SIAR-Global Journal of Engineering & Agricultural Review (GJEAR)
www.siarpublications.org ISSN: 3121-9896
info@siarpublications.org Vol. 2 Issue 1 Jan.-March, 2025

ECO-FRESH Nigeria: Integrating Circular Bioenergy, Solar Cold Chains, and Agroecology for Methane Mitigation and Food Security.

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Abstract

ECO-FRESH Nigeria is an integrated circular food-system model linking organic waste–to–bioenergy (anaerobic digestion), solar-assisted cold storage, and agroecological production support to address methane mitigation and food security simultaneously. We evaluated ECO-FRESH using a mixed-methods, quasi-experimental design across three pilot hubs with matched comparison communities and baseline endline measurement over 12 months. Operational monitoring tracked waste diversion, biogas production, and cold-room reliability, while impact evaluation assessed postharvest losses, quality outcomes, farmgate prices, and incomes. Methane mitigation was quantified using a measurement, reporting, and verification (MRV) framework with sensitivity analysis. Average organic waste diverted was 5.1 t/day and biogas production 410 m^3/day. Cold-room throughput averaged 6.8 t/day with 95.2% uptime and 92.3% temperature compliance. Difference-in-differences estimates show postharvest losses declined by 12.0 percentage points (95% CI: -14.3 to -9.7), accompanied by higher Grade A share and lower rejection rates ($p < .001$). Farmgate prices increased by ₦40/kg, and monthly net farm income rose by ₦20,700 (≈24% growth). MRV results estimate an annualized net climate benefit of 18,540 tCO_2e/year (range: 14,200–23,900). Impacts were broadly inclusive, though smaller for producers farthest from hubs, highlighting logistics as a key equity constraint.

Keywords: methane mitigation; anaerobic digestion; solar cold chain; postharvest loss; circular economy; agroecology; Nigeria; inclusive food systems

1. INTRODUCTION

Nigeria's food system faces three interconnected pressures: rising climate risks and emissions, substantial postharvest losses of perishable foods, and persistent food and nutrition insecurity. These challenges reinforce one another. Weak cold-chain infrastructure accelerates spoilage of nutrient-dense foods, reducing farmer incomes and limiting the availability and affordability of healthy diets. At the same time, unmanaged organic waste from households, markets, and farms often decomposes under low-oxygen conditions and contributes to methane (CH_4) emissions, while cooking and enterprise energy needs are frequently met with fuels that impose health, cost, and environmental burdens. Addressing these problems separately can shift impacts across the system for example, expanding refrigeration without clean energy may increase emissions and operating costs, while waste management programs disconnected from value chains may fail to generate sustained livelihood or nutrition benefits. Methane mitigation is particularly important for near-term climate progress because methane has a strong warming effect relative to carbon dioxide over standard reporting horizons. Updated global-warming-potential (GWP) values aligned with IPCC AR6 are now widely referenced in greenhouse gas accounting and reporting guidance (Greenhouse Gas Protocol, 2024). In Nigeria, the scale of solid waste generation and the high share of organic waste strengthen the case for diversion-based interventions. A Federal Ministry of Environment presentation hosted by UNIDO reports that Nigeria generates more than 32 million tonnes of solid waste annually, with a substantial organic fraction (Ikeah, 2022). Where organic waste is poorly managed, circular treatment pathways can deliver climate benefits while also producing local energy and soil-fertility co-products. Anaerobic digestion is a well-established waste-to-value pathway that converts organic waste into biogas and digestate, capturing methane that would otherwise be emitted during uncontrolled decomposition and producing usable fuel and nutrient-rich soil amendments (U.S. Environmental Protection Agency, 2025). These dual outputs are particularly relevant for community-scale systems seeking both climate and livelihood co-benefits.

Postharvest loss represents a second major constraint on food security and farmer profitability, especially for fresh fruits and vegetables. In Nigeria, GAIN reports high losses for nutrient-rich perishables, with substantial losses occurring after harvest during transport, storage, and marketing (Global Alliance for Improved Nutrition [GAIN], 2022). Cold-chain access is therefore a critical lever for food system efficiency and nutrition outcomes, but scaling storage in weak-grid contexts requires reliable, cost-effective energy solutions. Decentralized solar-powered cold storage has emerged as a promising approach, with reviews highlighting the importance of system sizing, reliability, and user-centered business models (Amjad et al., 2023). Evidence from northeast Nigeria indicates that solar cold storage can reduce spoilage and improve market outcomes when appropriately deployed (Takeshima et al., 2021). Against this background, ECO-FRESH Nigeria is designed as a closed-loop model integrating circular bioenergy, solar-assisted cold storage, and agroecological production support to jointly address methane mitigation, postharvest loss reduction, and food security

Fig 1: Conceptual framework of the ECO-FRESH Nigeria integrated circular bioenergy-cold chain-agroecology system.

