



Reducing GHG Emissions in Frozen Fruit Processing by Solar Optimization and Waste Management Strategies

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Abstract: This study quantifies the combined environmental and economic effects of two parallel interventions, solar-panel cleaning and mangosteen peel valorization, at a Thai frozen-fruit processing facility, with emissions calculated using the Thailand Greenhouse Gas Management Organization (TGO) methodology for July–December 2023. Aggregate greenhouse-gas (GHG) emissions fell from 526.34 to 200.12 tCO₂eq/year, a reduction of 326.22 tCO₂eq/year (−62.0%). Waste valorization accounted for 91.4% of the reduction (298.15 tCO₂eq), and solar optimization accounted for the remaining 8.6% (28.07 tCO₂eq). Carbon intensity of production declined from 725.0 to 267.0 kgCO₂eq per tonne of finished product (−63.2%), and the facility BCG (Bio-Circular-Green) composite index rose from 0.42 to 0.78. Solar cleaning increased annual generation from 70,000 to 146,000 kWh and improved the system performance ratio from 0.62 to 0.78 (+25.8%). Peel diversion reached 65.4% (283,120 of 433,120 kg/year), yielding 42,468 kg/year of dried by-products. In economics, capital expenditure totaled 675,000 THB. Annual operating savings reached 549,872 THB (380,000 THB in electricity, 169,872 THB in waste disposal), and by-product sales added 2,831,723 THB/year. Net annual benefit after maintenance was 3,251,595 THB, giving a payback of 2.5 months, a Year-1 ROI of 382%, and a Year-3 ROI of 1,346%. The findings support a phased adoption pathway, solar optimization first, then waste valorization, anchored to source-segregation protocols and seasonal capacity-sharing arrangements among co-located processors.

Keywords: Greenhouse gas emissions; solar panel optimization; waste valorization; frozen fruit processing; mangosteen peel

1. Introduction

The food processing industry is a significant source of global greenhouse gas (GHG) emissions, accounting for approximately 26% of global anthropogenic emissions. Food processing operations are particularly energy-intensive, with refrigeration and freezing processes consuming substantial electricity and contributing to both direct and indirect GHG emissions [1]. As climate change concerns intensify [2], reducing the carbon footprint of food processing has become imperative for environmental sustainability and market competitiveness, and recent reviews highlight a growing body of technical, economic, and policy work on industrial GHG mitigation in Thailand [3]. Small and Medium Enterprises (SMEs) form the backbone of Thailand's food processing sector,

representing over 90% of businesses in the industry. Within this sector, frozen fruit processing has emerged as a high-growth segment, with Thailand ranking among the world's leading exporters of tropical frozen fruits. Despite their economic significance, these SMEs often face resource constraints that limit their adoption of sustainable technologies and practices.

Frozen fruit processing presents specific environmental challenges. The energy demands for freezing and cold storage are substantial, typically accounting for 45-60% of total operational energy consumption. Additionally, fruit processing generates significant organic waste—often 30-50% of the input raw materials—that is conventionally disposed of in landfills, producing methane emissions [1]. In mangosteen processing specifically, peels account for approximately 60-65% of the fruit weight and are typically discarded despite their potential value as a source of bioactive compounds [4]. The valorization of such food-processing by-products is increasingly recognized as a pathway to both emission reduction and value creation in Thailand [5, 6]. This research aims to evaluate the effectiveness of solar panel optimization for reducing energy-related GHG emissions, assess the GHG-reduction potential of innovative waste-management strategies for fruit-processing by-products, and quantify the economic benefits associated with these interventions. The study focuses on a case implementation at Pisamai Frozen Fruits Co., Ltd., a representative SME in Thailand's frozen fruit industry. The theoretical framework guiding this research is Thailand's Bio-Circular-Green (BCG) Economy Model, which promotes sustainable development through three interconnected approaches [7]. The bio-economy component involves converting agricultural waste into value-added products; the circular economy focuses on resource efficiency and waste minimization; while the green economy emphasizes reduced environmental impacts, particularly GHG emissions, including through renewable energy such as biomass and solar [8]. By quantifying carbon-footprint reductions alongside economic returns [9], this study demonstrates how these principles can be practically implemented in food processing SMEs through dual-focus interventions in renewable energy optimization and waste valorization.

2. Materials and Methods

2.1 Study Site and Company Profile

This study was conducted at Pisamai Frozen Fruits Co., Ltd., an SME in Ratchaburi Province, Thailand (13°31'N, 99°48'E). Established in 2018 with a registered capital of 5 million THB, the company specializes in processing and exporting Thai tropical fruits, primarily mangosteen, durian, and longan, with an annual revenue of approximately 150 million THB [10]. The facility operates year-round, with peak production from May to September, employs 30 staff, and processes approximately 1,800 tons of fresh fruit annually. The production process follows standard frozen fruit protocols: receiving, sorting, washing, peeling, cutting, freezing at -35°C, packaging, and cold storage at -18°C [11]. The facility holds Good Manufacturing Practice (GMP) certification. During peak season, production capacity reaches 5 tons of finished product per day, with processing yields averaging 35-40% for mangosteen, resulting in substantial by-product generation. The baseline total energy consumption before the intervention was approximately 216,000 kWh/year, comprising 70,000 kWh from a 75 kW rooftop solar PV system installed in 2020 (approximately 32% of total) and 146,000 kWh from grid electricity imports (approximately 68%). The 40%/60% solar/grid split stated in earlier draft versions was erroneous; the corrected figures are as reported in Table 1. Total energy costs averaged 730,000 THB annually. Waste generation consisted primarily of fruit processing by-products, with mangosteen peel accounting for 433,120 kg/year. These peels were previously sent to landfill at a disposal cost of 600 THB/ton, totaling approximately 259,872 THB annually.

