve efficiency in waste management. In particular, reducing large environmental and public health problems is achieved by reducing waste volume and removing microbial contamination at the source. A powerful, cost-effective approach for reducing the environmental footprint of urban waste systems is offered through a twofold effect: reducing collection frequency and minimizing the quantities of waste to be transported and ultimately disposed of. By reducing the risks associated with contaminated waste and promoting sustainable, environmentally friendly management practices, a contribution is made toward more sustainable urban waste management. Furthermore, alignment is demonstrated with national policies focused on sustainable waste management and pandemic preparedness.

2 Materials and Methods

2.1 *Design of a hybrid smart bin*

A comprehensive methodology focused on core operational challenges and technical prerequisites was adopted for the conceptualization and development of the hybrid smart bin. First, a rough concept pattern was drawn, and then it was converted into a high-fidelity technical pattern by using professional design software, as shown in Figure 1.

Within this architectural framework, a multi-component integration is featured. Sustainable energy capture is achieved via a top-mounted solar panel array, by which power is supplied to the entire system. Mechanical compaction is performed by an electric actuator-driven, highly efficient compactor so as to maximize the volume of the waste portion. At the same time, an internal ozone generator enables automated microbial-load reduction within the bin. For context, a commercial ozone generator of the class used for room- or enclosure-scale disinfection is rated at 15 g/h of ozone, with a rated concentration of 15–20 mg/L and a power draw of 120 W [18]. The output concentration, gas flow rate, and leakage safeguards of the generator installed in this prototype were not measured in this study, and the resulting in-bin dose during the 1–10 min

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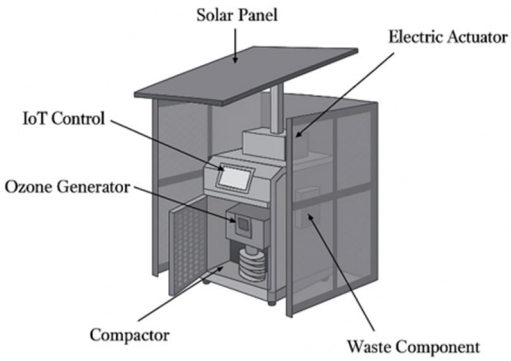


Figure 1: Model design of a hybrid smart bin.

treatment periods described below is therefore not reported (Section 3.5). Because the OSHA 8-hour permissible exposure limit for ambient ozone is 0.1 ppm, these quantities should be characterised before any public-facing deployment. The synchronization and real-time monitoring of these subsystems are entirely managed via an advanced IoT control interface, through which operational efficiency and data acquisition are optimized (Figure 1).

2.2 *Construction of the hybrid smart bin*

The construction process involved assembling the steel framework, cutting, and welding the steel based on the design model of the hybrid smart bin. The completed structure was shown in Figure 2. Thereafter, the system was established using a solar cell package that included a 12V to 220V 3000W inverter, a PV panel, power connectors, terminals, breakers, and a 12/24V 30A charge controller. Within a 17 x 30 x 46 cm weatherproof steel cabinet, the equipment was put together and connected for instant use. The cabinet has MC4 connectors, battery clamps, a cigarette lighter outlet, and four USB ports. The system comprised a 340 W solar panel (mounted on the roof of the bin), a 50 Ah lithium battery, and a solar charge controller. An IoT control system and an ozone system were also installed. Figs. 3 through 5 explain the installation procedure, and Fig. 6 shows the hybrid smart bin prototype. The hybrid smart bin was governed via the eWeLink application and IoT control system. The real-time reporting of key performance indicators to a centralized cloud platform was enabled by the IoT suite. Because this cloud reporting channel carries operational and location-linked data, data-privacy and integrity safeguards for the cloud-connected IoT layer (e.g., secure data-auditing schemes for cloud-based IoT environments [19]) are an important design consideration and are noted here as an area for further specification rather than a validated feature of the current prototype. The IoT system monitored and reported the battery (voltage/charge level), the ozone system (e.g., ON/OFF status, period of operation), and the waste level using built-in sensors. The app interface for the user and provider was provided by the eWeLink app, which enabled remote real-time monitoring of the running status of the system and time control of the process of ozone-based disinfection. This enabled automated operation of the bin.

To initiate the operation of the solar-powered, IoT-managed system, the installation of the eWeLink application is required as the preliminary step. After the installation is successful, a new user account must be registered, through which access to the platform is subsequently gained via the sign-in interface. To evaluate the operational efficiency of the system, the duration of ozone emission is systematically examined in proportion to the battery capacity. This evaluation is commenced utilising a battery that has been fully charged via solar energy, allowing the correlation between energy storage and disinfection performance to be accurately determined (Figure 2 – Figure 6).



Figure 2: Hybrid smart bin structure (pre-assembly).

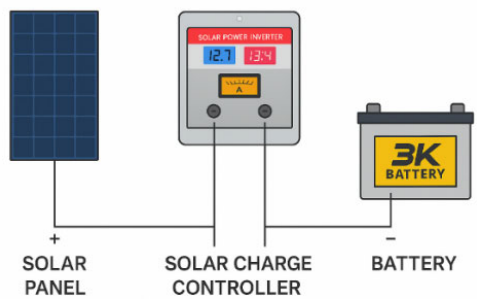


Figure 3: Configuration of the solar cell system.

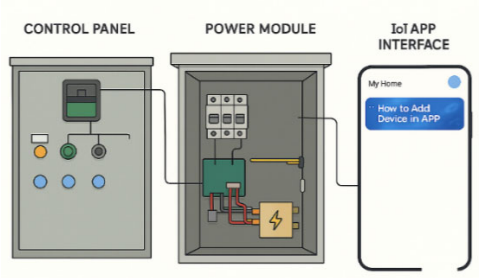


Figure 4: IoT system suite for the development of a hybrid smart bin.



Figure 5: Ozone system suite for the development of a hybrid smart bin.



Figure 6: Final prototype of the hybrid smart bin**.**

2.3 *Performance testing of the developed hybrid smart bin*

2.3.1 Evaluation of the waste compression system

To evaluate the mechanical efficiency and structural integrity of the waste compression system, mechanical activation of the internal waste compactor was initiated by applying physical pressure onto the designated foot pedal area. The pedal input activated the electric actuator, which pushed the compactor plate downward into the waste storage bin. The compression procedure was carefully monitored by measuring the motion of the waste matrix before and after a compression cycle, in terms of linear displacement. The initial height of the waste is non-compacted (h_0), and the compressed waste's final height (h_f) is measured with a built-in digital distance sensor. From these measurements, the volume reduction (%) was calculated as $(h_0 - h_f)/h_0 \times 100$ and the compaction ratio as h_0/h_f, assuming a constant cross-sectional area [20]-[25].