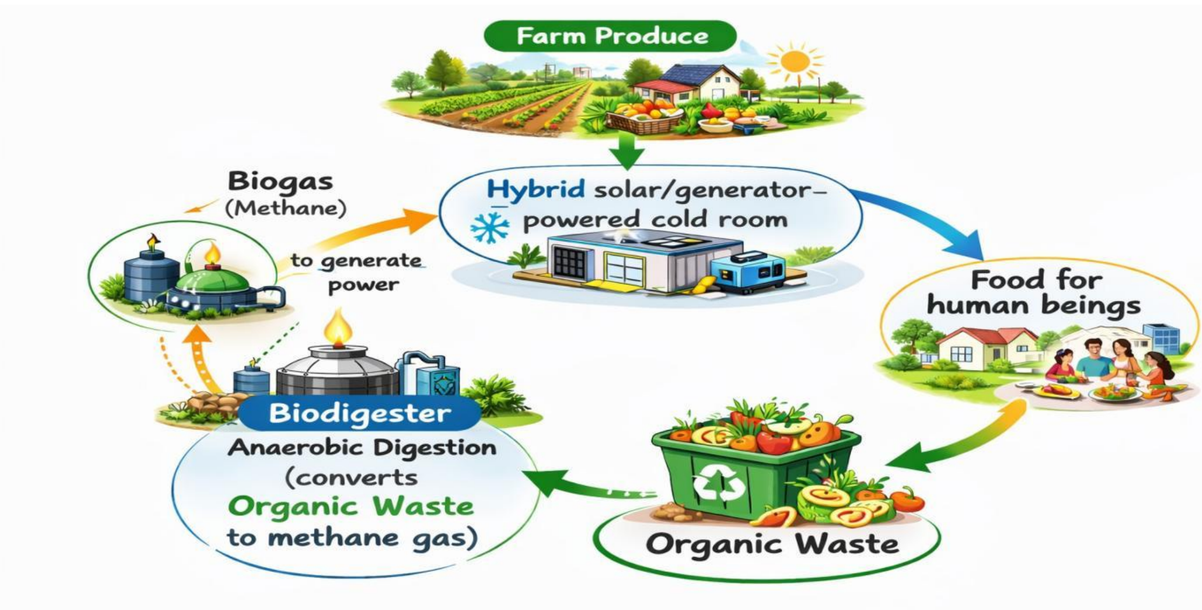


Figure 1 presents the ECO-FRESH system logic and material/energy flows from organic waste capture to biogas and digestate outputs, cold-chain services, market distribution, and residual *return loops. By treating waste, energy, cold-chain infrastructure, and production practices as one connected system, the ECO-FRESH approach aims to convert Nigeria's organic waste challenge into a triple-win pathway for climate action, food security, and inclusive rural livelihoods.*

2. LITERATURE REVIEW

A. Methane mitigation, organic waste, and the circular economy opportunity in Nigeria

Methane (CH_4) is increasingly prioritized in climate policy due to its strong warming effect relative to CO_2 over standard accounting horizons, with reporting frameworks now reflecting IPCC AR6-aligned global warming potential values (Greenhouse Gas Protocol, 2024). In Nigeria, organic waste management represents a significant methane pathway because biodegradable waste frequently enters open dumping systems where anaerobic decomposition generates methane. Nigeria produces over 32 million tonnes of solid waste annually, much of it organic, underscoring the mitigation potential of diversion-based approaches (Ikeah, 2022). City-level strategies, such as the Rocky Mountain Institute playbook for Lagos, highlight methane mitigation opportunities across collection, treatment, and disposal systems (Rocky Mountain Institute, 2024). Together, this literature identifies organic waste diversion and recovery as a high-leverage mitigation strategy with co-benefits in sanitation, energy access, and local economic activity.

B. Anaerobic digestion as a waste-to-value pathway

Anaerobic digestion (AD) is a mature technology that converts organic waste into biogas and digestate under oxygen-free conditions. AD reduces methane emissions by capturing biogas that would otherwise be released during uncontrolled decomposition and produces renewable energy and nutrient-rich soil amendments (U.S. Environmental Protection Agency, 2025a, 2025b). Performance depends on reliable feedstock supply, effective operations and maintenance, leakage control, and viable digestate utilization pathways. In agro-food systems, AD links methane abatement with substitution benefits: biogas can offset traditional fuels, while digestate can reduce dependence on synthetic fertilizers (U.S. Environmental Protection Agency, 2025a, 2025b). This integration strengthens the circular economy rationale for community-scale deployment.

C. Postharvest loss and cold-chain constraints in Nigeria

Postharvest loss is widely recognized as a binding constraint on food security, diet quality, and smallholder incomes. In Nigeria, up to 50% of nutrient-rich fresh fruits and vegetables may be lost or wasted, with nearly half occurring after harvest during transport, storage, and processing (Global Alliance for Improved Nutrition [GAIN], 2022). Reducing spoilage increases effective food supply and enhances value capture without expanding production inputs, reframing cold chains as nutrition-sensitive efficiency interventions rather than mere infrastructure upgrades.

D. Solar-powered cold storage and resilience design

Renewable-powered cold storage is frequently proposed for weak-grid contexts, but evidence emphasizes that outcomes depend on reliability, utilization, and business models rather than hardware alone (Amjad et al., 2023). Empirical evidence from northeast Nigeria shows that solar cold storage increased horticulture sales and revenues for market agents, though careful attention to design and governance is required to ensure equitable access (Takeshima et al., 2021). Thermal energy storage, including phase change materials (PCMs), is often proposed to enhance resilience by stabilizing temperatures during short interruptions. Reviews highlight performance sensitivity to material selection and system integration (Liang et al., 2025; Ouaouja et al., 2025). In off-grid Nigerian contexts, PCMs are best viewed as reliability enhancers rather than standalone solutions.

E. Agroecology and circular supply chains

Agroecology integrates ecological and social principles to strengthen resilience and food security, with outcomes shaped by knowledge systems and market access (Dagunga et al., 2023). For cold-chain hubs, diversified production and improved soil health can stabilize supply and enhance quality. Circular food-system models also require robust reverse logistics and measurable performance indicators. Research on reusable packaging systems stresses the importance of system-level metrics such as recovery rates and logistics costs to assess feasibility and circularity (Betts et al., 2022).

