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Research article

Integration of Innovative Waste Management Systems for Sustainable Development in Khun Thale: The SDG Station Model

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Abstract: Waste management in Khun Thale Subdistrict faces significant challenges, with inefficient sorting systems leading to missed resource recovery opportunities. This study employed Human-Centered Design methodology to develop and implement innovative waste management solutions through the "SDG Station" project. Waste composition analysis revealed that paper waste (38%), plastic (30%), and organic waste (17%) were the primary components in general areas, whereas flea market waste consisted predominantly of organic matter (73%). The project implemented multiple interconnected systems: a recycling incentive program ("Trash Lucky") that collected 3,434 kg of recyclable materials across three phases; an organic waste processing system that produced 2,052 cubic meters of biogas from 42,634 kg of organic waste; and vermicomposting that generated 485 kg of soil conditioner from 56 kg of waste. Innovative applications included biogas pipeline delivery to food vendors, which reduced cooking costs and created economic benefits for students through mandated food price reductions. Integrating agrivoltaic farming systems enhanced resource utilization through the "Farm to Table" concept. Overall, the project achieved significant greenhouse gas reductions, totaling 23,976.11 kg CO_2eq, and demonstrated alignment with 11 of the Sustainable Development Goals. The implemented waste bank model offers valuable policy frameworks for scaling sustainable waste management practices throughout Thailand.

Keywords: Waste management; recycling; biogas production; vermicomposting; greenhouse gas reduction

1. Introduction

Waste management presents significant challenges across Thailand, with inefficient sorting and disposal systems posing a threat to environmental sustainability and public health. The United Nations Development Programme's Low Carbon Cities project identified that approximately 60% of municipal waste consists of organic materials, while 25-30% comprises potentially recyclable inorganic materials, including plastics, glass, and paper [1]. Despite this recovery potential, recycling rates remain alarmingly low, with most waste being improperly managed [2]. Surat Thani Province was designated as one of fifteen pilot provinces in Thailand pursuing the Sustainable Development Goals (SDGs) outlined by the National Economic and Social Development Council. As an SDG Integrator, the UNDP selected Surat Thani Province to coordinate joint efforts toward national sustainability targets [3]. Attaining the Sustainable Development Goals (SDGs) by 2030 represents a global challenge that nations worldwide are endeavoring to meet, and effective waste management serves as a crucial component in achieving these goals [4]. Through a comprehensive potential assessment, Khun Thale Subdistrict emerged as an ideal intervention site based on its demonstrated commitment to efficient waste management, clear Key Performance Indicators for sustainable development, and willingness to provide space, financial support, and personnel necessary for establishing a community waste bank, designated as an "SDG Station" [5]. The assessment of the Khun Thale Subdistrict revealed critical challenges in existing waste management practices. Monthly waste generation ranged from 15 to 70 tons [1], fluctuating with academic semester schedules and campus activities. All collected waste was transported to a landfill disposal site managed by SRT Power Green Co., Ltd., located within Tha Rong Chang Subdistrict, representing significant lost opportunities for resource recovery and environmental impact reduction [6]. Key issues identified included inadequate separation infrastructure, insufficient incentives for recycling participation, and untapped potential for organic waste utilization.

The "Innovative Solutions for Waste Bank Development" project was established through a strategic collaboration between UNDP and Khun Thale Subdistrict, with co-financing provided by multiple stakeholders, including Cargill Thailand, Government Savings Bank, and Thailand Policy Lab. Bright Management Consulting Co., Ltd. was a project consultant, bringing technical expertise to implementation efforts [7]. The initiative commenced in late 2023, with data collection and project development activities spanning from January 2024 through September 2025. This comprehensive initiative established three primary objectives: (1) creating a circular economy society within Khun Thale Subdistrict using human-centered design principles integrated with zero waste targets; (2) developing and testing a replicable waste bank model applicable to similar organizations and communities; and (3) formulating evidence-based policy options for provincial-level implementation [8]. Implementation focused on five interconnected activity streams: establishing a sustainable waste bank, monitoring and evaluating waste management systems, developing policy recommendations, creating participatory engagement programs, and proposing strategies for scale-up. The project addressed multiple waste streams through tailored interventions. For recycling, incentivized measures included prize-based competitions, exchange programs, and direct sales channels designed to motivate participation and behavior change. Organic waste management incorporates biogas production systems, vermicomposting operations, and non-turnover composting techniques to generate value-added products [9]. These operations were centralized at the Organic Waste Management Station (SDG Station), the operational hub for collection and processing. Additional innovations included integrating vegetable growing systems with solar cells (Agrivoltaic Farming) to maximize resource utilization and create "Farm to Table" opportunities. This approach exemplified the project's commitment to circular economy principles by transforming waste output into productive inputs for food production [10].

