



Article

Integrated Methodological Framework for Small-Scale Anaerobic Biodigesters: Traceability Between Design, Operation, and Sustainability

Rommel Angel Mayorga Vargas ¹, Yoisdell Castillo Alvarez ^{1,*}, Reinier Jiménez Borges ², Luis Angel Iturralde Carrera ^{3,*}, Perla Yazmín Sevilla-Camacho ⁴, José Billerman Robles-Ocampo ⁵ and Juvenal Rodríguez-Reséndiz ³

¹ Department of Mechanical Engineering, Universidad Tecnológica del Perú, Lima 15046, Peru; u18204680@utp.edu.pe

² Department of Mechanical Engineering, Faculty of Engineering, Universidad de Cienfuegos “Carlos Rafael Rodríguez”, Cienfuegos 59430, Cuba; rjimenezborges@gmail.com

³ Facultad de Ingeniería, Universidad Autónoma de Querétaro, Santiago de Querétaro 76010, Mexico; juvenal@uaq.edu.mx

⁴ Cuerpo Académico de Energía y Sustentabilidad, Universidad Politécnica de Chiapas, Carretera Tuxtla Gutiérrez–Portillo Zaragoza Km 21+500, Col. Las Brisas, Suchiapa 29150, Mexico; psevilla@upchiapas.edu.mx

⁵ División de Innovación en Tecnologías Avanzadas, Universidad Politécnica de Chiapas, Carretera Tuxtla Gutiérrez–Portillo Zaragoza Km 21+500, Col. Las Brisas, Suchiapa 29150, Mexico; jrobles@upchiapas.edu.mx

* Correspondence: c19773@utp.edu.pe (Y.C.A.); liturralde28@alumnos.uaq.mx (L.A.I.C.)

Abstract

Small-scale anaerobic digestion offers a decentralized pathway for organic waste recovery; however, its performance is often evaluated through fragmented modules that do not ensure formal traceability between design, operation, sustainability assessment, and decision-making. This study proposes an integrated five-stage methodological framework—diagnosis, design, operational control, economic-environmental assessment, and decision-making validation with feedback—whose ACT (Acceptance–Control–Traceability) decision block applies three sequential filters: data-quality control ($C_{data} \geq 0.90$), multi-variable operational stability ($SR \geq 0.75$), and comprehensive sustainability verification (Ω : $GEI_{net} > 0$, $NPV > 0$, $\phi < 1$, and $\beta \geq 0.10$). A phased bibliographic mapping of 48 references confirmed the modular structure of the state of the art: 60.4% address operation/optimization and 39.6% address economic-environmental evaluation, whereas only 2.1% incorporate a formal decision closure. The framework was inductively derived from two Peruvian case studies: Chillón, as a structural-predictive reference, and Huaycán, focused on active pH–EC control through stoichiometric NaHCO_3 dosing. It was then prospectively evaluated on an independent 200-L co-digestion prototype in Lurín. The Lurín reactor delivered a mean biogas production of $96.9 \text{ L} \cdot \text{d}^{-1}$, a methane fraction of 54.2%, and a specific methane yield of $177.4 \text{ L} \cdot \text{CH}_4 \cdot \text{kgVS}^{-1}$; nevertheless, the ACT decision yielded $SR = 0.33$, classifying the system as not validated (Type A failure) due to ionic drift and thermal variability. Although the co-product scenario showed conditionally positive economic ($NPV > 0$) and environmental ($GEI_{net} = 38.2 \text{ kgCO}_2\text{eq/a}$) indicators, Ω could not be evaluated because Stage 1 territorial inputs (E_{dem} , P_{energy}) were undefined. By rejecting a system that a fragmented modular assessment would have classified as viable, the framework demonstrates the practical value of enforcing operational-stability verification before any sustainability claim and prescribes targeted feedback to Stage 3 for ionic and thermal management.



Academic Editor: Pablo Martín-Ramos

Received: 12 May 2026

Revised: 1 July 2026

Accepted: 9 July 2026

Published: 11 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](#)

[Attribution \(CC BY\)](#) license.

Keywords: small-scale anaerobic digestion; methodological framework; biodigester design; process monitoring and control; techno-economic; environmental assessment

1. Introduction

The valorization of organic waste through bioenergy conversion technologies constitutes one of the fundamental pillars of the circular bioeconomy and of strategies aimed at climate-change mitigation and reduction of fossil-fuel dependence [1–3]. Within this context, anaerobic digestion (AD) has been consolidated as a key decentralized technology for the simultaneous treatment of agro-industrial, food, and municipal organic wastes, generating biogas and digestate of agronomic value [4–9]. Despite its scientific maturity, the effective implementation of small-scale anaerobic biodigesters under real operating conditions and resource-limited contexts remains constrained by recurrent operational failures and insufficient methodological integration [10–14]. Small-scale anaerobic digestion is defined here as systems with reactor volume not exceeding 10 m³—typically 0.1–5 m³ in industrialized contexts and 1–15 m³ in regional household typologies [15]—operating under decentralized regimes without active process control (no external heating, mechanical mixing, or automated feeding) and with minimal field instrumentation.