F. Synthesis and research gap

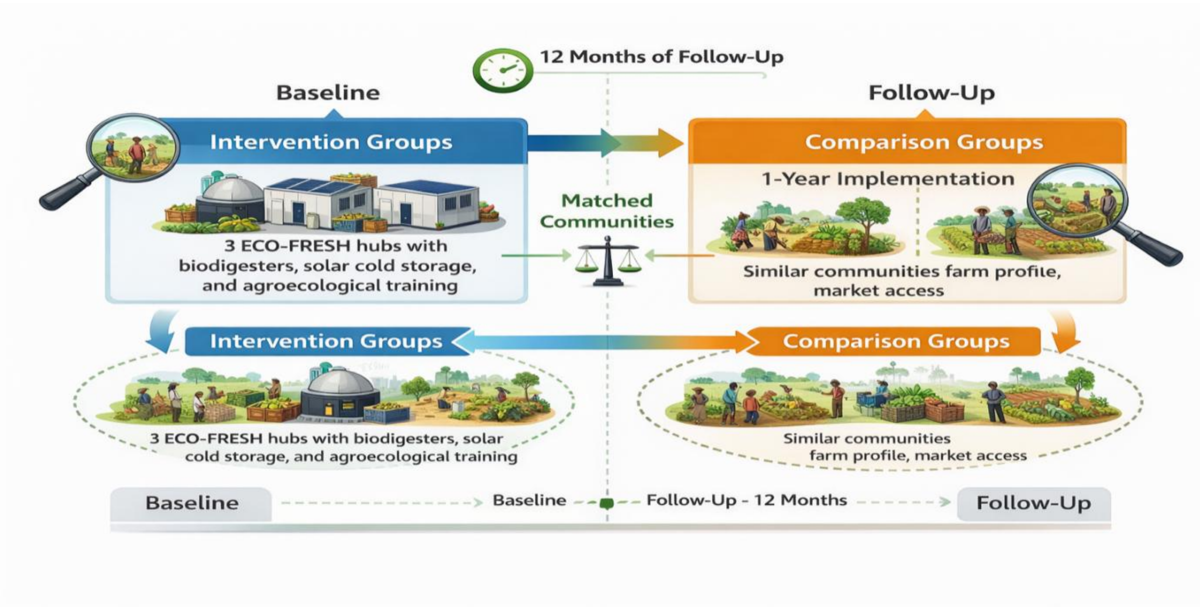
The literature strongly supports each component of the ECO-FRESH model: organic waste diversion for methane mitigation, AD for energy and nutrient recovery, solar cold storage for loss reduction, thermal storage for resilience, and agroecology for sustainability. However, most studies evaluate these components independently. Evidence remains limited on integrated, closed-loop hub models that simultaneously connect waste-to-energy, renewable cold chains, and nutrient cycling while jointly measuring climate, loss-reduction, and livelihood impacts using quasi-experimental designs and MRV-aligned accounting. While Nigeria-specific evidence exists for waste and solar cold storage (Ikeah, 2022; Takeshima et al., 2021), the integrated "hub" model remains under-evaluated. This gap motivates research focused on system performance, equity outcomes, and net climate impacts rather than isolated technological interventions.

3. MATERIALS AND METHODS

A. Study design

This study used a mixed-methods quasi-experimental design to assess the performance and impacts of ECO-FRESH Nigeria, an integrated intervention that combines circular bioenergy (anaerobic digestion of organic waste), solar-assisted cold-chain hubs, and agroecological capacity building. The evaluation followed a theory of change framework in which operational performance (waste diversion, biogas output, cold-room reliability, service uptake) was hypothesized to drive environmental outcomes (methane avoidance and net climate impact), food-system outcomes (postharvest loss reduction and quality retention), and livelihood outcomes (prices, incomes, and distribution of benefits). Quantitative analysis was paired with qualitative inquiry to explain technology adoption behavior, governance dynamics, and barriers to equitable and inclusive access.

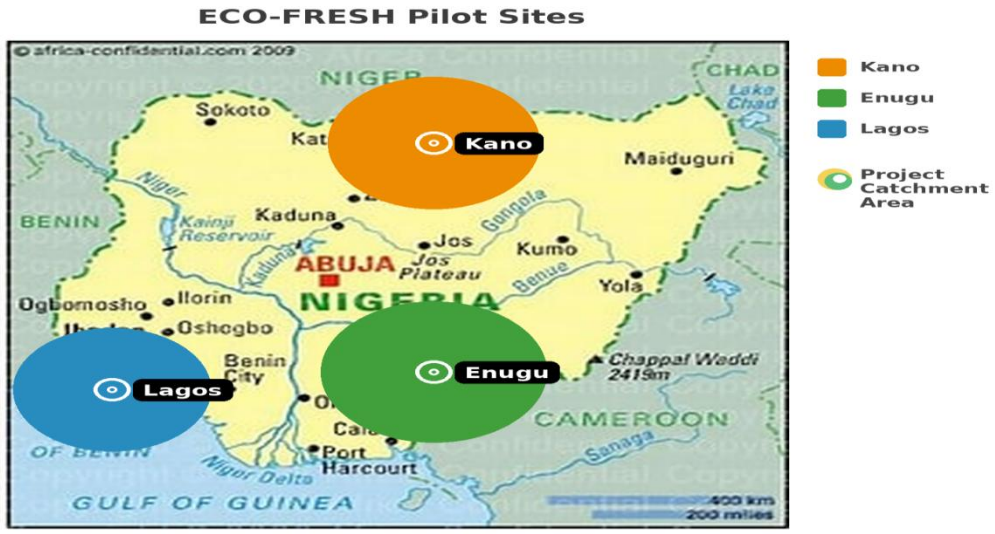
Figure 2. Quasi-experimental evaluation design and data collection timeline for ECO-FRESH Nigeria.