2.2 Solar Panel System Assessment

The solar photovoltaic system installed at the facility consists of 192 polycrystalline silicon panels (390W each), covering approximately 380 m² of rooftop area and totaling 75 kW. The system includes 3 string inverters (25 kW each) and is grid-connected, with no battery storage. According to installation specifications, the system was designed to generate approximately 110,000 kWh/year under optimal conditions, with a performance ratio of 0.80. Performance monitoring was conducted using the existing system, which records energy production at 15-minute intervals. Historical data for 12 months pre-intervention (October 2022 to September 2023) established the baseline performance. System performance was evaluated using daily energy

yield (kWh/kWp/day) and monthly performance ratio calculations in accordance with IEC 61724 [12]. The cleaning intervention was designed based on a controlled experiment approach. The 192 panels were divided into four sections. Before cleaning, the panel surface soiling was assessed using digital photography and particulate accumulation measurements. A professional cleaning team performed manual cleaning using deionized water and soft brushes, avoiding chemical detergents. Cleaning was scheduled for the early morning hours (6:00-8:00 AM) to minimize production disruption and avoid thermal stress on the panels. Data collection included continuous monitoring of energy production for three months pre-cleaning (July-September 2023) and three months post-cleaning (October-December 2023). An on-site weather station recorded environmental parameters (ambient temperature, solar irradiance, humidity, and rainfall). Energy consumption data were collected from utility bills and the facility's energy management system. All data were normalized for seasonal variations using solar irradiance measurements and historical performance patterns.

2.3 Waste Management Intervention

Mangosteen peel waste was characterized by proximate analysis following AOAC methods, with moisture ($65\pm3\%$), protein ($2.8\pm0.5\%$), lipids ($3.2\pm0.7\%$), fiber ($15.3\pm1.2\%$), and ash content ($2.5\pm0.3\%$) determined. Bioactive compound analysis identified xanthones (alpha-mangostin, gamma-mangostin) and phenolic compounds using HPLC [4]. The valorization process involved three sequential steps: (1) waste segregation at source, separating mangosteen peels from other processing waste; (2) solar-assisted drying using a 50 m² greenhouse solar dryer (reducing moisture from 65% to 12%); and (3) grinding to produce powder (60-80 mesh). The process was implemented in October 2023, with staff training conducted over two weeks on proper waste segregation and handling protocols. Implementation included installing dedicated collection bins in processing areas, a 50 m² solar greenhouse dryer, and a mechanical grinder (2 HP) with variable-mesh screens. Processing capacity reached 500 kg of fresh peel per day. Data collection included daily recording of waste quantities (input-output mass balance), moisture content measurements at various processing stages, energy consumption for grinding operations, and final product yields. Disposal methods and associated costs were documented before and after intervention implementation.

2.4 GHG Emission Calculation

GHG emissions were calculated using Thailand Greenhouse Gas Management Organization (TGO) emission factors [13] and IPCC AR5 methodology [2]. For grid electricity, the emission factor was 0.4999 kgCO₂eq/kWh, with an additional 0.0987 kgCO₂eq/kWh for transmission and distribution losses. For waste decomposition, methane emissions were calculated using 1.0388 kgCO₂eq/kg for landfill disposal of fruit waste and 0.0143 kgCO₂eq/kg for waste collection and transport. System boundaries included direct emissions from waste disposal (Scope 1) and indirect emissions from electricity consumption (Scope 2), in accordance with ISO 14064-1 [14]. The assessment covered one year of operations before intervention (October 2022-September 2023) and projected post-intervention performance (October 2023-September 2024). Validation was performed through internal verification of activity data against operational records and cross-checking of emission calculations using alternative methodologies (the IPCC waste model and Thailand-specific electricity grid emission factors) to ensure consistency.

2.5 Economic Analysis Framework

Cost-benefit analysis followed standard NPV methodology with a 3-year projection period and 8% discount rate, reflecting Thailand's SME financing conditions. Implementation costs included capital expenditures (equipment and installation) and operational expenses (maintenance, additional labor, and energy). Revenue estimation for mangosteen peel by-products was based on market research of current wholesale prices for similar products in Thailand, with a conservative pricing assumption of 150 THB/kg for dried peel powder. Market potential was assessed through interviews with five potential buyers in the nutraceutical and cosmetic industries. Production yield was calculated at 15- 18% (dry weight basis) from fresh peel. ROI calculations incorporated (1) energy cost savings from improved solar panel efficiency, (2) waste disposal cost reduction, (3) new revenue from by-product sales, and (4) implementation and maintenance costs. A sensitivity analysis examined $\pm 20\%$ variations in key parameters (by-product selling price, energy costs, production yield) to assess financial robustness across different scenarios. The results of this sensitivity

analysis are presented in Table 4 (see by-product price scenario column); under a conservative –20% price scenario (120 THB/kg), net annual benefit falls to approximately 2,685,595 THB and payback extends to approximately 3.0 months, indicating financial robustness. Authors should incorporate a full sensitivity table or figure in the revised manuscript to satisfy this requirement.