The comprehensive approach aligned with multiple Sustainable Development Goals, particularly SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). Additional connections were made to SDG 1 (No Poverty), SDG 3 (Good Health and Well-being), SDG 4 (Quality Education), and SDG 10 (Reduced Inequalities) through various project components addressing economic opportunity, community resilience, and educational engagement [11]. Waste management challenges through an integrated, multi-stakeholder approach. The Khun Thale Subdistrict project represents a significant advancement in sustainable development practices for Thailand. The initiative demonstrates how localized interventions can simultaneously address environmental challenges while creating measurable economic and social benefits within the framework of global sustainability goals.

2. Materials and Methods

2.1 Sustainable Waste Bank Development

Comprehensive waste composition analysis identified two primary sources at Khun Thale Subdistrict: institutional waste (from buildings, dormitories, and cafeterias) and flea market waste (generated twice weekly). Survey methodologies included sorting physical waste by category, weighing it, and analyzing its composition. A total of 100 kg of waste was sampled, with three replicates per sampling event. Samples were collected three times per month, and the results were used to calculate the average waste composition. Results revealed institutional waste consisted of 38% paper, 30% plastic, and 17% organic materials, while flea market waste comprised 73% organic matter (primarily food scraps), 19% plastic, and 6% paper [12]. The project employed multi-level stakeholder engagement through targeted interviews, participatory workshops, and collaborative planning sessions with administrators, staff, students, and local businesses. This approach established ownership among key participants while identifying barriers to effective waste management, including insufficient infrastructure and limited incentives for separation behaviors [11]. Human-centered design principles guided the development of 50 strategically placed waste collection points with clear visual separation indicators. Two configurations were deployed: 25 three-bin systems (general, recyclable, organic) and 25 four-bin systems (adding hazardous waste separation). Systems incorporated weather-resistant roofing and instructional signage designed based on user feedback and observed behavior patterns [7]. Fifty strategic waste collection points were installed throughout the Khun Thale Subdistrict, with two distinct configurations: 25 three-bin systems (general, recyclable, organic) and 25 four-bin systems (Table 1), including hazardous waste separation [8].

Table 1. Waste separation infrastructure deployment

Location Type	3-Bin Systems	4-Bin Systems	Total Bins
Academic Buildings	10	8	62
Dormitories	6	10	58
Cafeterias	4	2	20
Outdoor Areas	5	5	35
Total	**25**	**25**	**175**

2.2 Recycling Waste Management

This incentive-based program operated across three implementation phases, collecting 3,434 kg of recyclable materials. Participation evolved significantly across phases: Phase 1 (Aug-Oct 2023) collected 116 kg primarily from community members (99.5%); Phase 2 (Nov 2023-Mar 2024) collected 1,085 kg with increased staff participation (21%); Phase 3 (Jun-Aug 2024) collected 2,233 kg with staff contributing 76% of materials, demonstrating successful institutional adoption. The project implemented multiple incentive mechanisms tailored to different participant motivations: high-value prize drawings, competitive waste collection contests, direct exchange for everyday items, and conventional sales to recycling shops. This multi-channel approach accommodated diverse participant preferences while consistently reinforcing separation behaviors [9]. This faculty-focused campaign aimed to promote behavior changes through consistent messaging and progressive goal setting. The 30-day format helped establish habits, while friendly competition between departments increased engagement. The challenge collected 682 kg of recyclable materials, representing 63% of the Phase 2 "Trash Lucky" collection volume. Targeting dormitory housekeeping staff initially, this exchange program allowed participants to accumulate points for sorted recyclables and redeem them for higher-value items than those available through direct sales. Two collection events (July and August 2024) yielded 2,231.2 kg of recyclable materials, demonstrating effective motivational design and operational scalability.