2.3.2 Ozone disinfection efficiency and microbial sampling

In order to have a quantitative measure of the total culturable microbial load in the hybrid smart bin, a scheduled ozone emission was executed to study the depletion kinetics and the total population of the microbial community at a series of time points. Since ozone (O_3) is a strong oxidant that can penetrate and damage microbial cell walls [26], the internal generation system was set to release the gaseous ozone at five different time points (1, 3, 5, 7, and 10 min), consistent with the sampling points reported in Section 3.2.2. Each treatment was applied as a single continuous exposure of the stated duration, allowing gas penetration into the waste matrix. Temperature and relative humidity at the bin level were monitored and maintained constant, as these parameters influence ozone stability and half-life. At the end of each exposure period, the waste was sampled aseptically from several standardized depths within the bin using sterile forceps, and the treated samples were placed into sterile containers. The harvested specimens were plated for total microbial counts on nutrient agar (NA) (nutrient broth, NB, was used for enrichment; Section 2.3.3), and log-reduction survival curves were constructed from the counts [27]-[32].

2.3.3 Preparation of microbiological media

NA was used as the solid culture medium for isolation and bulk recovery of heterotrophic bacterial colonies. To prepare a homogeneous batch of this medium, 5 g of peptone (a source of nitrogen and amino acids), 3 g of beef extract (a source of carbon and vitamins), and

15 g of agar (the solidifying agent) of the powdered components were precisely measured, and the mixture was suspended in 1,000 mL of distilled water in a borosilicate glass beaker for the preparation of the formulation. Continuous stirring was performed mechanically until a homogeneous suspension was obtained. In order to achieve full dissolution and hydration of the agar molecules, the combination was heated following a controlled microwaving protocol. A full thermal dissolution was kept as a vital QC indicator, as an incomplete breakdown of the gelling agents is known to cause chemical heterogeneity, and therefore the finalized agar plates or tubes may be either too soft or too rigid, both of which are reported to inhibit the growth of bacterial colonies optimally. The pH of the molten medium was measured using a calibrated digital pH probe and was adjusted to a neutral physiological value of 7.0 ± 0.2 with the addition of either 0.1 M HCl or 0.1 M NaOH dropwise after visual and thermal confirmation of complete dissolution, and the temperature was verified [17], [26], [33].

NB was prepared by a similar method as described above for the solid medium and used as a liquid medium for the primary enrichment of the microbes and for studies on their physiology. The dehydrated peptone (5 g) and beef extract (3 g) were dissolved in 1,000 mL of distilled water, without adding agar. The liquid mixture was dispensed into 9-mL portions in test tubes that were then stoppered with cotton plugs and covered with a layer of aluminum foil. The pH of the medium was verified and adjusted to 7.0 ± 0.2, and the material was then taken through final sterilization by autoclaving at 121 °C for 15 min. After sterilization, the liquid was allowed to cool to room temperature before use. For subsequent analysis, these sterilized broth tubes were stored at 4°C in a dark place to prevent biochemical degradation.

2.3.4 Serial dilution and microbial enumeration

In order to measure the exact microbial load and assess the log reduction imparted by the smart bin, collected waste samples were subjected to a serial ten-fold dilution series inside a Class II biosafety cabinet following all aseptic procedures. One 10 g aliquot of the homogenized waste sample was weighed on an analytical balance and placed in a sterile, heavy-duty stomacher bag. To the bag were added 90 mL of sterile 0.1% peptone water to release the entrapped bacteria from the solid waste material into the liquid. Mechanical blending & homogenization were done using a Stomacher lab blender (Seward Ltd., UK) for 30 s at a standardized speed to produce an initial suspension (designated Tube 1) of 1:10 (10^{-1} dilution). Then 1 mL of supernatant from Tube 1 was accurately pipetted out using a calibrated micropipette with a sterile tip and was transferred into Tube 2 containing 9 mL of sterile 0.1% peptone solution, making a 1:10 suspension (10^{-2} dilution) under aseptic conditions. The bacterial suspension was vortexed at high speed for 15 s to mix well. The serial dilution technique was used again in a successive fashion for the following tubes until it arrived at the 9th tube with the final dilution of 10^{-9}; this was to prevent high-density microbes from overgrowing the culture plates.

After preparation of the entire serial dilution series, 0.1 mL aliquots of each of the desired dilution tubes were plated on the surfaces of the nutrient agar plates that were prepared already. The liquid sample was spread on the surface of the agar using an L-shaped sterile glass rod, rubbing the surface of the agar after flaming and cooling before and after use to avoid cross-contamination. Plates were then inverted and transferred to a digitized incubator and incubated for a maximum of 24 h at an optimal physiological temperature of 37 °C. Following incubation, the bacterial colonies were viewed and counted with the aid of a computerized digital colony counter. Only plates showing colony counts in the statistically valid and dependable range of 30 to 300 colonies were used for further mathematical analyses, since plates outside this range are subject either to artifacts of overpopulation or to statistical insignificance. The final microbial contamination levels and the efficacy of the ozone treatment were expressed quantitatively as log colony-forming units per millilitre (log CFU/mL) of the initial suspension (Tube 1), calculated from the first term of Equation (1), in which the dilution factor refers to the plated tube relative to the initial suspension. Multiplying by the final term of Equation (1) (90 mL/10 g) converts the result to CFU per gram of waste.

$$\mathrm{CFU/mL} = \frac{\text{Number of Colonies}}{\text{Volume Plated (mL)} \times \text{Dilution Factor}} \times \frac{\text{Total Volume of Diluent (mL)}}{\text{Sample Weight (g)}} \quad (1)$$

2.4 *Evaluate the economic feasibility of investing in a hybrid smart bin*

To assess the financial viability and long-term economic sustainability of investing in the hybrid smart bin, a comprehensive multi-year discounted cash-flow evaluation was conducted. The financial results of the investment were estimated consistently by calculating the Net Present Value (NPV) over the operational life of the project and the total profit of the project. The NPV is computed using the standard financial formula given in Equation (2).

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \quad (2)$$

Where:

C_0 = Initial investment
C_i = Net cash flow in year i
r = Discount rate
T = Time period (project lifespan)

Concurrently, the capital recovery timeline was established by calculating the payback period, which determines the exact number of years required for the accumulated net annual cash flows to equal the initial capital outlay. In this analysis, the annual income was the net income after corporate tax, depreciation of assets, and interest on finance. The payback period was calculated by using the following equation (3).

$$\text{Payback Period} = \frac{\text{Initial investment}}{\text{Net annual cash flow}} \quad (3)$$

A meaningful NPV, IRR, and payback assessment requires a full project lifetime with explicit operating and component-replacement costs, rather than a 3-year cash-flow snapshot (see Section 3.3 for the underlying derivation). The model below extends the reported Year 1–3 annual cash flows (25,000 / 30,000 / 35,000 THB, taken as reported and treated here as gross, i.e., before O&M) over an assumed 10-year evaluation horizon, and explicitly separates the following cost and revenue components rather than reporting only a single net figure: (i) capital cost (C_0 = 300,000 THB, as reported); (ii) annual gross revenue/cost-avoidance, held constant at the Year 3 level (35,000 THB/year) for Years 4–10 in the absence of further reported data (a conservative, explicitly labelled no-growth assumption); (iii) annual operation-and-maintenance (O&M) cost, assumed at 2% of capital cost per year (6,000 THB/year), an engineering assumption at the upper end of the 1–2% of installed capital cost per year commonly assumed for small-scale solar PV systems [27]; (iv) battery replacement cost, set at 8,600 THB every 8 years, consistent with the lithium chemistry stated in Section 3.4. This figure is based on a Thailand retail price for a comparable-capacity (12.8 V, 50 Ah, ≈640 Wh) $LiFePO_4$ battery [28]; the 8-year interval is a conservative assumption relative to the rated 4,000+ cycles at 100% depth of discharge [29] and the 10–15-year life generally quoted for lithium solar batteries [24], [34]; and (v) salvage value, conservatively set to zero at the end of the evaluation horizon given the undeveloped resale market for used small-scale solar-IoT waste-management hardware. Items (ii)–(v) are engineering/literature-based assumptions, not measured data, and are labelled as such throughout.