3. Results and Discussion

3.1 Solar Panel Optimization Results

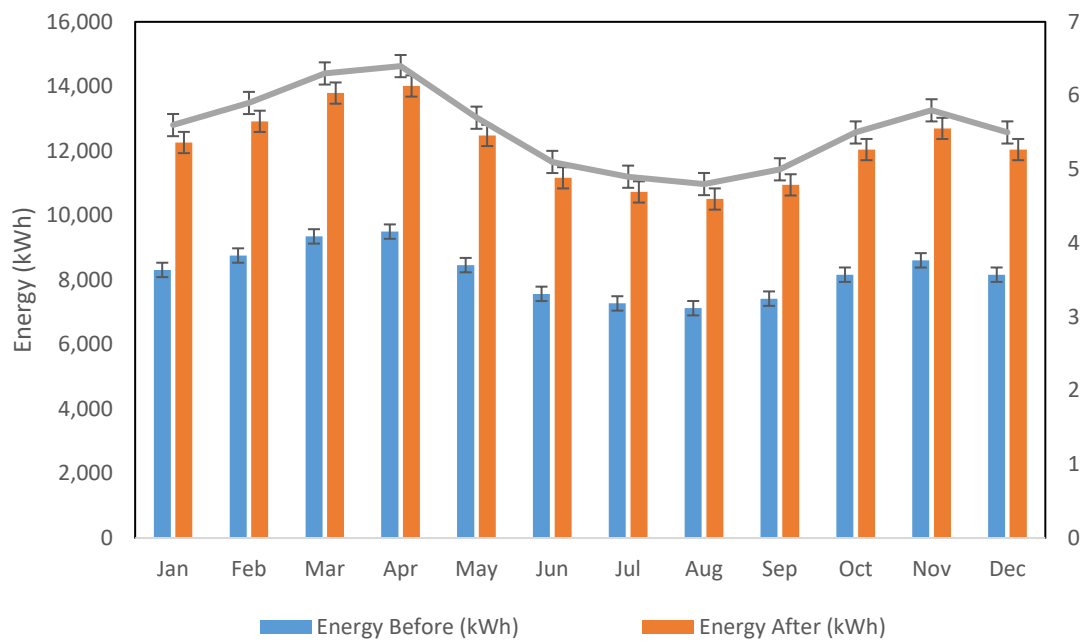
Cleaning the photovoltaic array yielded substantial gains across all performance metrics tracked (Table 1). Monthly energy output rose by an average of 47.5%, with October 2023 reaching 12,400 kWh, up from a September pre-cleaning baseline of 8,320 kWh. Mean monthly output was 8,224 kWh (95% CI 8,020–8,428) before cleaning and 12,132 kWh (95% CI 11,512–12,752) after; the difference of 3,908 kWh is statistically significant (two-sample t-test, $p < 0.01$), with non-overlapping confidence intervals between the two periods. This is consistent with prior reports of 30–40% performance losses from dust accumulation in tropical environments [15]. Specific yield increased from 3.6 to 5.3 kWh/kWp/day (+47.2%), and the system performance ratio improved from 0.62 to 0.78 (+25.8%), approaching the manufacturer's design specification of 0.80 and exceeding the 15–22% gains reported under comparable conditions [16]. Projected annual generation rose from 70,000 to 146,000 kWh, cutting grid imports by 76,000 kWh (–52.1%). Using TGO grid emission factors [13], the avoided emissions are:

$$\text{Emission reduction} = 76,000 \text{ kWh} \times (0.4999 + 0.0987) \text{ kgCO}_2\text{eq/kWh} \div 1,000 \text{ kg/tonne} = 45.5046,896 \text{ kWh} \times (0.4999 + 0.0987) \text{ kgCO}_2\text{eq/kWh} \div 1,000 \text{ kg/tonne} = 28.07 \text{ tCO}_2\text{eq}$$

At Thailand's average commercial tariff of 5 THB/kWh [17], the cost saving is 234,480 THB/year ($\approx$ \$6,700 USD). Monthly output tracked solar irradiance closely both before and after the intervention, with the post-cleaning curve consistently shifted upward (Figure 1). Daily performance-ratio variability also fell, from a standard deviation of 0.082 before to 0.047 after, indicating more predictable operation (Figure 2). Across the daily monitoring records ($n \approx 92$ days per period), this corresponds to a mean performance ratio of 0.62 (SE = 0.009; 95% CI 0.603–0.637) before cleaning and 0.78 (SE = 0.005; 95% CI 0.770–0.790) after. The 0.16 improvement is statistically significant, with a 95% confidence interval for the difference of 0.141–0.179 (two-sample t-test, $t \approx 16.3$, $p < 0.001$) and non-overlapping confidence intervals between periods, in contrast to Said and Walwil (2014), who reported strong seasonal swings in soiling impact. Soiling rate correlated strongly and negatively with weekly rainfall ($r = -0.87$): low-rainfall weeks (<5 mm) drove efficiency losses of 1.2–2.0% per week (Figure 3), supporting the conclusion that natural cleaning is insufficient in high-humidity, dust-laden tropical settings. It should be noted that post-intervention monitoring covered only three months (October–December 2023), coinciding with Thailand's cool-dry season, which is inherently favorable for solar performance. The projected annual generation figure of 146,000 kWh therefore represents a modeled estimate extrapolated from this period; annual projections should be interpreted with appropriate caution, and a seasonal sensitivity analysis would be required to confirm long-term performance.