B. Study area and site selection

Within each study setting, an ECO-FRESH hub was established and its catchment area defined as the intervention zone. Comparison communities were selected within the same setting (or an immediately comparable zone) using matching criteria designed to approximate counterfactual conditions in the absence of the intervention. Matching criteria included dominant crop/value-chain profile, baseline postharvest loss levels, population and market participation characteristics, distance to primary markets, baseline access to storage, and observed seasonal price patterns. The final evaluation sample included 36 communities in total (18 intervention; 18 comparison). Baseline data were collected prior to full operational rollout of the intervention, followed by endline measurement after 12 months of continuous operations. Continuous operational monitoring occurred throughout implementation to capture reliability and seasonal variation effects.

Figure 3 *Map of ECO-FRESH Nigeria pilot locations and hub catchment areas in Lagos, Kano, and Enugu States.*



Note: This map is used to contextualize site selection, interpret logistical constraints (especially distance-to-hub and market access), and support transparency regarding the spatial scope of the intervention.

C. *Intervention description*

ECO-FRESH was delivered as a bundled package rather than independent components, because system impacts depend on integration. Organic waste-to-bioenergy was implemented through community-scale anaerobic digesters that processed farm residues, household/market organics, and other locally available biodegradable inputs. Digesters produced biogas for energy services and digestate intended for beneficial agricultural use subject to nutrient analysis and soil suitability assessment. Solar-assisted cold-chain hubs provided temperature-controlled storage near production clusters. Solar energy supplied the primary electricity demand, with resilience features that included thermal buffering and biogas backup during low-solar periods or short disruptions. Cold-room services were designed to support aggregation, maintain product quality, and reduce spoilage. Agroecological capacity building was implemented through structured training and extension support focused on regenerative and low-input practices, including diversified systems, soil cover practices, integrated pest management, and circular nutrient use via digestate substitution (subject to agronomic validation protocols). Circular market linkage mechanisms were implemented to strengthen utilization and close loops, using aggregation rules, reusable logistics practices, and incentive structures that supported consistent service use and waste return to treatment pathways.

D. *Implementation fidelity and process monitoring*

Because integrated interventions can show weak outcomes when individual components are not delivered consistently, implementation fidelity was monitored continuously. Fidelity indicators included completion of installation and commissioning, digester feeding and stability logs, biogas production logs, cold-room throughput records, uptime and downtime event logs, maintenance response records, training participation registers, digestate output records, and digestate distribution and on-farm application records. These indicators served two functions: operational learning (identifying bottlenecks) and interpretation of impacts (testing whether stronger implementation intensity produced stronger outcomes).

E. Data sources and measurement procedures

Cold-chain technical performance

Cold-room performance was monitored using continuous temperature logging and energy metering. Temperature compliance was calculated as the proportion of operating time within commodity-relevant target ranges. Reliability was assessed through uptime and downtime logs, including downtime frequency, duration, and attributed cause. Energy performance was assessed using total electricity consumption and source contribution shares (solar, biogas backup, and contingency supply). Thermal buffering performance was assessed during interruption events using time-to-threshold indicators, comparing the time required for temperatures to exceed target thresholds during disruptions.

Anaerobic digestion performance and material flows

Digester performance was measured using routine recording of organic waste inflows (mass per day), feedstock type composition (systematically categorized by standardized waste typology), biogas volume output, and periodic measurement of methane concentration to characterize energy quality. Digestate output was recorded, and application to farms was tracked through distribution logs and farmer reporting, supported by spot checks. These measurements supported both system performance assessment and climate accounting.

Postharvest loss and quality outcomes

Postharvest losses were measured for priority perishables selected per hub based on local importance and spoilage risk. Loss measurement combined repeated physical loss audits at key nodes (farmgate/harvest, aggregation, storage, and market) with quality grading and rejection rates. Physical loss was measured as the proportion of product mass lost or rendered unmarketable. Economic loss was assessed by incorporating price differences associated with grade outcomes and rejected produce. Where available, trader transaction records and market logs were used to triangulate self-reported quantities and reduce recall bias.

Socioeconomic outcomes and market behavior

Producer and trader surveys measured farmgate price received (₦/kg), volumes sold, share of produce sold in higher grades, timing of sales relative to seasonal glut periods, and net income proxies (₦/month). Household surveys collected basic food security proxies where within scope. Equity variables were collected for all respondents, including gender, youth status (18–35), farm size (for farm-size quartiles), and distance-to-hub (for distance quartiles). These variables were used to assess whether access and benefits were equitably distributed.

Qualitative inquiry

Key informant interviews and focus group discussions were conducted with farmers, traders, hub operators, cooperative leaders, and local authorities. Qualitative tools focused on perceived constraints to adoption, willingness to pay, service allocation rules, trust and governance, operational pain points, and inclusion barriers (especially transport/coordination and participation in decision-making). Qualitative findings were used to interpret heterogeneous impacts and validate mechanism pathways identified in quantitative analysis.