In addition to NPV and the simple payback period (Equations 2–3), the Internal Rate of Return (IRR) — the discount rate r* that sets NPV to zero — was solved numerically from Equation (2), and a discounted payback period was additionally calculated as the first year in which the cumulative discounted cash flow becomes non-negative, i.e., the smallest T for which $\sum_{i(0,T)} C_i/(1+r)^i \geq 0$. Unlike the simple payback period, discounted payback accounts for the time value of money and is therefore the more conservative and defensible capital-recovery metric for this comparison. A one-way sensitivity analysis was subsequently performed on the discount rate, project lifetime, O&M rate, and battery replacement cost/interval, and post-Year-3 cash-flow growth (Section 3.3, Table 3) to bound the result given the assumptions introduced.

2.5 *Streamlined operational use-phase carbon & energy screening of the hybrid smart bin system*

A streamlined operation-phase life cycle assessment (LCA) was conducted in parallel with the technical and economic evaluation, using the same goal and scope, inventory and impact-assessment approach of the general LCA framework, as previously applied to bins [35] and to carbon-footprint accounting in Thai industry [25]. The functional unit was determined as 1 smart bin unit with an autonomous duty cycle (7 Days or 168 Hours), which is the same as the field-tested prototype. Rather than a complete cradle-to-grave inventory of the hardware, a streamlined-boundary approach recommended for distributed, solar-powered IoT deployments was adopted [30],

[36]-[38]. The system boundary was restricted to the use phase of the bin and comprised two subsystems: the solar–battery energy subsystem (340 W monocrystalline panel tilted 15° south, charging the battery over a single 6-hour period centred on solar noon, with peak irradiance between 11:00 AM and 1:00 PM); and the ozone-based sanitation subsystem. The life-cycle inventory parameters that are used as inputs for the model are summarized in Section 3.4. Two outcome indicators were monitored that were proxies for downstream environmental and public-health impact: (i) the waste-volume reduction ratio accomplished by the compaction subsystem, as an indicator of avoided landfill burden and associated transport- and leachate-related emissions, and (ii) the microbial log-reduction accomplished by the ozone subsystem, as an indicator of avoided microbial-transmission risk. This reduction-based logic would be similar to a recent comparative life cycle assessment of smart and sensor-enabled waste collection systems where route optimization and automated monitoring were demonstrated to reduce impacts on global warming potential and resource depletion by approximately 46% (45.7% for global warming potential) compared with conventional waste collection [31]. The figures reported here are unit-level emissions and should be understood as first-order environmental screening rather than as fully quantified midpoint impact categories (e.g., kg CO_2 eq or DALY) and are not a full cradle-to-grave LCA, but a prototype, a single decentralized unit.

3 Results and Discussion

3.1 *Operational outcomes and environmental impacts of the hybrid smart bin*

The developed hybrid smart bin integrates an IoT sensing suite and an automated compaction mechanism. The PV module is installed on the roof of the bin, which avoids grid electricity use and the associated fossil-fuel emissions (quantified for the operation phase in Section 3.4). The IoT-managed monitoring platform is intended to reduce localized waste buildup. This is intended to help limit the local buildup of microbial vectors within the enclosure, contributing to a safer surrounding environment; pathogen-specific field validation is required before broader public-health claims can be made. In addition, the system is intended to help reduce reliance on fossil-fuel-powered collection and the associated risks of traditional waste handling, though this has not been separately quantified here.

The system combines automated monitoring with local waste-volume reduction as a proposed contribution to municipal waste management and urban environmental protection. The smart integrated trash bin is specially designed for high pedestrian traffic, maximizing convenience in the waste-collecting process. Reducing the volume of solid waste awaiting collection is intended to lower the opportunity for local disease transmission, though this link has not been directly measured in this study. This reflects the combined action of the ozone generator and the IoT interface, which together are intended to reduce the viable microbial count within the bin itself, rather than sanitizing the surrounding urban space more broadly. In the past, a similar technical approach was implemented with the development of a specialized decontamination platform based on IoT architecture, robotic array, ozonizer (O_3), and ultraviolet light (UVL) to successfully disinfest chicken farms of mites, insects, and pathogenic microorganisms in aviary systems [15]. A working prototype of the hybrid smart bin was developed and field tested, as shown in Figure 7. These preliminary performance tests indicate that the system may be a promising approach to help mitigate biohazard risk, support public health, and facilitate more sustainable waste management, pending further field-scale and pathogen-specific validation. This approach is intended to align with long-term global sustainability goals and environmental protection objectives by offering a more environmentally friendly waste-disposal option, though epidemiological safety claims would require dedicated field validation beyond the scope of this study.

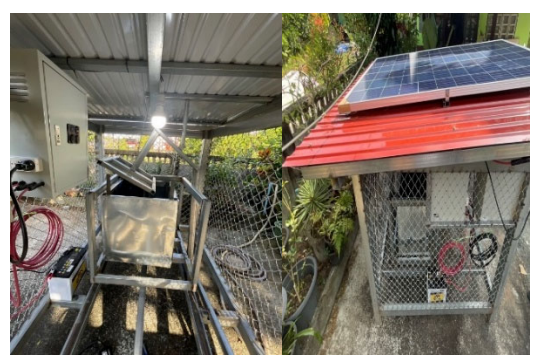


Figure 7: Operational hybrid smart bin in use.

3.2 *Results of performance testing for the developed hybrid smart bin*

3.2.1 Solar energy harvesting and system autonomy

For the assessment of operational efficiency of the PV subsystem, one monocrystalline 340 W solar panel was used. The solar irradiance for a whole-day cycle was obtained by tilting the solar panel 15° to face south. The maximum power was obtained during this stage of experimental verification under clear skies, with approximately 2 h per day of peak-irradiance exposure (11:00 AM–1:00 PM) feeding the battery through the solar charge controller. The integrated system, including the ozone unit, ran autonomously for 168 hours (one week) on a single charge without grid input. In a demonstration at the field scale, a charging block of approximately 6 hours was sufficient to fully charge the storage battery and ensure system reliability for a full week of fully automated operation, consistent with the charging cycle reported in the energy-balance derivation.

Charging the battery (approximately 600 Wh at 12 V) within 1 hour would require an average charging power of approximately 600 W, which exceeds the 340 W rated output of the panel. A 6-hour charging period is therefore the physically realistic case; it corresponds to an average delivered power of approximately 100 W, or 29% of the panel's rated capacity, which is plausible given variations in solar irradiance, panel orientation, and charge-controller efficiency.