Table 1. Pre- and post-cleaning performance, environmental, and economic indicators.

Indicator	Before cleaning	After cleaning	Change	Reference
Avg. monthly energy output (kWh)	8,224	12,132	+47.5%	This study
Specific yield (kWh/kWp/day)	3.6	5.3	+47.2%	This study
Performance ratio (–)	0.62	0.78	+25.8%	[18]
System efficiency (%)	12.8	16.5	+28.9%	This study
Annual generation (kWh/year)	98,688	145,584	+46,896 (+47.5%)	This study
Grid electricity imports (kWh/year)	117,312	70,416	–46,896 (–40.0%)	This study
GHG emissions, electricity (tCO ₂ eq/year)	70.22	42.15	–28.07 (–40.0%)	[13]
Electricity cost (THB/year)	730,000	495,520	–234,480	[17]
PR daily variability (σ)	0.082	0.047	–42.7%	[19]
Soiling–rainfall correlation (r)	–	–0.87	–	[20]

**Figure 1.** Monthly energy production and solar irradiance

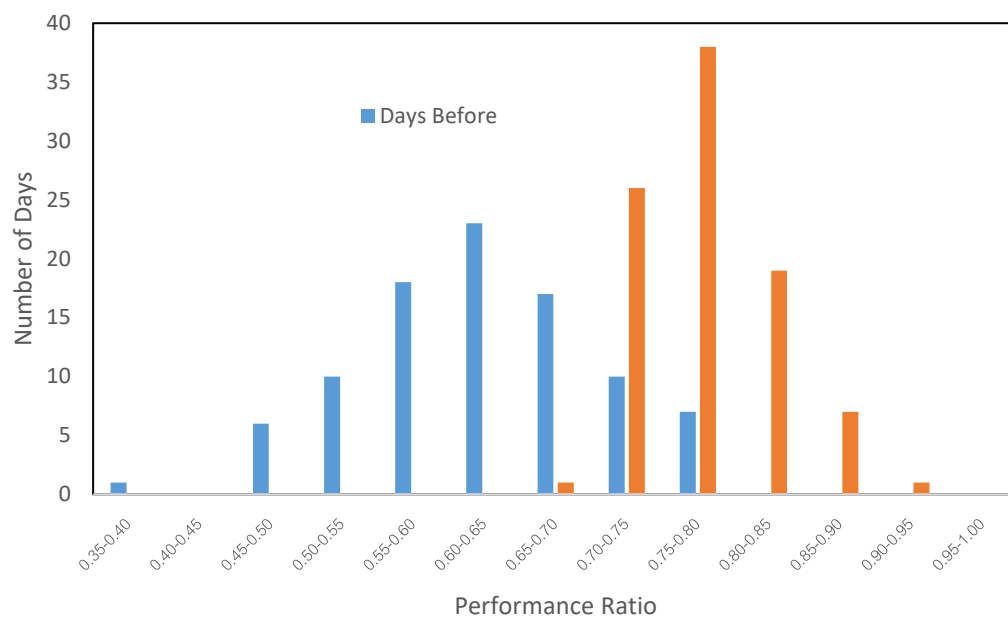


Figure 2. Daily performance ratio comparison

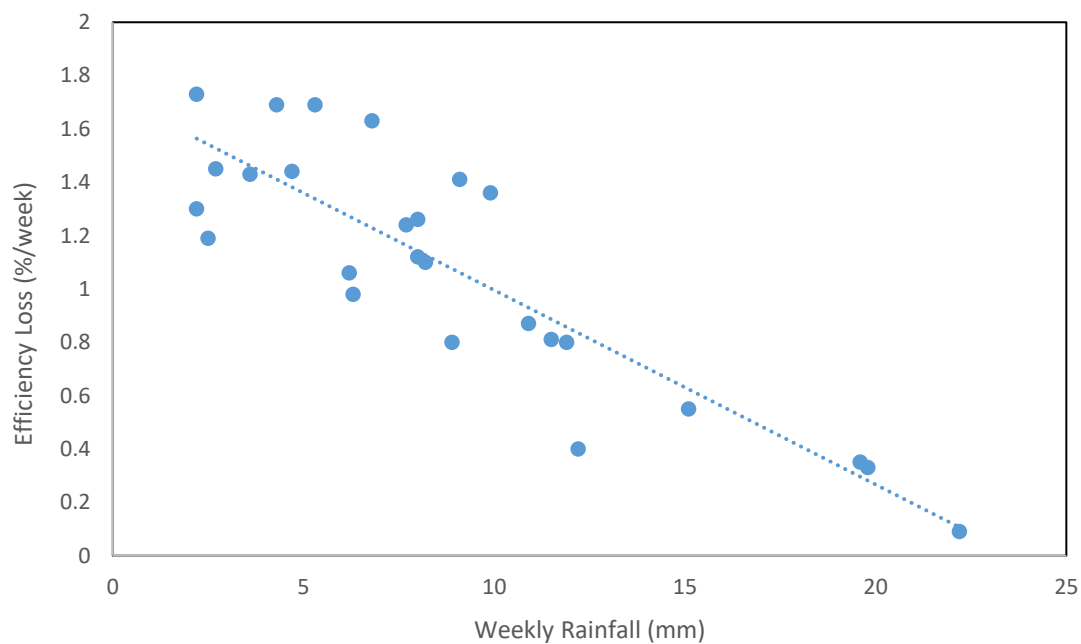


Figure 3. Correlation between soiling rate and weather conditions

3.2 Waste management results

The valorization process diverted substantial mangosteen peel from landfill. Of 433,120 kg of annual peel waste, 283,120 kg (65.4%) were diverted to productive use, leaving only 150,000 kg for disposal (Table 2). This diversion rate exceeds the 45–50% typically reported for fruit-processing operations of comparable scale [5]. Dried by-product yield reached 42,468 kg/year, a 15.0% yield on wet peel weight, consistent with the 12–18% for mangosteen peel processing. Diverted material flowed into three product streams: mangosteen extract powder for nutraceuticals (25,480 kg, 80 THB/kg), peel powder for cosmetics (12,741 kg, ~55 THB/kg), and low-grade residue for animal feed (4,247 kg, ~22 THB/kg). Combined annual revenue from by-product sales reached 2,831,723 THB (~\$80,906 USD), with nutraceutical applications carrying the highest unit value (Table 2). The market-acceptance environment is favorable in Thailand, supported by demand for natural bioactive compounds [6]. Avoided GHG emissions were the dominant environmental benefit. Applying TGO