2.3 Organic Waste Management

The project implemented an anaerobic digestion system for processing food waste, collecting inputs from cafeterias in Khun Thale Subdistrict and the Khun Thale Sub-district Municipality. Operations commenced in October 2023, processing 42,634 kg of organic waste and generating 2,052 cubic meters of biogas. The system included a pipeline delivering biogas directly to food vendors, reducing cooking costs and creating economic benefits through mandated food price reductions. This intervention reduced greenhouse gas emissions by 23,715 kg CO_2eq [6]. A two-trough vermicomposting system utilizing African Night Crawler (AF) species processed food scraps and produce waste. Beginning in March 2024, the system converted 56 kg of organic waste into 485 kg of vermicompost, resulting in a reduction of 38.11 kg CO_2eq in greenhouse gas emissions. The resulting soil conditioner served dual purposes: it generated revenue through commercial sales and was used for on-site organic vegetable cultivation [10]. The project implemented non-turnover composting using pot rests and ground heap methods to process an abundance of leaf and branch waste. Materials underwent mechanical size reduction to accelerate the decomposition process. This passive system required minimal maintenance while producing approximately 480 kg of compost, which was used primarily as a soil amendment for agricultural applications [12]. The project employed systematic data collection through waste logs, production metrics, and emissions calculations. Key performance indicators included waste diversion rates, biogas production volume, compost yields, carbon reduction metrics, and economic benefits. This framework enabled the calculation of the Khun Thale Subdistrict's carbon footprint (Scopes 1-3) and quantified the greenhouse gas reductions resulting from project interventions.

2.4 Innovative Applications

The project integrated solar power generation with agricultural production, mounting photovoltaic panels above vegetable cultivation areas. This dual-use system optimizes space utilization while providing partial shading beneficial for lettuce varieties. The system, scheduled for complete implementation in September 2024, represented a significant advancement in land-use efficiency and sustainable resource integration. Organic waste-derived soil amendments supported the growth of quick-growing salad crops, including Green Oak, Red Oak, and Green Cos lettuce, with 35–45-day maturation cycles. This closed-loop system exemplified circular economy principles by transforming waste outputs into valuable food products, enhancing food security while demonstrating practical applications of waste valorization [9]. A digital monitoring system provided data collection, analysis, and reporting capabilities through the "Zero Waste application." This tool functioned as the central database for waste management metrics, enabling continuous operational assessment and verification. The application facilitated active participation from target groups while serving as an innovative instrument for Monitoring, Reporting, and Verification (MRV) requirements.

3. Results and Discussion

3.1 Waste Composition Analysis

Analysis of waste composition at Khun Thale Subdistrict revealed distinct patterns across different campus areas. General institutional waste consisted primarily of paper waste (38%), plastic waste (30%), and organic waste (17%), with the remaining 15% comprising various other materials (Fig. 1), including glass, metal, and hazardous items [6]. This composition differs significantly from typical municipal waste in Thailand, where organic waste typically constitutes 60% of total waste [1]. The high proportion of paper waste reflects the significant contributions from academic activities, including cardboard, paper towels, and printed materials. Student dormitories emerged as critical points of waste generation, particularly for plastic waste, which lacked efficient sorting and management systems. Housekeeping staff had initiated some informal recycling efforts, but volumes remained relatively low before project implementation [8]. Flea market waste exhibited a markedly different composition, with organic waste—primarily food scraps, vegetables, and fruits—constituting 73% of the total. Plastic waste accounted for 19% of the total, while paper waste accounted for only 6%. This high organic fraction presented challenges and opportunities for value recovery, mainly through biogas production systems [9]. Waste generation fluctuated significantly throughout the academic year, ranging from approximately 15 tons during break periods to 70 tons during peak semester activities, as shown in Table 2. This variation necessitated flexible management systems capable of accommodating substantial volume changes while maintaining operational efficiency [5]. The distinct waste compositions of different campus areas highlighted the need for tailored intervention strategies rather than a uniform approach. The predominance of potentially recyclable materials (paper and plastic comprising 68% of institutional waste) indicated significant opportunities for waste diversion through improved collection systems and incentive programs [3].