3.2.2 Quantitative microbial inactivation and ozone efficacy

A marked decrease in total bacterial load was found for the ozone-treated waste samples relative to the untreated control baselines. Especially under the smart containment unit after 10 min exposure, a near 6-log reduction of bacterial viability was obtained. In order to systematically describe these disinfection dynamics, sampling was done strategically along the X axis of Figure 8 for microbial analyses. The following parameters were evaluated and included an untreated control and then exposure times which were increased by 1, 3, 5, 7 and 10 min. The greatest cumulative reduction in microbial count was observed at the final 10-minute time point. The targeted microbial community was defined as the culturable heterotrophic microbial load typically present in general municipal solid waste, assessed via total plate counts rather than identification of specific pathogens.

3.2.3 Waste detection and classification (conceptual extension)

Beyond the compaction and disinfection functions reported above, the hybrid smart bin concept also envisages automated waste detection and material classification, intended to further improve sorting efficiency and reduce localized accumulation. To this end, two standardized benchmark datasets called "detect-waste" and "classify-waste" were identified as the basis for a proposed classification approach. As currently described, the physical prototype's IoT suite is based on the eWeLink application together with ultrasonic and battery sensors, with no camera or edge-AI hardware reported; this classification approach should therefore be read as a conceptual extension for future work rather than a demonstrated feature of the built system. In both repositories, the setups of several open datasets are combined and consolidated for the most important categories of municipal waste: organic, glass, metal, plastic, non-recyclables, paper, and unspecified waste. Thus, the training algorithms and analytical analysis of the computer vision models used for garbage identification have been greatly enhanced [20]. Prior work combining such datasets has reported improved training and validation performance for garbage-identification computer-vision models in general [21]; however, as noted above, this capability has not itself been implemented or tested on the physical prototype described here, and no claim is made that biohazard risk, infection spread, or hospital-derived infection vectors have been reduced by the present system through this mechanism.

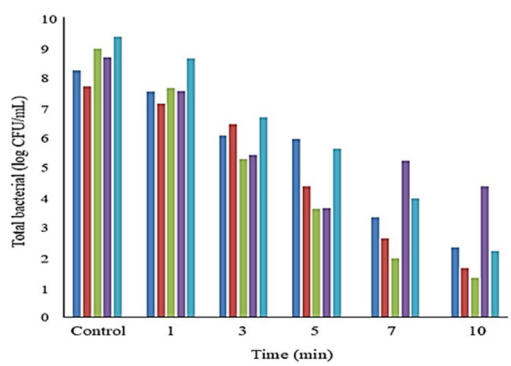


Figure 8: Total bacterial count (log CFU/mL) in waste samples over time after ozone treatment using the hybrid smart bin.

3.3 *Economic feasibility assessment of the developed hybrid smart bin system*

NPV is calculated as the net monetary value: Cash inflow over the future expected life of the project minus all of the initial investment and operating costs. If the NPV is positive, the project is expected to add value, whereas if the NPV is negative, then the project is economically non-feasible [22]. The summary of the cash-flow model is shown in Table 1, which was calculated for 10 years with explicit operating costs, battery replacement costs, and a baseline discount rate of 10% (see Section 2.4); the base-case NPV is negative (–139,043 THB), and the Profitability Index (PI = present value of inflows/capital cost) is 0.54. The Internal Rate of Return (IRR), the discount rate that sets the NPV of the project to zero, was solved iteratively. A full cash-flow model with explicit operation-and-maintenance and battery-replacement costs over the project life is needed for the IRR and payback period to be meaningful, as opposed to three-year net cash-flow figures alone.

In the previous research, similar optimizations for logistics were described, such as an integrated IoT-based smart bin allocation system for solid waste management, which works with an upgraded truck routing algorithm and Central Monitoring System (CMS). In this context, a penalty-based concept for waste management authorities not collecting the bins in time was proposed for the period limitation, and an intelligent Variable Neighborhood Search with Ant Colony Optimization (VNS-ACO) was proposed to overcome the routing inefficiency [12]. In addition, a prototype for a smart waste separation bin using the IoT was designed to reduce costs for the waste separation process. In the above-mentioned contest, three concepts came up as winners, which showed that the costs for labor and administration could be drastically cut down through IoT-based setups, among which were spectroscopic analysis, image processing, and sensory technologies [13]. Finally, by optimizing integrated smart bins with advanced data analytics, operational efficiency is improved, and the overhead costs are minimized [14].

More broadly, recent IoT research relevant to a deployed, cloud-connected bin such as this one includes lightweight edge-based anomaly and integrity detection for consumer IoT devices [34], IoT-assisted real-time sensor-based recommendation systems in other application domains [35], and reinforcement-learning-based caching strategies for information-centric IoT networks [36], all of which point to directions for hardening and scaling the present system's IoT layer in future work.

Evaluating only the reported Year 1–3 cash flows at a 10% discount rate gives a cumulative net present value of –226,183 THB (Table 2, first row; reported cash flows without O&M) — a partial-horizon figure,

Table 1: 10-year net cash-flow model for the hybrid smart bin system (discount rate = 10%; capital cost = 300,000 THB). Years 1–3 use the cash flows reported in the original data; Years 4–10, O&M, and battery replacement are engineering/literature-based assumptions (see Section 2.4 and Table 2).

Year	Gross CF (THB)	O&M (THB)	Battery repl. (THB)	Net CF (THB)	PV @10% (THB)	Cumulative nominal (THB)	Cumulative PV (THB)
0	–	–	–	–300,000	–300,000	–300,000	–300,000
1	25,000	6,000	0	19,000	17,273	–281,000	–282,727
2	30,000	6,000	0	24,000	19,835	–257,000	–262,893
3	35,000	6,000	0	29,000	21,788	–228,000	–241,104
4	35,000	6,000	0	29,000	19,807	–199,000	–221,297
5	35,000	6,000	0	29,000	18,007	–170,000	–203,290
6	35,000	6,000	0	29,000	16,370	–141,000	–186,921
7	35,000	6,000	0	29,000	14,882	–112,000	–172,039
8	35,000	6,000	8,600	20,400	9,517	–91,600	–162,522
9	35,000	6,000	0	29,000	12,299	–62,600	–150,223
10	35,000	6,000	0	29,000	11,181	–33,600	–139,043

Base-case result: NPV = –139,043 THB; IRR = not economically meaningful (nominal inflows of 266,400 THB do not recover the 300,000 THB outlay even before discounting); simple and discounted payback are not reached within the 10-year horizon. See Section 3.3 for the full derivation, bounding scenarios, and sensitivity analysis.

not a completed project valuation. Even under the most generous idealisation, in which the Year 3 cash flow (35,000 THB) continues unchanged as an infinite annuity with no further capital cost, the maximum attainable present value of future inflows at a 10% discount rate is 336,777 THB (Equation 4), i.e., an NPV of +36,777 THB against the 300,000 THB capital cost, before any O&M or replacement costs.

$$PV_{max} = CF_1/(1+r) + CF_2/(1+r)^2 + CF_3/(1+r)^3 + (CF_3/r)/(1+r)^3 \quad (4)$$

Where $CF_{1..3}$ are the reported Year 1–3 cash flows (25,000 / 30,000 / 35,000 THB), r = 10%, and the final term is the present value, at Year 3, of an infinite annuity equal to the Year-3 cash flow continuing unchanged forever — the most generous possible idealisation of "cash flow never declines and never stops." Solving Equation (4) gives PV_{max} = 336,777 THB. A meaningful NPV and IRR therefore require the full multi-year cash-flow model developed below, which incorporates a realistic project horizon together with ongoing operating and replacement costs.