F. Methane mitigation accounting and MRV approach

Methane mitigation and net climate impacts were quantified using a Monitoring, Reporting, and Verification (MRV) approach grounded in measured activity data and standardized greenhouse gas inventory methods. The MRV system used organic waste diversion volumes, biogas production and utilization, baseline waste disposal practices, and baseline fuel-use patterns to estimate net impacts. Net tCO_2e avoided was estimated as the sum of avoided methane emissions from diverting organics from uncontrolled decomposition plus avoided emissions from displaced baseline fuels due to biogas utilization, minus deductions for leakage and inefficiencies. Climate reporting used AR6-aligned global warming potentials where methane-to-CO_2e conversion was required. To avoid overstatement, uncertainty was addressed through sensitivity analysis on high-influence parameters including baseline disposal pathway assumptions, waste composition, methane emission factors, and leakage rates. This produced best estimates plus plausible bounds rather than a single-point claim.

G. Statistical analysis

Primary impacts were estimated using difference-in-differences (DiD), comparing changes from baseline to endline in intervention communities relative to changes in matched comparison communities. The main model included controls for distance-to-market, commodity type (where relevant), and other baseline covariates, with community- or market-level clustering of standard errors to account for within-site correlation. Outcomes analyzed included postharvest loss rate (%), rejection rate (%), Grade A share (%), marketable shelf-life (days), farmgate price (₦/kg), monthly net income (₦), and market timing indicators (e.g., share of sales after peak glut). Distributional impacts were tested using interaction models that estimated differential treatment effects by gender, youth status, farm-size quartile, and distance-to-hub quartile. The interaction term between treatment status, time, and group membership was interpreted as the differential impact for that group relative to the reference group. This enabled inclusion to be evaluated as a core outcome domain, not simply as descriptive reporting. To test whether observed impacts follow the ECO-FRESH mechanism, additional analyses related outcomes to implementation intensity and technical performance. For example, postharvest loss reduction was examined relative to cold-room utilization and temperature compliance, controlling for commodity and site. Income changes were examined relative to frequency of cold storage use and changes in grade outcomes. These checks were used to assess whether the pathway from reliability to quality to price/income is supported by the data.

H. Techno-economic analysis and life-cycle assessment

Techno-economic analysis

A hub-level techno-economic analysis (TEA) combined capital costs (digesters, solar systems, cold rooms, thermal storage, installation) and operating costs (labor, maintenance, replacements, logistics) with observed revenues (storage fees, biogas sales/subscriptions, digestate value). Financial performance was summarized using unit economics, payback behavior, and sensitivity tests for utilization rates, pricing, and maintenance assumptions. Carbon finance was treated as a scenario-based upside rather than a required condition for viability.

Life-cycle assessment

A comparative life-cycle assessment (LCA) estimated net environmental impacts of ECO-FRESH relative to baseline conditions using a defined functional unit (per tonne of organic waste treated and/or per kilogram of produce delivered in marketable condition). The system boundary included waste diversion and treatment, biogas use, cold storage operations, and baseline disposal and energy pathways necessary for comparison. Scenario analysis compared baseline and intervention conditions, and uncertainty was assessed through sensitivity analysis for methane factors, leakage, cold-room utilization, and digestate substitution rates.

I. Ethics and data quality assurance

All participants provided informed consent. Survey data were anonymized and securely stored. Enumerators were trained and instruments piloted prior to baseline deployment. Quality assurance included back-checks, consistency and logic checks, and triangulation across sensor logs, operational records, and transaction data. For climate accounting, assumptions and uncertainty bounds were reported transparently to support replicability and policy relevance.

4. RESULTS

A. Study sample, follow-up, and baseline comparability

The evaluation covered 36 communities, including 18 intervention communities linked to ECO-FRESH hubs and 18 matched comparison communities. Data were collected from 900 producers (450 intervention; 450 comparison), 180 market agents/traders (90 intervention-linked; 90 comparison), and 600 households (300 intervention; 300 comparison). Follow-up rates were high and similar across groups, with endline completion of 93.1% among intervention producers and 92.4% among comparison producers, limiting concerns about differential attrition. Baseline balance diagnostics indicate that intervention and comparison samples were closely matched on key pre-intervention characteristics. Farm size, baseline postharvest loss rates, baseline farmgate prices, access to cold storage, gender composition, and youth share were statistically similar. Distance to the nearest market was modestly higher in the comparison group, and this variable was included as a control in all main models. Table 1 reports baseline characteristics and standardized mean differences and confirms that the matched design produced broadly comparable groups prior to implementation.

Table 1. Baseline characteristics and balance

Variable	Intervention (n=450)	Comparison (n=450)	Std. Mean Diff.
Farm size (ha)	1.42 (0.88)	1.39 (0.91)	0.03
Distance to nearest market (km)	18.6 (9.7)	19.9 (10.2)	-0.13
Baseline postharvest loss (%)	39.6 (12.1)	38.9 (11.8)	0.06
Baseline farmgate price (₦/kg)	265 (54)	268 (56)	-0.05
Access to any cold storage (%)	6.2	6.8	-0.03
Female primary decision-maker (%)	41.8	40.9	0.02
Youth (18–35) (%)	34.0	33.1	0.02