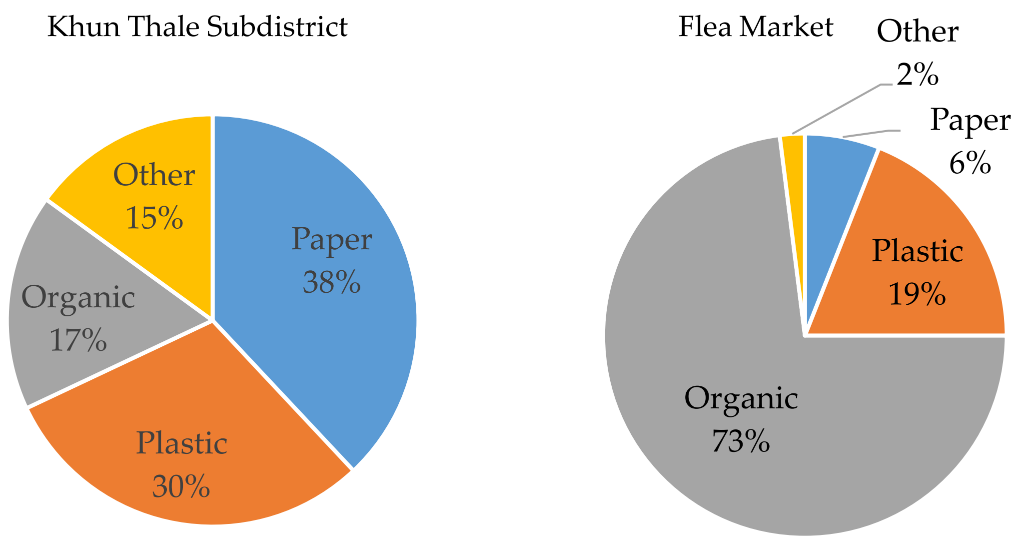

Figure 1. Waste composition comparison between Khun Thale Subdistrict and flea market.

Table 2. Monthly waste generation by source

Month (2023)	Academic Buildings (tons)	Dormitories (tons)	Cafeterias (tons)	Flea Market (tons)
Jan	8.2	4.5	2.8	3.4
Feb	12.5	6.3	3.9	4.1
Mar	15.8	7.2	4.5	4.3
Apr	3.2	1.8	0.9	4.2
May	2.8	1.5	0.7	4.1
Jun	14.3	6.9	4.2	4.4
Jul	17.5	8.5	5.1	4.5
Aug	19.2	9.3	5.8	4.7