Table 1 rebuilds the cash-flow model over a 10-year evaluation horizon with explicit O&M and battery-replacement costs (Section 2.4). Under this base case, nominal inflows over 10 years (266,400 THB) do not even recover the 300,000 THB capital outlay before discounting, so the base-case NPV is negative (–139,043 THB at 10%) and the IRR is not economically meaningful. Table 2 summarizes this base case alongside three bounding scenarios: the as-reported 3-year horizon (mirroring the original data, NPV = –226,183 THB), a moderate case that omits the battery-replacement cost (NPV = –135,031 THB), and an optimistic upper-bound case (zero O&M, zero replacement cost, and an extended 25-year service life — still longer than the 8–10-year lithium battery life used in the base case [28], [29], [33]) that reaches a marginally positive NPV of +4,473 THB (IRR ≈ 10.2%, discounted payback ≈ 23.7 years). Even this best-case bound requires 9.0 years for simple payback and 23.7 years for discounted payback (Table 2); the base-case discounted trajectory is shown in Figure 9. In short, at the reported cash-flow magnitude, the investment is not attractive under standard assumptions and only approaches breakeven under an unrealistically favourable, cost-free, multi-decade scenario.

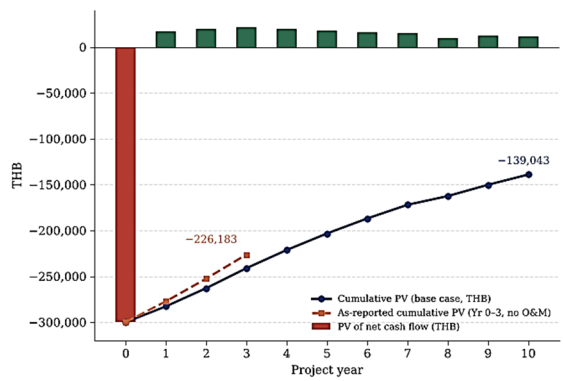


Figure 9: Discounted cash flow and cumulative net present value of the hybrid smart bin investment over a 10-year evaluation horizon (discount rate = 10%; includes O&M and battery-replacement costs). The dashed line shows the as-reported cumulative PV for Years 0–3 (no O&M) for comparison.

Table 2: Techno-economic indicators for the hybrid smart bin system: base case and bounding scenarios.

Scenario	Horizon (yr)	O&M	Battery repl.	NPV (THB)	IRR	Simple payback	Discounted payback
As-reported (Yr 0–3 only, no O&M)	3	–	–	–226,183	–41.1%	not reached	not reached
Base case	10	2%/yr	8,600 THB /8 yr	–139,043	not meaningful*	not reached	not reached
Moderate (no battery replacement)	10	2%/yr	none	–135,031	–1.5%	not reached	not reached
Optimistic upper bound	25	0%	none	+4,473	≈10.2%	9.0 yr	23.7 yr

*Nominal inflows (266,400 THB) are below the 300,000 THB outlay, so no economically meaningful positive discount rate solves NPV = 0; the numerically closest root is a negative rate (≈ –2.1%), reflecting a nominal capital shortfall rather than a rate of return.

Table 3: One-way sensitivity of the base-case NPV (THB) to the major uncertain TEA assumptions.

Assumption varied	Low case	Base case	High case
Discount rate (8% / 10% / 12%)	–123,600 (8%)	–139,043 (10%)	–152,531 (12%)
Project lifetime (5 / 10 / 15 yr)	–203,290 (5 yr)	–139,043 (10 yr)	–96,659 (15 yr)
O&M rate (0% / 2% / 4% of CAPEX)	–102,175 (0%)	–139,043 (2%)	–175,910 (4%)
Battery replacement (0 / 8,600 / 17,200 THB, 8-yr interval)	–135,031 (0 THB)	–139,043 (8,600 THB)	–143,055 (17,200 THB)
Gross-CF growth after Yr 3 (0% / 5%/yr)	–139,043 (0%/yr)	– (base uses 0%)	–113,582 (5%/yr)

Table 3 summarizes the one-way sensitivity analysis. Across every one-way variation tested — including a discount rate as low as 8%, an O&M cost as low as 0%, and gross cash-flow growth of 5%/year — the NPV remains negative within a 10-year horizon. Extending the lifetime to 15 years leaves the NPV at –96,659 THB (–72,213 THB at 20 years under the same assumptions); breakeven is approached only in the optimistic bound in Table 2, which combines zero O&M, no battery replacement, and a 25-year life. The single most influential lever is project lifetime, followed by the O&M rate; the discount rate and battery-replacement cost have comparatively minor effects. This indicates the economics are structurally constrained by the ratio of annual net benefit to capital cost, rather than by any single assumption, and cannot be fixed by adjusting the discount rate alone. The 10% discount rate itself is consistent with rates typically applied in small-scale solar PV project evaluations [33]-[37], so the shortfall documented here reflects the cash-flow-to-capital-cost ratio rather than an unusually conservative discount assumption.

3.4 *Streamlined operational use-phase carbon and energy screening results for the hybrid smart bin system*

Table 4 summarises the operational parameters used as input to the streamlined LCA model described in Section 2.5, and the two headline outcome indicators. A 340 W panel tilted 15° south to match the local peak-irradiance window (11:00 AM to 1:00 PM) charged a 50 Ah lithium battery that supported 168 hours of autonomous operation, an energy-input-to-service-time ratio suited to a distributed, off-grid unit of this size [30]. The compaction subsystem reduced the volume of waste 3.15-fold (equivalent to a volume reduction of about 68%), and a 10-minute ozone exposure reduced the microbial load by about 6 logs (Figure 10). The bactericidal action of gaseous ozone is well documented [32], [38]; however, the reduction possible in a field waste matrix (as opposed to a controlled laboratory suspension) will depend on the organic loading, humidity, and ozone diffusion path.

Table 4: Life-cycle inventory parameters and outcome indicators for the hybrid smart bin system.

Parameter	Data
Solar panel capacity	340 W
Battery capacity	50 Ah
Solar charging period	6 hours
Autonomous operation	168 hours (7 days)
Waste-volume reduction	3.15-fold
Ozone exposure	10 min
Microbial reduction	≈ 6-log
Solar panel tilt	15° south
Peak solar exposure	11:00 AM–1:00 PM

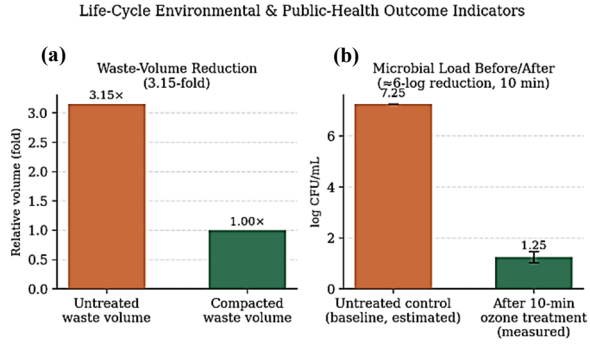


Figure 10: Life-cycle environmental and public-health outcome indicators: (a) waste-volume reduction achieved by the compaction subsystem; (b) microbial load before and after a 10-minute ozone treatment cycle (baseline back-calculated from the reported ≈6-log reduction and is shown as an estimate, not an independently measured value).