B. Hub operations, utilization, and service intensity

Operational data show that the three hubs achieved stable use levels sufficient to test the ECO-FRESH theory of change under real conditions. Across 12 months, average organic waste diverted to anaerobic digestion was 5.1 tonnes/day per hub, ranging from 4.4 tonnes/day in Kano to 5.9 tonnes/day in Lagos. Biogas output averaged 410 m³/day per hub, with methane content averaging 59%, indicating consistent energy quality across sites. Cold-room throughput averaged 6.8 tonnes/day per hub, and mean utilization reached 74% of rated capacity, suggesting that storage services were actively used rather than underutilized demonstration assets. Reliability indicators were strong. Cold-room uptime averaged 95.2%, with downtime concentrated in a small number of maintenance-related incidents and short solar-system faults rather than persistent system failure. Lagos recorded the highest utilization and throughput, Kano had the lowest utilization and higher variability, and Enugu achieved comparatively stable performance across the year. Table 2 summarizes the operational results that form the "implementation intensity" foundation for interpreting climate and food-system outcomes.

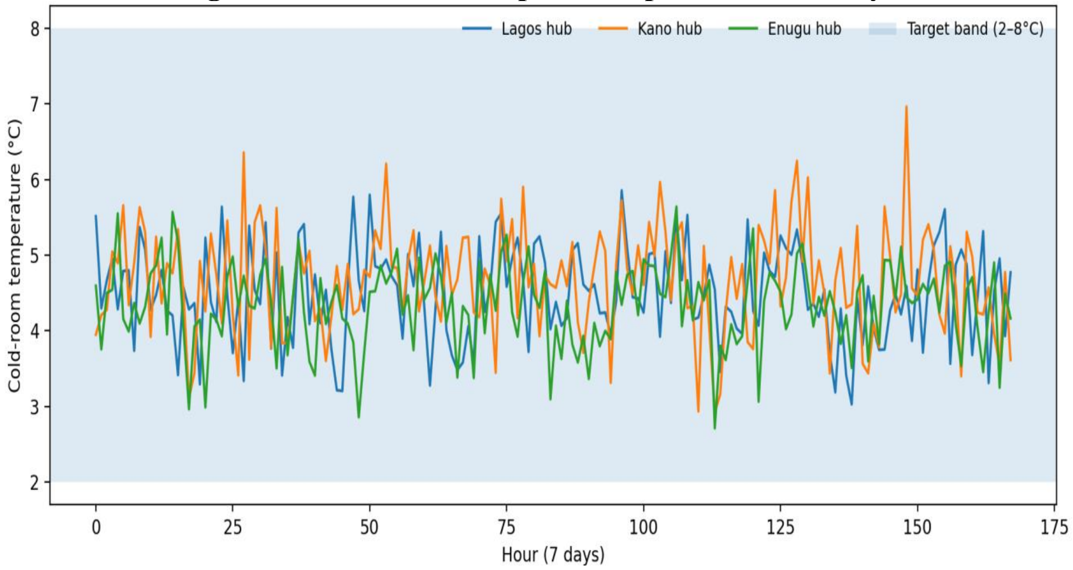
Table 2. Hub operational performance (12-month means)

Indicator	Lagos Hub	Kano Hub	Enugu Hub	Overall Mean
Organic waste diverted (t/day)	5.9	4.4	5.0	5.1
Biogas produced (m^3/day)	470	360	400	410
Methane content in biogas (%)	60	58	59	59
Cold-room throughput (t/day)	7.6	5.9	6.8	6.8
Cold-room utilization (%)	78	69	75	74
Uptime (%)	96.4	94.1	95.1	95.2
Temperature compliance (%)	93.5	90.8	92.6	92.3
Solar share of energy (%)	89	86	89	88
Biogas backup share (%)	6	9	7	7

C. Cold-chain performance: temperature compliance and energy reliability

Sensor-based monitoring indicates strong cold-chain stability across hubs. Average temperature compliance within commodity-relevant target bands was 92.3% of operating time, with mean daily deviation of ±1.6°C. Downtime averaged 34 hours per month per hub, but excursions were generally short-lived rather than prolonged disruptions. Where thermal buffering was deployed, resilience improved materially: the average time-to-threshold during interruptions increased from 2.1 hours (without buffering) to 6.4 hours (with buffering), enabling commodities to remain within safe ranges during brief outages and maintenance windows. Energy performance results align with the project's low-carbon design. Average energy intensity was 0.086 kWh per kilogram stored. Solar supplied 88% of electricity demand, biogas backup supplied 7%, and grid/diesel contingency accounted for 5%. Kano's higher backup share reflects a slightly lower solar share and greater variability in operational conditions. Figure 4 visualizes representative hourly temperature trajectories across the three hubs over a seven-day period and illustrates the overall pattern of stable storage with intermittent, recoverable excursions.

Figure 4. Cold-room temperature profile over 7 days



D. Methane mitigation and net climate impacts

MRV estimates indicate substantial net climate benefits, driven primarily by avoided methane emissions from diverting organic waste away from uncontrolled decomposition and secondarily by avoided emissions from fuel substitution through biogas use. Across the three hubs, total annualized net climate benefit was 18,540 tCO_2e/year. Sensitivity analysis reflecting uncertainty in baseline disposal assumptions, waste composition, and leakage in the 1–5% range produced a plausible bound of 14,200-23,900 tCO_2e/year, indicating that net benefits remain positive under conservative scenarios provided diversion volumes are maintained and leakage remains low. The distribution of net mitigation across hubs reflected operational intensity. Lagos achieved the largest net benefit (6,740 tCO_2e/year), Kano the lowest (5,420 tCO_2e/year), and Enugu a similarly high benefit (6,380 tCO_2e/year).