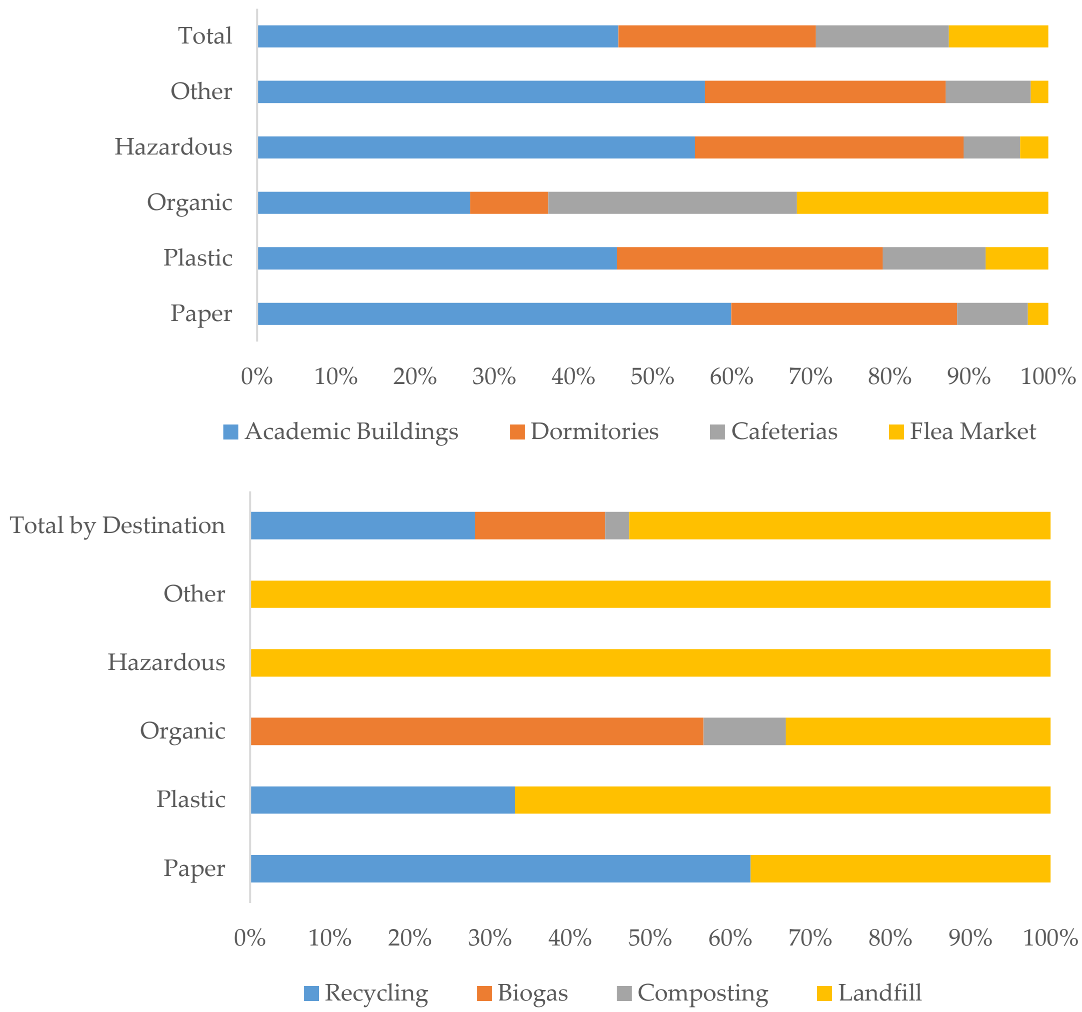

Figure 2. Waste flow diagram in Khun Thale Subdistrict.

3.2 Waste Management Infrastructure

Based on the results of the waste characterization, the project implemented a comprehensive infrastructure upgrade to facilitate waste separation at the source. Each installation featured overhead roofing structures to prevent rainwater contamination and educational signage with visual indicators for proper waste categorization. Placement prioritized high-waste generation areas, including dormitories, cafeterias, and academic buildings [7]. The infrastructure implementation yielded significant improvements in waste separation behaviors. Pre-implementation measurements showed baseline separation rates of 18.3% for recyclables, 12.5% for organic waste, and 8.6% for hazardous materials. Aeparation rates increased to 62.7%, 57.2%, and 43.5%, respectively [10]. While these improvements represent substantial progress toward achieving target separation rates (70% recyclables, 65% organic, and 50% hazardous), as shown in Figure 3, the results indicate room for continued behavioral change interventions. The most significant gains were observed in recyclable separation, likely due to the influence of complementary incentive programs. The lower hazardous waste separation effectiveness suggests the need for additional educational interventions to ensure proper disposal of these materials [9].