A first-order energy balance and an illustrative estimate of avoided emissions can also be obtained from Table 4 inventory parameters (Table 5). These are calculations that are based on reported parameters as well as two explicitly labeled assumptions (a 12 V nominal battery voltage, consistent with the 12 V inverter and charge controller described in Section 2.2, and Thailand's official grid emission factor of 0.475 $kgCO_2e/kWh$, for organizational Scope 2 accounting [39], used as a counterfactual grid-electricity baseline) and are reported as derived/illustrative indicators rather than independently measured quantities.

These values show that the reported 340 W panel power, 50 Ah battery, and 6 hours charge/168 hours autonomy are consistent with a physically plausible duty-cycled load at low average power (not necessarily the power of the ozone generator or actuator, but rather an internally consistent set that should be confirmed directly; e.g., using the current logged by the charge controller, or the ozone generator's datasheet rating). The avoided-emissions estimate is a small, per-unit, operational-phase indicator only; it does not include embodied emissions from panel and battery manufacturing, transport or end-of-life disposal, which cannot be done without a full cradle-to-grave inventory (e.g., using a secondary LCI database) and should be considered as future work for all fleet-scale environmental claims. Here, the waste-volume reduction ratio (3.15-fold) is reported as an LCA-relevant proxy for avoided landfill burden in a manner similar to that done in Section 2.5, while the microbial log-reduction (≈6-log) is reported only as a disinfection-efficacy-measured indicator and not as evidence of complete elimination or sterilization of pathogens. Taken together, the LCA screening and TEA results suggest a nuanced picture: the environmental and public-health performance of the hybrid smart bin (reduction in waste volume, measured ≈6-log reduction in microbial load, and an energy source that is not grid-electric but is renewable) is well-supported by the reported and derived data, however, this performance is not yet matched by a positive investment return at the scale of capital costs and cash flows reported in Section 3.3. That is not unusual, however, for the early-stage, decentralized IoT-enabled infrastructure reported elsewhere in the literature, since the environmental and operational benefits are most often proven before a fully mature, cost-optimized supply chain makes the economics competitive [31]; but it does mean that economic feasibility claims for this system should be lowered until either a lower per-unit capital cost or a longer-lived battery chemistry is achieved, or additional revenue/cost-avoidance streams are independently verified. To make any comparative or fleet-scale claim, a full cradle-to-grave LCA (including end-of-life treatment of the electronics) and a longer, field-validated TEA horizon should be undertaken.

Table 5: Derived energy balance and illustrative avoided-emissions estimate for the hybrid smart bin (assumptions labelled).

Quantity	Value	Basis
Usable battery energy (50 Ah × 12 V nominal)	600 Wh	Derived; 12 V nominal system voltage (a 12.8 V $LiFePO_4$ pack would give 640 Wh)
Average delivered charge power (600 Wh / 6 h)	100 W	Derived from reported charging period
Panel utilisation ratio (100 W / 340 W nameplate)	≈29%	Derived; plausible given non-STC irradiance, tilt, and controller losses, but not independently verified against logged irradiance data
Average continuous system load (600 Wh / 168 h)	≈3.6 W	Derived; consistent with an intermittently duty-cycled ozone/actuator load rather than continuous full-power draw
Weekly energy delivered per unit (one full charge)	0.6 kWh/wk	Derived from battery capacity
Annual energy delivered per unit (×52 wk)	≈31.2 kWh/yr	Derived; assumes full weekly utilisation year-round
Illustrative avoided grid CO_2e (vs. an equivalent grid-powered unit)	≈14.8 $kgCO_2e$/yr per unit	Derived using TGO grid emission factor (0.475 $kgCO_2e/kWh$) [39]; excludes panel/battery manufacturing, transport, and end-of-life emissions

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3.5 *Limitations*

This study has several limitations that should be considered when interpreting the results. (i) A single prototype unit was fabricated and field-tested; performance figures reported here have not yet been replicated across multiple units, seasons, or waste-stream compositions. (ii) The 168-hour solar autonomy claim is based on a single clear-sky field trial and has not been confirmed across multiple weather conditions or seasons. A full charge in 1 hour would require the 340 W panel to deliver an average of 600 W (176% of rated output), which is not physically achievable, whereas the 6-hour charge used here corresponds to a realistic 100 W average (29% of rated output). (iii) The actual gaseous ozone concentration/dose (ppm or mg h^{-1} output), gas flow rate, and chamber volume were not directly measured or reported; the ~6-log microbial reduction is therefore reported as a disinfection-efficacy indicator rather than a fully characterised dose-response relationship. (iv) Ambient ozone leakage risk and containment design (e.g., an ozone-destruct catalyst such as MnO_2, or an automatic lid-interlock relay preventing exposure when the lid is opened during or immediately after a sanitisation cycle) were not characterised in this study and should be confirmed and reported before public deployment, given the OSHA 8-hour exposure limit of 0.1 ppm for ambient ozone and the public-facing deployment context. (v) The battery chemistry is lithium ($LiFePO_4$) throughout, and the techno-economic replacement-cost assumption is 8,600 THB every 8 years, a Thailand retail benchmark for a comparable-capacity unit [28] with a rated life of 4,000+ cycles [29], [40]-[41]. As with all TEA inputs, this is a literature/retail benchmark rather than a project-specific vendor quote and should be replaced with an actual quote if available. (vi) Microbial characterisation was limited to culturable heterotrophic counts on nutrient agar/broth and does not identify organisms to species level; the treated waste stream is best regarded as general, non-infectious municipal solid waste rather than infectious or healthcare-associated waste, for which no validation has been performed. (vii) The waste detection and classification approach ("detect-waste"/"classify-waste" and computer-vision classification; Section 3.2.3) is a conceptual, literature-based extension and was not implemented or tested on the physical prototype, whose IoT suite comprises the eWeLink application together with ultrasonic and battery sensors. (viii) Several techno-economic parameters (O&M rate, battery-replacement cost, project lifetime, and the Year 1–3 cash-flow figures underlying the entire NPV/IRR analysis) are engineering/literature-based assumptions rather than independently verified measurements or a documented revenue/savings source, and are labelled as such throughout Sections 2.4, 3.3, and Table 3. (ix) The reported environmental indicators are a streamlined, operation-phase carbon and energy screening rather than a full cradle-to-grave LCA; embodied emissions from panel, battery, electronics, steel-structure manufacture, transport, and end-of-life treatment are excluded and are recommended as a priority for future work. (x) The 3.15-fold volume-reduction ratio is reported as a single value; the underlying h_0 and h_f measurements, number of replicate trials, and waste composition are not tabulated, and the microbial counts in Figure 8 are shown as individual sample values without a statistical comparison.