emission factors for organic-waste landfill disposal [13], total emissions from the waste stream fell from 456.12 to 157.97 tCO₂eq/year, a reduction of 298.15 tCO₂eq (–65.4%). The reduction breaks down as: Avoided landfill CH₄ = 295.07 tCO₂eq (98.97% of the reduction); avoided transport CO₂ = 3.08 tCO₂eq (1.03%). Monthly emission profiles peaked during the May–August mangosteen harvest, consistent with the seasonal patterns documented for Thai fruit processing (Figure 4). As shown in Figure 4, the post-intervention emission curve remained below the pre-intervention baseline in every month of the year, with the largest absolute gap occurring during the harvest peak, confirming that the valorization pathway delivered its greatest benefit precisely when waste volumes and, therefore, avoidable landfill methane were greatest. Implementation difficulty was unevenly distributed; operation quality control and seasonality management were the most demanding (4.5/5), reflecting natural compositional variability in mangosteen peel reported by Okonogi et al. (2018) and the storage demands of a four-month harvest window. Staff training scored 4.0/5, while market acceptance was relatively low-risk at 2.5/5.

Table 2. Mass balance, GHG impact, and economic returns of the mangosteen-peel valorization intervention

Indicator	Before intervention	After intervention	Change	Reference
Total peel waste generated (kg/year)	433,120	433,120	0 (0.0%)	This study
Peel to landfill (kg/year)	433,120	150,000	–283,120 (–65.4%)	[5]
Peel diverted to valorization (kg/year)	0	283,120	+283,120	This study
Dried by-product output (kg/year)	0	42,468	+42,468 (15.0% yield)	[21]
– Nutraceuticals: extract powder (kg/year, THB/kg)	—	25,480 @ 80	+2,038,400 THB/year	[6]
– Cosmetics: peel powder (kg/year, THB/kg)	—	12,741 @ 55	+701,755 THB/year	This study
– Animal feed: residue (kg/year, THB/kg)	—	4,247 @ 22	+91,568 THB/year	This study
By-product revenue (THB/year, USD/year)	0	2,831,723 (≈ \$80,906)	+2,831,723 THB/year	This study
GHG, landfill CH ₄ (tCO ₂ eq/year)	450.90	155.83	–295.07 (–65.4%)	[13]
GHG, transport (tCO ₂ eq/year)	5.22	2.14	–3.08 (–59.0%)	[13]
GHG, total waste stream (tCO ₂ eq/year)	456.12	157.97	–298.15 (–65.4%)	[13]; [22]
Implementation difficulty: quality control & seasonality (1–5)	—	4.5	—	[4]
Implementation difficulty: staff training (1–5)	—	4.0	—	This study
Implementation difficulty: market acceptance (1–5)	—	2.5	—	[6]

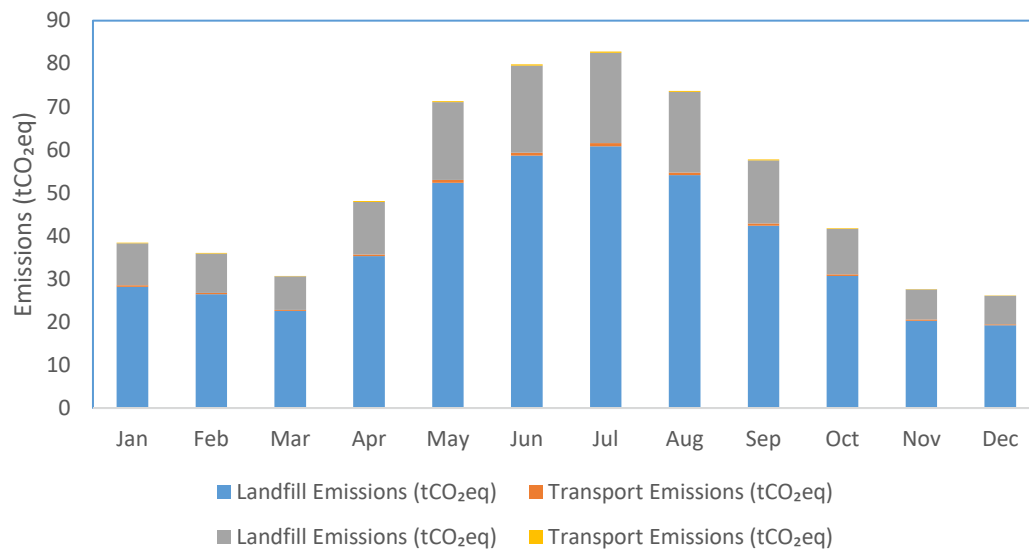


Figure 4. Monthly GHG emissions from waste management before and after the valorization intervention, showing the May–August harvest-season peak and the year-round reduction (tCO₂eq/month).