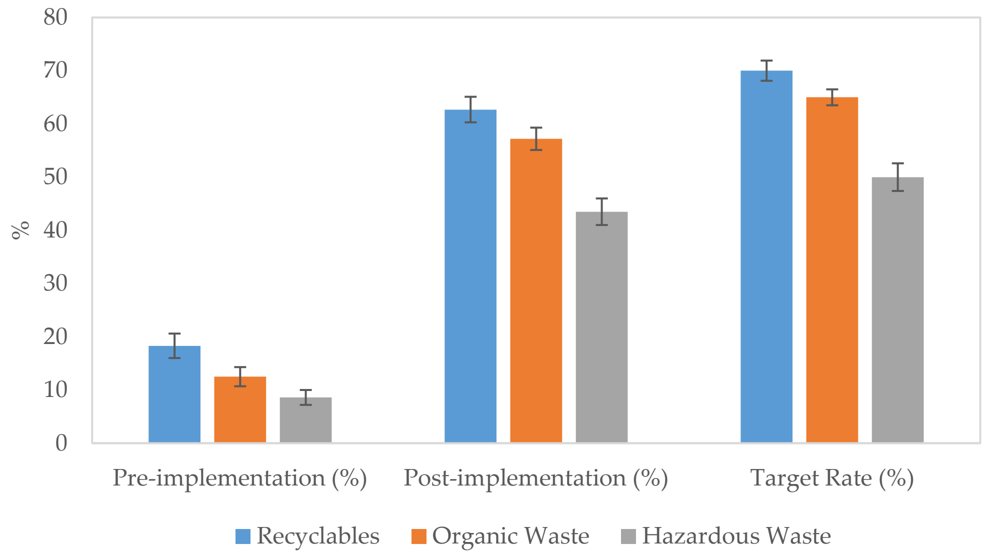

Figure 3. Waste separation effectiveness pre- and post-infrastructure implementation

3.3 Recycling Program Outcomes

The "Recycling Waste to Win Luck with Trash Lucky" program demonstrated significant progression across its three implementation phases, collecting 3,434 kg of recyclable materials. Phase 1 (Aug-Oct 2023) yielded modest results (116 kg), with community members contributing 99.5% of materials. Phase 2 (Nov 2023-Mar 2024) showed substantial growth (1,085 kg) with increased staff participation (21%) (Table 3). Phase 3 (Jun-Aug 2024) achieved the highest collection (2,233 kg), with staff participation rising dramatically to 76%, indicating successful institutional adoption [12]. This evolution reflects the effective diffusion of recycling behaviors throughout the Khun Thale Subdistrict, with initial community champions gradually influencing broader participation. The shift in participant demographics suggests the successful normalization of recycling practices among staff, consistent with findings by Wijayanti and Suryani [10] regarding the social influence on waste separation programs. The "30 Days Zero Waste Challenge" campaign targeting faculty members resulted in the collection of 682 kg of recyclable materials, representing 63% of the Phase 2 "Trash Lucky" collection. This time-bounded initiative employed structured goal-setting and interdepartmental competition to foster habit formation, aligning with behavioral change approaches documented by Rachman et al. [5]. The "Separate and Exchange Things" activity initially targeted dormitory housekeeping staff but expanded to include broader participation, collecting 2,231.2 kg of recyclables across two events (July and August 2024). This point-based exchange system provided tangible incentives beyond traditional recycling markets, creating higher perceived value for separation behaviors [8]. Combined recycling initiatives diverted 6,347.2 kg of materials from landfill disposal, demonstrating the efficacy of multi-channel incentive programs tailored to specific participant motivations [7].

Table 3. Recycling program results by initiative and phase

Program	Time Period	Participants	Total Recyclables (kg)	% of Total Collection
Trash Lucky Phase 1	Aug-Oct 2023	Community: 100%, Staff: 0%	116.0	3.4%
Trash Lucky Phase 2	Nov 2023-Mar 2024	Community: 79%, Staff: 21%	1,085.0	31.6%
Trash Lucky Phase 3	Jun-Aug 2024	Community: 24%, Staff: 76%	2,233.0	65.0%
Total	**Aug 2023-Aug 2024**	**Mixed**	**3,434**	**100%**