4. Conclusions

A prototype of a solar-powered hybrid smart bin that uses gaseous ozone to reduce bacterial load was developed and field-tested. It also offers a substantially automated mode of operation via an in-built Internet of Things (IoT) platform, which could contribute to the next generation of technology in the field of sustainable urban waste management. To this end, localized bacterial contamination is reduced at the source in this novel system, corresponding to a measured ≈6-log reduction in culturable microbial load and a 3.15-fold reduction in waste volume. These results indicate that both ecological sustainability and public-health benefits may be achievable, including a potentially reduced risk of microbial transmission (not directly measured here) and a lower burden at municipal landfills. Under clear-sky conditions, the system remained operational for 168 h on a six-hour charge. The 300,000 THB capital cost reflects a one-off, custom-fabricated R&D prototype rather than a mass-produced unit; at projected mass-production volumes, unit costs for comparable small-scale IoT/solar hardware are typically substantially lower, though a specific target cost-reduction curve for this system requires vendor/production quotes that are outside the scope of this assessment. The 300,000 THB capital cost, the magnitude of cash flows reported, and the inclusion of normal operating and battery replacement costs indicate that a positive return is not obtained from the system within the 10-

year evaluation period; a positive return is reached only in an optimistic scenario in which operating and battery-replacement costs are negligible, and the service life is extended beyond 20 years (base-case NPV ≈ –139,043 THB at a 10% discount rate). These findings suggest that the short-term economic argument for the developed system is therefore based on its environmental and public health benefits – in terms of waste volume reduction, reduction of microbial load and renewable energy as opposed to energy from the grid – rather than a current economic costing argument. Closing the remaining gap would require a lower capital cost per unit (likely with fleet-scale manufacturing) and/or a more substantial annual net benefit than presented here, with smart design and renewable energy integration reducing the frequency of waste collections and operational footprint to support cities' overall environmental objectives even if the unit economics are not strictly quantified.

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Author Contributions

A.S.: conceptualization, investigation, methodology, original draft preparation, data curation, research design, statistical analysis, supervision, writing—review and editing, funding acquisition, and project administration. A.S.; P.P.; P.P.; J.K.; W.H.; I.Y.S.: conceptualization, data curation, Research design and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors have no conflicts of interest to declare.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that AI-assisted writing tools were used during manuscript preparation solely to improve language clarity and readability. All scientific content, data, analyses, interpretations, and conclusions are entirely the authors' own. The authors accept full responsibility for the integrity of this work.

References

[1] E. Singh, A. Kumar, R. Mishra, and S. Kumar, "Solid waste management during COVID-19 pandemic: Recovery techniques and responses," *Chemosphere*, vol. 288, Feb. 2022, Art. no. 132451, doi: 10.1016/j.chemosphere.2021.132451.

[2] D. Hantoko, X. Li, A. Pariatamby, K. Yoshikawa, M. Horttanainen, and M. Yan, "Challenges and practices on waste management and disposal during COVID-19 pandemic," *Journal of Environmental Management*, vol. 286, May 2021, Art. no. 112140, doi: 10.1016/j.jenvman.2021.112140.

[3] D. Predali, "COVID-19: A worldwide hecatomb in long-term care facilities," in *Handbook on COVID-19 Pandemic and Older Persons,* pp. 21–54, 2023, doi: 10.1007/978-981-99-1467-8_3.

[4] K. J. C. Kalala, "Assessing the effectiveness of infectious waste management in Bobirwa Sub-District health facilities," M.P.H. thesis, Faculty of Health Sciences, University of Johannesburg, Johannesburg, South Africa, 2022. [Online.] Available: https://hdl.handle.net/10210/501112

[5] J. Peng, X. Wu, R. Wang, C. Li, Q. Zhang, and D. Wei, "Medical waste management practice during the 2019–2020 novel coronavirus pandemic: Experience in a general hospital," *American Journal of Infection Control*, vol. 48, no. 8, pp. 918–921, Aug. 2020, doi: 10.1016/j.ajic.2020.05.035.

[6] H. A. Aziz, F. M. Omar, H. A. Halim, and Y.-T. Hung, "Health-care waste management," in *Solid Waste Engineering and Management,* vol. 3, pp. 163–229, 2022, doi: 10.1007/978-3-030-96989-9_4.

[7] I. Luhar, S. Luhar, and M. M. A. B. Abdullah, "Challenges and impacts of COVID-19 pandemic on global waste management systems: A review," *Journal of Composites Science*, vol. 6, no. 9, 2022, Art. no. 271, doi: 10.3390/jcs6090271.

[8] S. Capolongo, M. Gola, A. Brambilla, A. Morganti, E. I. Mosca, and P. Barach, "COVID-19 and healthcare facilities: A decalogue of design strategies for resilient hospitals," *Acta Biomedica*, vol. 91, no. 9-S, pp. 50–60, 2020, doi: 10.23750/abm.v91i9-S.10117.

[9] C. Sussangkarn and D. Nikomborirak, "Thailand's long-term growth: Aspiration, reality and challenges," *Asian Economic Papers*, vol. 15, no. 2, pp. 23–43, 2016, doi: 10.1162/ASEP_a_00423.

[10] O. A. Adejumo and O. F. Oluduro, "Ticking time bomb: implications of the COVID-19 lockdown on e-waste management in developing countries," *UCL*

Open Environment, vol. 3, 2021, Art. no. e023, doi: 10.14324/111.444/ucloe.000023.

[11] P. Chounchaisit and C. Moorapun, "A systematic review for advancing inclusive and sustainable waste management in Thailand," *Environment-Behaviour Proceedings Journal*, vol. 8, no. 24, pp. 361–367, 2023, doi: 10.21834/ebpj.v8i24.4691.

[12] A. Roy, A. Manna, J. Kim, and I. Moon, "IoT-based smart bin allocation and vehicle routing in solid waste management: A case study in South Korea," *Computers & Industrial Engineering*, vol. 171, Sep. 2022, Art. no. 108457, doi: 10.1016/j.cie.2022.108457.

[13] J.-H. Huh, J.-H. Choi, and K. Seo, "Smart trash bin model design and future for smart city," *Applied Sciences*, vol. 11, no. 11, 2021, Art. no. 4810, doi: 10.3390/app11114810.

[14] A. De Nicola and M. L. Villani, "Smart city ontologies and their applications: A systematic literature review," *Sustainability*, vol. 13, no. 10, 2021, Art. no. 5578, doi: 10.3390/su13105578.

[15] A. K. Cechinel et al., "Mobile robot + IoT: Project of sustainable technology for sanitizing broiler poultry litter," *Sensors*, vol. 24, no. 10, 2024, Art. no. 3049, doi: 10.3390/s24103049.

[16] R. J. P. Latiza and R. V. Rubi, "Circular economy integration in 1G+2G sugarcane bioethanol production: Application of carbon capture, utilization and storage, closed-loop systems, and waste valorization for sustainability," *Applied Science and Engineering Progress*, vol. 18, no. 1, 2025, Art. no. 7448, doi: 10.14416/j.asep.2024.07.005.