Table 3. Net climate impacts (annualized MRV; tCO_2e with sensitivity bounds)

Metric	Lagos Hub	Kano Hub	Enugu Hub	Total (3 hubs)
Waste treated (t/year)	2,154	1,606	1,825	5,585
Net tCO_2e avoided (best estimate)	6,740	5,420	6,380	18,540
Sensitivity range (low–high)	5,300–8,200	4,100–6,900	4,800–8,800	14,200–23,900

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Figure 5. Net climate impact decomposition by hub (MRV)

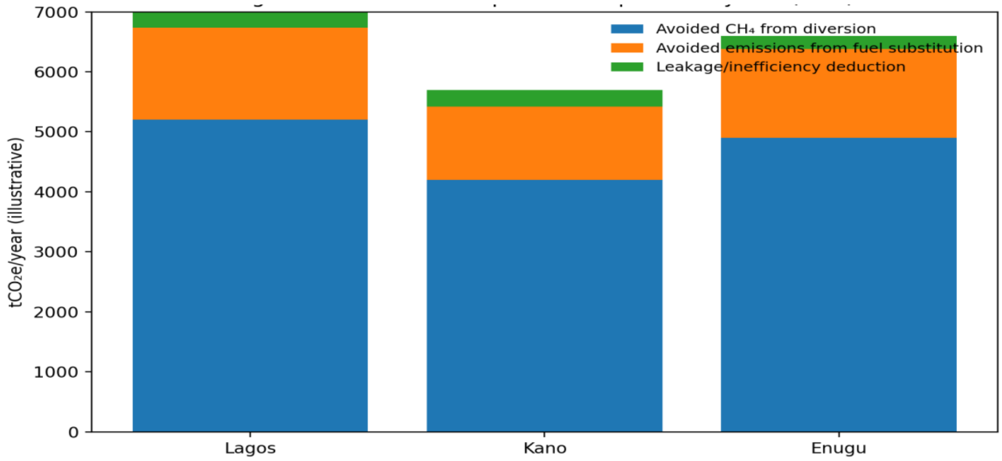

Table 3 reports annualized net climate results and sensitivity bounds, while Figure 5 decomposes the net climate impact by hub into avoided emissions from diversion, avoided emissions from fuel substitution, and deductions for leakage/inefficiency

E. Postharvest loss reduction and quality retention

Difference-in-differences analysis indicates that ECO-FRESH significantly reduced postharvest losses for priority perishables. Average loss rates declined from 39.6% to 24.8% in intervention communities, compared with a smaller decline from 38.9% to 35.7% in comparison communities. The estimated intervention effect was -12.0 percentage points (95% CI: −14.3 to -9.7; $p < .001$), representing roughly a 34% relative loss reduction among active users. Quality improvements moved in the same direction as physical loss reductions. Rejection rates fell by 9.1 percentage points ($p < .001$), Grade A share increased by 14.7 percentage points ($p < .001$), and marketable shelf-life increased by 2.0 days ($p < .001$). These quality shifts are economically meaningful because they convert potential losses into higher-value sales and reduce forced low-price selling due to spoilage risk.

Table 4. Difference-in-differences estimates: postharvest loss and quality outcomes

Outcome	Baseline Int.	Endline Int.	Baseline Comp.	Endline Comp.	DiD Effect	95% CI	p-value
Postharvest loss (%)	39.6	24.8	38.9	35.7	-12.0 pp	[-14.3, -9.7]	<.001
Rejection rate (%)	18.4	8.9	17.8	16.5	-9.1 pp	[-10.8, -7.4]	<.001
Grade A share (%)	31.2	47.1	30.8	33.0	+14.7 pp	[11.9, 17.5]	<.001
Marketable life (days)	3.8	6.3	3.9	4.4	+2.0 days	[1.4, 2.6]	<.001

Table 4 summarizes the Difference-in-Differences estimates for loss and quality outcomes.

Figure 6. Estimated postharvest loss reduction by commodity

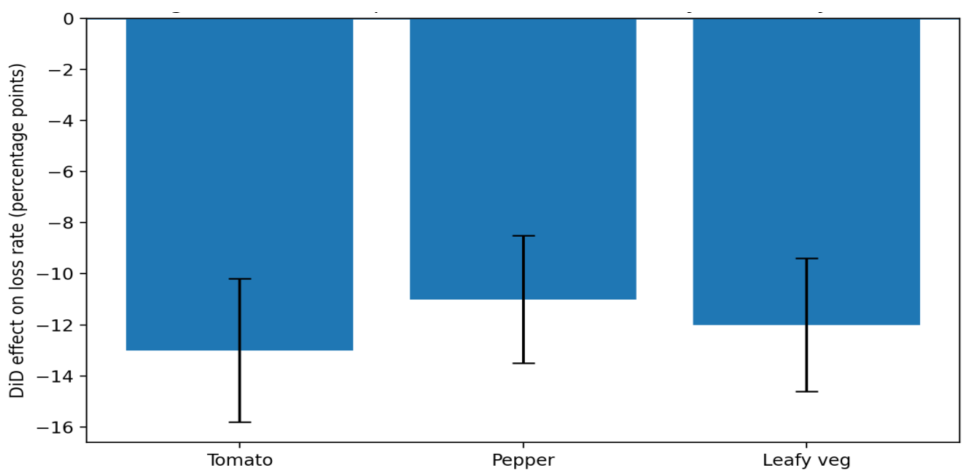

Figure 5 presents loss reductions by commodity, showing consistent improvements across tomatoes, peppers, and leafy vegetables