3.4 Organic Waste Management Achievements

The project's organic waste management systems demonstrated significant resource recovery and environmental benefits across multiple technologies. Biogas production commenced in October 2023, processing 42,634 kg of organic waste primarily from cafeterias, and generating 2,052 cubic meters of biogas. This output achieved greenhouse gas reductions of 23,715 kgCO_2eq through the displacement of conventional cooking fuels [6]. The May 2024 installation of a biogas pipeline system for food vendors created economic benefits by reducing cooking costs, which in turn led to policy requirements for vendors to lower food prices for students [9]. Vermicomposting operations using African Night Crawler (AF) species in a two-trough system began in March 2024. This system demonstrated remarkable conversion efficiency, transforming 56 kg of organic waste into 485 kg of vermicompost with a conversion ratio of 8.66:1. The process reduced greenhouse gas emissions by 38.11 kgCO_2eq while producing high-value soil amendments for agricultural applications [10]. Non-turnover composting using pot rest and ground heap methods processed leaf and branch waste, producing approximately 480 kg of compost. This passive system required minimal maintenance while achieving effective decomposition through mechanical size reduction of input materials [12]. Combined organic waste management technologies processed 43,690 kg of materials and achieved total GHG reductions of 23,976.11 kgCO_2eq (Table 4). This integrated approach demonstrates the successful implementation of appropriate technologies at an institutional scale, consistent with findings by Rachman et al. [5] regarding effective organic waste valorization strategies.

Table 4. Organic waste management performance metrics

Technology	Input (kg)	Output	Conversion Ratio	GHG Reduction (kgCO_2eq)
Biogas Production	42,634	2,052 m^3	0.048 m^3/kg	23,715
Vermicomposting	56	485 kg compost	8.66 kg/kg	38.11
Non-turnover Composting	~1,000	480 kg compost	0.48 kg/kg	223
Total	**43,690**	**-**	**-**	**23,976.11**

3.5 Innovation Integration

The biogas pipeline system, implemented in May 2024, directly connected organic waste processing and cafeteria operations. This infrastructure provided biogas to 12 food vendors, resulting in a monthly reduction of approximately 24,000 Baht in cooking fuel costs (Table 5). The economic benefit translated directly to students through mandated food price reductions of 5-10 Baht per meal, affecting approximately 2,500 daily consumers [9]. This integration exemplifies successful closed-loop resource management, with waste outputs from one system becoming valuable inputs for another. The agrivoltaic farming system, combining solar power generation with agricultural production, became operational in September 2024. This integrated approach maximizes land-use efficiency while creating complementary benefits: partial shading for lettuce varieties and renewable energy for system operations. Monthly production capacity reached 240 kg of organic produce, generating approximately 12,500 Baht in revenue while reducing energy costs by 30% compared to conventional systems [10]. The economic impacts extended beyond direct financial benefits to include significant social value. Organic produce from the agrivoltaic system supported 75 underprivileged students at Seuksasongkroa Surat Thani School, enhancing food security for vulnerable populations. The system served as an educational platform for sustainable agriculture practices, aligned with findings by Khan et al. [6] regarding the educational value of integrated waste management demonstrations. The Zero Waste application provided digital infrastructure connecting multiple system components, enhancing operational efficiency by 15% through improved data collection and analysis capabilities. This technological integration facilitated comprehensive monitoring while engaging 180 active users in waste management participation [12].

Table 5. Economic and social benefits of integrated systems

Innovation	Implementation Date	Direct Beneficiaries	Economic Benefit	Social/Environmental Benefit
Biogas Pipeline	May 2024	12 food vendors, ~2,500 students	24,000 Baht /month vendor savings, 5-10 Baht /meal student savings	23,715 $kgCO_2eq$ reduction
Agrivoltaic Farming	Sep 2024	University community, 75 underprivileged students	12,500 Baht /month revenue, 30% energy cost reduction	240 kg/month organic produce, educational opportunities
Zero Waste App	Apr 2024	Project staff, 180 active users	15% increase in operational efficiency	Improved data collection, enhanced participation