3.3 Combined Environmental Impact

Stacking the two interventions produced an aggregate GHG reduction of 326.22 tCO₂eq/year — a 62.0% cut against the 526.34 tCO₂eq/year baseline (Table 3). The pattern of contributions is uneven: waste valorization accounts for 298.15 tCO₂eq (91.4% of the total reduction), while solar-panel cleaning accounts for 28.07 tCO₂eq (8.6%). The asymmetry reflects the relative scale of the underlying emission pools; landfill methane from organic waste dwarfs grid electricity emissions on a per-facility basis [13]. The 62.0% reduction substantially exceeds the 25–30% average reported by the Thailand Department of Industrial Works (2022) for food-processing SMEs implementing single-focus measures, and is consistent with the gains achievable through combined mitigation strategies in Thailand's industrial sector [3]. It is consistent with the synergistic gains documented by Sethi et al. (2020) when energy and waste interventions are deployed together rather than in isolation. Carbon intensity of production fell from 725.0 to 267.0 kgCO₂eq/ton of finished product (−63.2%), moving the facility from above to well below the 520 kgCO₂eq/ton industry average reported by Kanjanajuntorn et al. (2021) for Thai frozen-fruit processors; life-cycle assessments of other Thai food products report comparable reductions achievable through process optimization [9]. Under the TFFA (2022) sustainability classification, this re-rates the facility from “standard” to “high-performance.” Multi-indicator performance improved in parallel. Water-use efficiency rose 22% via the recovery loop integrated into the peel-processing line — a co-benefit rather than a primary design target, but one that reinforces the multi-criterion framing advocated by Mungkung et al. (2020). The facility's composite BCG (Bio-Circular-Green) index, defined by Thailand's Ministry of Higher Education, Science, Research and Innovation (2021), advanced from 0.42 to 0.78 (0–1), reflecting simultaneous gains in biological resource utilization, circular material flows, and GHG reduction. It should be noted that, because both interventions were launched simultaneously in October 2023, the GHG and economic apportionments between solar optimization and waste valorization reported herein were derived from individual emission factors applied to activity data (modeled attribution), rather than from observed post-intervention measurements of each intervention in isolation. The BCG composite index was scored using the three-domain framework of MHESI (2021), with equal weighting across bio-economy, circular economy, and green economy sub-indices; readers are referred to that source for full methodological details.

Table 3. Combined environmental impact of solar optimization and waste valorization

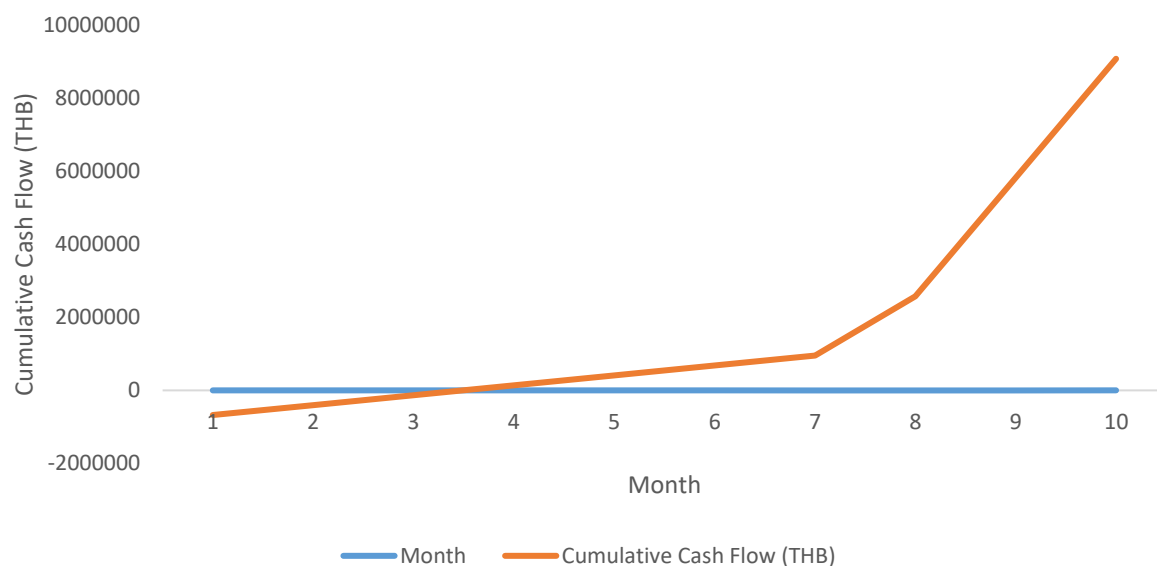
Indicator	Baseline	Post-intervention	Reduction	% change	Reference
GHG, electricity (tCO ₂ eq/year)	70.22	42.15	28.07	−40.0%	[13]
GHG, waste disposal (tCO ₂ eq/year)	456.12	157.97	298.15	−65.4%	[13]
GHG, total (tCO ₂ eq/year)	526.34	200.12	326.22	−62.0%	This study
– Share from waste valorization	—	—	298.15 (91.4%)	—	This study
– Share from solar optimization	—	—	28.07 (8.6%)	—	This study
Carbon intensity (kgCO ₂ eq/ton product)	725.0	267.0	458.0	−63.2%	[23]
Industry SME benchmark (Thailand)	—	25–30% reduction	—	—	[24]
TFFA sustainability tier	Standard	High-performance	—	—	[25]
Water-use efficiency	1.00 (index)	1.22 (index)	—	+22.0%	[26]
BCG index (0–1 scale)	0.42	0.78	+0.36	+85.7%	[27]