[17] A. Sukkaew, S. Phasuk, and P. Takolpuckdee, "Synthesis and characterization of carboxymethyl cellulose from sugarcane bagasse cellulose using physical and chemical pretreatments," *ASEAN Journal of Scientific and Technological Reports*, vol. 29, no. 5, 2026, Art. no. e261176, doi: 10.55164/ajstr.v29i5.261176.

[18] Tecnosystemi. "Ozone Generator 15 g/h — Technical Datasheet." Tecnosystemi. Accessed: Sep. 20, 2026. [Online.] Available: https://tecnosystemi.com/en/media/download/2024/07/ds_air-hygiene-equipment-and-systems-ozone-generator-15-g-h_uk_4541.pdf

[19] F. Ullah et al., "Privacy-Aware secure data auditing for cloud-based intelligence of things environment," *IEEE Internet of Things Journal*, vol. 12, no. 11, pp. 15288–15303, 2025, doi: 10.1109/JIOT.2025.3528117.

[20] S. Majchrowska et al., "Deep learning-based waste detection in natural and urban environments," *Waste Management*, vol. 138, pp. 274–284, Feb. 2022, doi: 10.1016/j.wasman.2021.12.001.

[21] S. S. Mookkaiah, G. Thangavelu, R. Hebbar, N. Haldar, and H. Singh, "Design and development of smart Internet of Things-based solid waste management system using computer vision," *Environmental Science and Pollution Research*, vol. 29, pp. 64871–64885, Sep. 2022, doi: 10.1007/s11356-022-20428-2.

[22] A. Mustafa et al., "Selective synthesis of alpha monoglycerides by a clean method: Techno-economic and environmental assessment," *Sustainable Chemistry and Pharmacy*, vol. 27, Jun. 2022, Art. no. 100690, doi: 10.1016/j.scp.2022.100690.

[23] S. Nižetić, N. Djilali, A. Papadopoulos, and J. J. P. C. Rodrigues, "Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management," *Journal of Cleaner Production*, vol. 231, pp. 565–591, Sep. 2019, doi: 10.1016/j.jclepro.2019.04.397.

[24] Renogy. "Solar battery lifespan: How long do they last?." Renogy Inc. Accessed: Sep. 10, 2026. [Online.] Available: https://www.renogy.com/blogs/general-solar/what-is-the-life-expectancy-of-a-solar-battery

[25] J. Kaewmanee and A. Sukkaew, "Carbon footprint assessment and GHG reduction guidelines for the rubberwood processing industry in Yala Province," *ASEAN Journal of Scientific and Technological Reports*, vol. 29, no. 7, Jul. 2026, Art. no. e263215, doi: 10.55164/ajstr.v29i7.263215.

[26] A. Sukkaew, P. Pisapak, J. Kaewmanee, and W. Harinppanwich, "Optimal conditions for ethanol production by simultaneous saccharification and fermentation using *Schizosaccharomyces pombe* and fungal consortium with selected Napier grass substrate," *Science and Engineering Connect*, vol. 48, no. 3, pp. 296–309, 2025.

[27] U.S. Department of Energy. "Solar photovoltaic system cost benchmarks." Accessed: Sep. 10, 2026. [Online.] Available: https://www.energy.gov/cmei/systems/solar-photovoltaic-system-cost-benchmarks

[28] Solar Thailand, "Battery Lithium 12.8V 50Ah Solar LiFePO4 640Wh BMS." Solar-Thailand.com. Accessed: Sep. 20, 2026. [Online.] Available: https://www.solar-thailand.com/TH/Product/LP-12V-50Ah/

[29] LiTime, "LiTime 12V 50Ah LiFePO4 Lithium Battery for Marine, Caravan." LiTime. Accessed: Sep. 20, 2026. [Online.] Available: https://au.litime.com/products/litime-12v-50ah-lifepo4-lithium-ion-battery

[30] E. Baldini, S. Chessa, and A. Brogi, "Estimating the environmental impact of Green IoT deployments," *Sensors*, vol. 23, no. 3, 2023, Art. no. 1537, doi: 10.3390/s23031537.

[31] H. Nematollahi, S. Gitipour, and N. Mehrdadi, "Comparative life cycle assessment and route optimization modeling of smart versus conventional municipal waste collection: Environmental impact analysis in an urban context," *Results in Engineering*, vol. 24, Dec. 2024, Art. no. 103408, doi: 10.1016/j.rineng.2024.103408.

[32] K. Rangel et al., "Detrimental effect of ozone on pathogenic bacteria," *Microorganisms*, vol. 10, no. 1, 2022, Art. no. 40, doi: 10.3390/microorganisms10010040.

[33] M. Ahmad, A. Khattak, A. K. Janjua, A. A. Alahmadi, M. S. Khan, and N. Ullah, "Techno-economic feasibility analyses of grid-connected solar photovoltaic power plants for small scale industries of Punjab, Pakistan," *Frontiers in Energy Research*, vol. 10, Nov. 2022, Art. no. 1028310, doi: 10.3389/fenrg.2022.1028310.

[34] F. Ullah et al., "Lightweight multimedia anomaly and integrity detection for consumer IoT using knowledge distillation," *IEEE Transactions on Consumer Electronics*, vol. 72, no. 1, pp. 2465–2475, Feb. 2026, doi: 10.1109/TCE.2025.3644297.

[35] A. A. Khan, M. Faheem, R. N. Bashir, C. Wechtaisong, and M. Z. Abbas, "Internet of things (IoT) assisted context aware fertilizer recommendation," *IEEE Access*, vol. 10, pp. 129505–129519, 2022, doi: 10.1109/ACCESS.2022.3228160.

[36] H. Asmat, F. Ullah, A. A. Khan, F. Ali, and M. I. Mohmand, "A novel caching framework for information-centric IoT using deep reinforcement proximal policy optimization," *Computer Communications*, vol. 241, Sep. 2025, Art. no. 108261, doi: 10.1016/j.comcom.2025.108261.

[37] J. Zhang, M. A. Bhuiyan, and G. Zhang, "Life cycle sustainability assessment of kerbside glass recycling: Separate vs. mixed bin collection and its reuse in asphalt and glass container production," *Journal of Cleaner Production*, vol. 476, Oct. 2024, Art. no. 143784, doi: 10.1016/j.jclepro.2024.143784.

[38] Z. C. Miao et al., "System boundary effects in prospective LCA of CFRP recycling: A comparison of pyrolysis and solvolysis across bin-to-gate and circular economy perspectives," *Composites Part A: Applied Science and Manufacturing*, vol. 210, Nov. 2026, Art. no. 110055, doi: 10.1016/j.compositesa.2026.110055.

[39] Nation Thailand, "TGO sets new emission factors for electricity generation and transmission." Accessed: Sep. 10, 2026. [Online.] Available: https://www.nationthailand.com/news/policy/40059019

[40] I. Gestring, "Life cycle and supply chain management for sustainable bins," *Procedia Engineering*, vol. 192, pp. 237–242, 2017, doi: 10.1016/j.proeng.2017.06.041.

[41] Thai PBS World, "Thailand's official population at December 31st 2022 was 66,090,475." Accessed: Oct. 15, 2026. [Online.] Available: https://www.thaipbsworld.com/?p=303192