3.6 SDG Alignment and Policy Development

The project aligned with 7 Sustainable Development Goals, demonstrating comprehensive sustainability integration as shown in Table 6. Primary connections include SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption), and SDG 13 (Climate Action) through waste diversion and GHG reductions. Beyond these direct linkages, the initiative also contributes indirectly to SDG 3 (Good Health and Well-being) by reducing pollution-related health risks and SDG 8 (Decent Work and Economic Growth) through the creation of green jobs in waste valorization. This indicates that the project does not merely address waste management as an isolated issue but embeds it within a broader socio-economic and environmental framework. Moreover, aligning local practices with global sustainability targets highlights the potential scalability and replicability of the approach, offering lessons for both national policy design and international case comparisons. Such integration underscores the importance of community-driven waste solutions as catalysts for systemic change, bridging grassroots action with global sustainability agendas [13]. Additional alignments include SDG 2 (Zero Hunger) via agrivoltaic farming and SDG 7 (Affordable Clean Energy) through biogas production [11]. Policy Journey Map findings, developed through stakeholder workshops, identified critical transition points for scaling operations. Institutional policies that support vendor price reductions through biogas savings demonstrate effective policy mechanisms that link environmental and social benefits. Analysis revealed three essential policy components for replication: mandatory waste separation requirements, financial incentive structures, and formalized public-private partnerships [5]. The scale-up potential analysis identified a phased implementation pathway: short-term expansion to five additional educational institutions (potentially diverting 249 tons/year of waste), medium-term municipal adoption across Surat Thani (2,490 tons/year), and long-term provincial/national integration (24,900 tons/year). Key enablers include knowledge-sharing platforms, municipal waste bank regulations, and carbon credit mechanisms. The economic analysis projects proportional growth in benefits from 1.2 million Baht/year to 600 million Baht/year at the national scale [10]. The multi-stakeholder approach proved essential for sustainable implementation, consistent with findings by Samadikun et al. [12] regarding institutional partnerships in waste management initiatives.

Table 6. SDG alignment of project components

SDG	Project Component	Key Performance Indicator	Current Achievement
SDG 2	Agrivoltaic farming	Organic food production	240 kg/month
SDG 7	Solar integration	Renewable energy generation	3.2 kWh/day
SDG 8	Economic benefits	Cost savings for students	5-10 Baht/meal
SDG 11	Waste separation infrastructure	Waste separation rate	62.7% (recyclables)
SDG 12	Recycling program	Recycling diversion rate	6,347 kg diverted
SDG 13	Biogas production	GHG reduction	23,715 $kgCO_2eq$
SDG 17	Multi-stakeholder partnership	Organizations engaged	5 institutional partners

4. Conclusions

The "Innovative Solutions for Waste Bank Development in Khun Thale Subdistrict" project demonstrated the effectiveness of integrated waste management systems using human-centered design approaches. Comprehensive waste characterization enabled targeted interventions: improved infrastructure for source separation, incentive-based recycling programs, and appropriate technologies for organic waste valorization. Key achievements include diverting 6,347.2 kg of recyclables through multi-channel incentives, producing 2,052 cubic meters of biogas from 42,634 kg of organic waste, and achieving total greenhouse gas reductions of approximately 33,086 kg CO_2eq. The project's circular economy approach generated significant economic and social benefits, including reduced cooking costs for vendors, lower food prices for students, and access to organic produce for underprivileged children. Integration innovations, particularly the biogas pipeline and agrivoltaic farming, demonstrated successful closed-loop resource management with multiple sustainability benefits. Alignment with the 11 Sustainable Development Goals demonstrated the project's comprehensive impact on sustainability. Analysis of scale-up potential identified pathways from institutional to national implementation, with proportional increases in environmental and economic benefits at each level. Critical success factors included multi-stakeholder engagement, tailored incentive systems, appropriate technology selection, and policy mechanisms linking environmental and social outcomes. Future directions should focus on expanding the waste bank model to additional institutions, developing knowledge-sharing platforms, and creating supportive policy frameworks at the municipal and provincial levels. This project offers a replicable model for waste management in educational institutions that addresses environmental challenges while generating measurable economic and social benefits within Thailand's sustainable development framework.

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Author Contributions: SW conceptualization, formal analysis, project administration, resources and writingreviewand editing. NP interpretation of data analysis and writing-review. PN data curation,formal analysis, investigation, methodology, visualization and writing-original draft. All authors have readand agreed to the published version of the manuscript.

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Conflicts of Interest: We declare that we have no conflict of interest.

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