3.4 Economic Benefits Analysis

Capital expenditure for the two interventions totaled 675,000 THB, dominated by the waste-management system (630,000 THB), with solar-panel optimization adding 45,000 THB (Table 4). The figure falls within the 500,000–700,000 THB range reported by Chaikitkaew et al. (2021) for comparable waste-valorization installations at Thai food-processing SMEs. Annual maintenance is modest at 130,000 THB (95,000 THB waste + 35,000 THB solar). Operating-cost savings reach 549,872 THB/year — 380,000 THB from displaced grid electricity [17] and 169,872 THB from reduced landfill disposal volumes. The proportional cost relief exceeds the 15–25% range documented by Boonkanit and Kantharos (2019) for single-intervention sustainability projects in the same sector, consistent with the magnitude of the underlying physical reductions. The dominant economic effect is the new revenue stream from by-product sales, valued at 2,831,723 THB/year [6]. Total gross annual benefit is therefore 3,381,595 THB, and net annual benefit after maintenance is 3,251,595 THB (Table 4). Taken together, these flows make the investment case unusually robust: the combined intervention recovers its full 675,000 THB outlay in 2.5 months and returns several times the initial capital within the first year. Payback against the 675,000 THB outlay is 0.21 years — 2.5 months — driven almost entirely by the by-product revenue line (Figure 5). Year-1 ROI is 382% and rises to 1,346% by Year 3, computed as (cumulative net benefit – investment) / investment. This substantially outperforms the 40–60% ROI benchmark Thailand’s Board of Investment (2023) reports for typical SME sustainability projects and the returns reported for utility-scale renewable-energy investments in Thailand [21], and is consistent with Sethaputra et al. (2022) observation that combined energy + waste-valorization projects deliver higher ROI than single-focus initiatives.

Table 4. Capital expenditure, operating savings, and return-on-investment summary

Line item	Solar optimization	Waste valorization	Combined	Reference
Capex — equipment/materials (THB)	25,000	420,000	445,000	[28]
Capex — installation (THB)	15,000	180,000	195,000	This study
Capex — training (THB)	5,000	30,000	35,000	This study
Total initial investment (THB)	45,000	630,000	675,000	This study
Annual maintenance (THB/year)	35,000	95,000	130,000	This study
Annual operating savings, electricity (THB/year)	380,000	—	380,000	[17]
Annual operating savings, waste disposal (THB/year)	—	169,872	169,872	This study
Annual by-product revenue (THB/year)	—	2,831,723	2,831,723	[6]
Gross annual benefit (THB/year)	380,000	3,001,595	3,381,595	This study
Net annual benefit, after maintenance (THB/year)	345,000	2,906,595	3,251,595	This study
Payback period (years)	0.13 (≈ 1.6 mo)	0.22 (≈ 2.6 mo)	0.21 (≈ 2.5 mo)	This study
Year-1 ROI (%)	667%	361%	382%	[29]
Year-3 ROI (%)	2,200%	1,284%	1,346%	[30]

**Figure 5.** Cumulative Cash Flow and Payback Analysis

3.5 Scalability and Policy Implications

Sectoral scalability potential for the two interventions, based on findings from this single-facility case study, appears uneven (Table 5). Solar-panel optimization may transfer across most food-processing sub-sectors because rooftop area and daytime electrical demand are common features of the building stock [22]; the main constraint is whether the facility already operates a PV array. Waste valorization, by contrast, scales with the bioactive-compound density of the by-product stream, which is high for fruit processors [5] but materially lower for vegetable and meat processing, where compositional value and regulatory pathways differ. Adoption barriers are concentrated on the financial side (Figure 6). As Figure 6 makes visually apparent, the two financial barriers rank highest and cluster closely together, standing clearly above the technical and operational barriers — indicating that capital, rather than know-how, is the binding constraint on adoption. Capital cost (score 4.2/5) and access to financing (3.9/5) are the dominant obstacles, consistent with Boonkanit

and Kantharos (2019)'s identification of capital constraints as the primary barrier to SME sustainability adoption in Thailand. Technical-knowledge requirements (3.8/5) are a secondary but substantive constraint, particularly for the extraction-and-quality-control workflows central to valorization [23]. Three policy levers follow from these findings. First, the Board of Investment's (2023) Green Industry incentive framework could be extended with food-processing-specific provisions — tax holidays and import-duty waivers on valorization equipment — to address the capital-cost barrier. Second, technical knowledge gaps would be addressed by sector-targeted technology-transfer programs of the kind proposed by Chanthawong et al. (2022). Third, demand-side measures such as eco-labeling and procurement preferences [24] would help create market pull for lower-footprint products. Thailand's BCG (Bio-Circular-Green) Economy Model offers an appropriate umbrella framework [8], but Chanthawong et al. (2022) note that regulatory fragmentation across agencies currently slows uptake of novel valorization routes; coordinated permitting and simplified compliance would materially accelerate diffusion.