F. Agroecological adoption and circular nutrient substitution

Agroecological adoption increased substantially in intervention communities, indicating that the circular nutrient pathway (digestate use) and accompanying training translated into farm-level practice changes. Cover cropping adoption rose from 12% to 44% in intervention sites, compared with 13% to 18% in comparison sites, yielding a +27% point intervention effect. Integrated pest management adoption increased by 19% points. Digestate use reached 62% of participating farms in intervention areas versus 5% in comparison areas, providing a strong signal that nutrient loop closure was operationalized beyond demonstration-scale. Synthetic fertilizer expenditure decreased by 11.8% relative to comparison communities, consistent with partial substitution through digestate and improved nutrient management practices. These results are best interpreted as short-run adoption and cost-shift outcomes within the evaluation period. They nonetheless provide direct empirical support for the agroecology–circular economy linkage that underpins the ECO-FRESH design: organic waste is not only diverted for methane benefits, but also reintegrated into production systems via digestate use at meaningful adoption levels.

G. Prices, market timing, and income impacts (₦)

Market and income outcomes show that reduced spoilage and improved quality translated into stronger price realization and higher net incomes. Average farmgate prices increased from ₦265/kg to ₦318/kg in intervention communities, compared with ₦268/kg to ₦281/kg in comparison communities. The DiD estimate was +₦40/kg (95% CI: ₦28-₦52; $p < .001$). Monthly net farm income increased from ₦85,400 to ₦111,900 among intervention producers, compared with ₦84,700 to ₦90,500 among comparison producers, producing a DiD estimate of +₦20,700/month (95% CI: ₦14,200-₦27,200; $p < .001$), which corresponds to approximately 24% income growth among active users. Behavioural indicators suggest the income effects occurred through improved market timing as well as better quality. The share of sales occurring after peak glut increased by 12.6 percentage points ($p < .001$), indicating that storage access enabled producers and traders to reduce distress selling and better target higher-price windows.

Table 5. Difference-in-differences estimates: prices and income (₦)

Outcome	Baseline Int.	Endline Int.	Baseline Comp.	Endline Comp.	DiD Effect	95% CI	p-value
Farmgate price (₦/kg)	265	318	268	281	+40	[28, 52]	<.001
Monthly net farm income (₦)	85,400	111,900	84,700	90,500	+20,700	[14,200, 27,200]	<.001
Share of sales after peak glut (%)	22.1	37.6	22.5	25.4	+12.6 pp	[8.9, 16.3]	<.001

H. Inclusion and equity: differential impacts across groups

Inclusive analysis tested whether benefits differed systematically by gender, youth status, farm size, and distance-to-hub. Across gender and youth categories, differential impacts were small and statistically insignificant, indicating broadly similar gains once access to services was achieved. Farm-size differentials were also statistically insignificant, suggesting that benefits were not concentrated among larger farms in this pilot configuration. Distance-to-hub produced the clearest inequity signal. Producers in the furthest distance quartile experienced smaller income gains relative to those nearest hubs. The interaction estimate indicates a ₦6,500/month reduction in income gains for the furthest quartile compared with the nearest ($p = .03$), consistent with higher transport costs, weaker coordination, and lower frequency of cold storage use among remote producers.

Table 6. Inclusive impacts (interaction results; differential effects by group)

Group comparison	Loss reduction differential (pp)	p-value	Income gain differential (₦/month)	p-value
Women vs men	-1.6	.18	+1,900	.41
Youth vs non-youth	-0.8	.52	+2,600	.33
Smallest farms (Q1) vs largest (Q4)	+1.2	.29	-3,800	.22
Furthest distance (Q4) vs nearest (Q1)	+4.1	.02	-6,500	.03

I. Integrated interpretation: linking operational performance to outcomes

Taken together, results support a coherent mechanism consistent with the ECO-FRESH theory of change. Strong cold-room reliability and temperature compliance align with observed reductions in losses and improvements in grade outcomes, which in turn align with higher farmgate prices and increased net incomes. The climate results indicate that organic waste diversion and biogas utilization delivered significant net methane-abatement benefits, while also contributing to energy resilience through biogas backup. The agroecological findings demonstrate that circular nutrient outputs (digestate) were adopted at scale among participating farms, supporting the claim that the intervention functioned as a closed-loop system rather than as disconnected technology deployments. The equity results show that benefits were broadly inclusive by gender and youth, but that distance-to-hub reduced gains for remote producers-implying that logistics, aggregation, and access rules are pivotal for equitable scaling.

5. CONCLUSION

ECO-FRESH Nigeria demonstrates that an integrated circular bioenergy solar cold chain agroecology hub can deliver simultaneous climate and food-system benefits when operated reliably. The pilots achieved strong utilization and cold-room performance, contributed to meaningful reductions in postharvest losses, improved produce quality, and increased farmgate prices and monthly net incomes in ₦ terms. MRV results also indicate substantial net methane-abatement benefits from organic waste diversion and biogas use. Inclusion analysis suggests impacts were broadly similar by gender, youth, and farm size, but gains were smaller for producers farthest from hubs, highlighting logistics and access as key constraints for equitable scaling. Overall, the model is promising for methane mitigation and food security in Nigeria, provided scale-up prioritizes sustained operations, transparent service rules, and transport/aggregation support for remote farmers.

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