Table 5. Sector-level scalability and adoption barriers for the integrated intervention

Sub-sector / barrier dimension	Solar optimization	Waste valorization	Combined potential	Key adaptation requirement	Reference
Frozen tropical fruits	High	High	High	Direct application; minimal adaptation	This study
Canned fruits	High	Medium	Medium–High	Modified drying for wet-waste streams	[31]
Fruit-juice production	High	Medium	Medium–High	Pulp-valorization process retrofit	[5]
Vegetable processing	High	Low–Medium	Medium	Alternative bioactive-extraction routes	[4]
Meat processing	Medium	Low	Low–Medium	Substantial process redesign required	This study
Adoption barrier — Capital cost (1–5)	—	4.2	—	Address via BOI Green Industry incentives	[29]; [32]
Adoption barrier — Access to financing (1–5)	—	3.9	—	Sector-targeted credit facilities	[32]
Adoption barrier — Technical knowledge (1–5)	—	3.8	—	Technology-transfer programs	[33]; [4]
Policy framework	—	—	BCG Economy Model	Coordinated permitting; eco-labeling	[27]; [26]

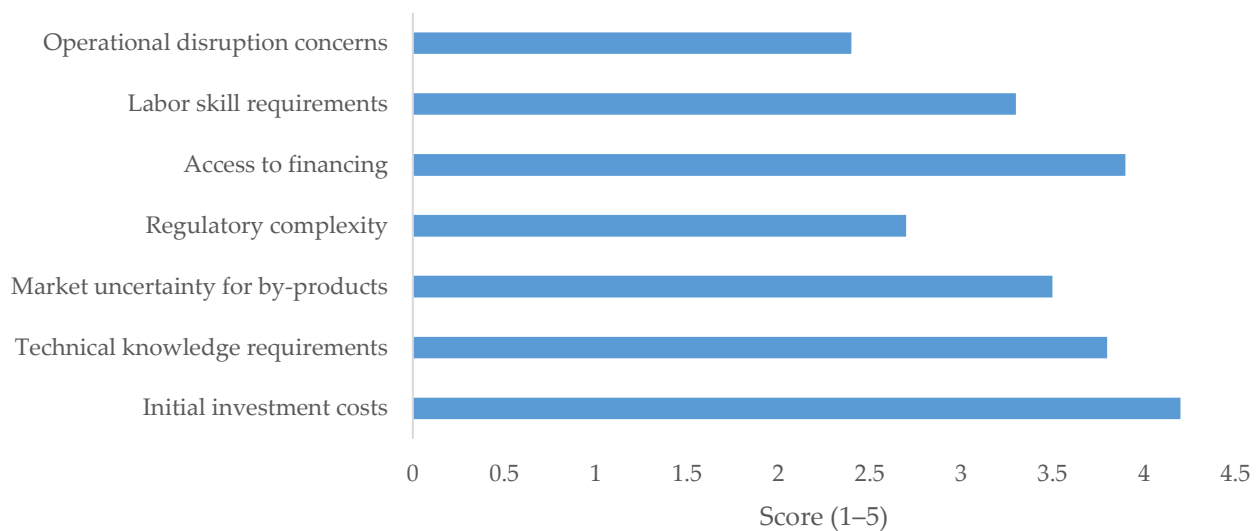


Figure 6. Adoption barriers for the integrated intervention, ranked by severity score (1–5 scale), showing financial barriers (capital cost, access to financing) above technical and operational barriers.

4. Conclusions

Integrating solar-panel optimization with mangosteen peel valorization reduced total greenhouse gas emissions at the study facility by 62.0% (326.22 tCO₂eq/year) while turning the sustainability program into a net profit center. Waste valorization accounted for the vast majority of the abatement (298.15 tCO₂eq, 91.4%), with solar optimization accounting for the remainder (28.07 tCO₂eq, 8.6%) — a split that reflects the dominance of landfill methane over grid electricity in the facility's emission profile. The economic case was decisive rather than marginal: 549,872 THB in annual operating savings combined with 2,831,723 THB in new by-product revenue produced a payback of roughly 2.5 months. Together, these results provide empirical evidence for the economic viability of combined sustainability measures in food-processing SMEs, challenge the perception that environmental improvements necessarily raise costs, and offer a practical implementation model for processors in tropical regions with comparable agricultural waste streams under Thailand's BCG Economy framework. Several limitations should be acknowledged. First, the short post-intervention monitoring period (3 months) necessitates caution when projecting long-term results. Second, the high-value mangosteen peel application may not be replicated for all fruit processing wastes, potentially limiting economic returns for different fruit processors. Third, local factors, including climate conditions and market dynamics, influence results and may differ in other regions. For industry adoption, we recommend (1) establishing monthly solar panel cleaning protocols calibrated to local dust accumulation rates; (2) implementing systematic waste segregation at source to ensure by-product quality; (3) developing phased investment approaches, beginning with low-cost energy optimization before larger waste valorization investments; and (4) pursuing industry collaborations to share processing facilities for seasonal fruit operations, improving capacity utilization. These approaches can help other food processors achieve similar environmental and economic benefits, contributing to Thailand's sustainability goals while enhancing business performance.

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