Operational parameters in AD—pH, hydraulic retention time (HRT), organic loading rate (OLR), temperature, and biogas composition—are mechanistically linked to the four sequential stages of the process (hydrolysis, acidogenesis, acetogenesis, methanogenesis) formally described by ADM1 [16] and integrated bioconversion frameworks [17]. Methanogenic archaea exhibit narrow tolerance ranges (pH 6.5–8.2) and high sensitivity to volatile fatty acid accumulation, free ammonia nitrogen inhibition, and thermal fluctuations [18], which disrupt syntrophic coupling between acetogenic bacteria and hydrogenotrophic methanogens and reduce methane yield. Co-digestion strategies that improve C/N balance and trace-element availability mitigate these instabilities. These mechanistic interdependencies are essential because operational variables do not act independently; rather, they manifest underlying biochemical equilibria that determine stability and energy output [19–22].

Complementarily, a growing body of work has incorporated economic and environmental assessments—life cycle analyses, energy balances, and greenhouse gas reduction estimates—to quantify the potential benefits of AD within sustainability and circular economy frameworks [23–25]. These evaluations, however, are typically conducted ex post and disconnected from system design and operational dynamics, limiting their usefulness as decision-support instruments during early project stages [26–31]. Several studies have combined Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) modules with operational data, and decision-support systems have been proposed for technology selection and reactor sizing [32,33]. These contributions, nevertheless, operate as modular ex post assessments without formal traceability between design variables and operational outcomes, and without explicit data-quality control, multivariable stability indices, or feedback mechanisms that redirect evaluation to specific stages upon non-compliance.

The methodological gap addressed here is therefore not the absence of integrated studies, but the absence of replicable decisional architectures that enforce quantitative acceptance/rejection criteria with corrective feedback loops. In most studies, design, operational control, and economic-environmental evaluation are treated as independent components, lacking explicit integration capable of revealing how their interaction governs real performance. This fragmentation is critical at a small scale, where design decisions directly condition operational stability, biogas quality, economic feasibility, and environmental

performance [34–36]. As a consequence, numerous systems reported as technically viable in experimental studies fail when implemented in real contexts, and few replicable methodological frameworks systematically integrate diagnosis, design, control, sustainability, and decisional closure as a unified reproducible process. This gap limits understanding of real performance and obstructs cross-context knowledge transfer.

To address this gap, this study proposes an integrated five-stage methodological framework with explicit decisional closure and stage-specific feedback, formalized as a falsifiable epistemic instrument rather than as a procedural guide. The novelty lies in conceiving the biodigester as a coupled design–operation–sustainability system in which operational variables are responses of the constructed system rather than isolated parameters, and in subjecting the framework to a falsification test on a dataset that did not participate in its construction. The framework was inductively distilled from a three-stage research trajectory—Chillón [37] (compact buried geometry and univariate predictive baseline) and Huaycán [28] (active pH–EC control with stoichiometric NaHCO_3 dosing and multivariable predictive model)—and prospectively tested on a 200 L co-digestion prototype in Lurín whose original research objective was independent of the framework’s quantitative criteria. The hypothesis is that a methodological architecture requiring simultaneous compliance with data quality control, multivariable operational stability, and integrated sustainability criteria can discriminate between genuinely stable systems and those that appear viable when evaluated through fragmented indicators. The case study functions as a falsification tool: if the framework correctly identifies an unstable system that would have been classified as viable under modular approaches, it demonstrates discriminatory power beyond descriptive assessment. The three main contributions are: (i) the formalization of a five-stage decisional architecture (E1 diagnosis–planning, E2 design–configuration, E3 operational control–monitoring, E4 economic–environmental evaluation, E5 decision–feedback) with a quantitative ACT (Acceptance–Control–Traceability) decision block that converts the monitoring and assessment outputs into a single reproducible verdict through three filters: data completeness (C_{data}), multivariable operational stability (SR), and integral sustainability (Ω); (ii) the prospective validation of its discriminatory capacity through application to the Lurín dataset; and (iii) a structured stage-based literature mapping (48 references) that quantitatively characterizes the prevalence of modular approaches and the near-absence of formal decisional closure (2.1%).

Section 2 formalizes the five-stage framework, its governing design equations, the monitoring scheme, and the ACT decision logic. Section 3 applies the framework to the Lurín prototype and reports the structural design, the operational dynamics (T , pH, EC, biogas production and composition), and the resulting energy, economic, and environmental indicators. Section 4 benchmarks these results against the stage-coded literature and discusses how enforcing operational-stability verification before sustainability claims alters the interpretation of performance relative to fragmented evaluations. Section 5 summarizes the conclusions and the priority research directions for refining and transferring the framework.

2. Materials and Methods

The analysis of small-scale anaerobic biodigesters requires a methodological approach that integrates system design and construction with the control of operational dynamics and sustainability assessment. Since the behavior of the anaerobic process is conditioned by the physical configuration of the biodigester, the characteristics of the organic waste, and the actual operating conditions, it is necessary to evaluate the system as an integrated whole rather than through isolated analyses of its individual components.

The methodological framework is structured into five sequential and interconnected stages (Figure 1), linking retrospective evidence with prospective validation: (1) system diagnosis and planning, in which system boundaries are defined, substrates are characterized, and operational objectives and site constraints are established; (2) design and constructive configuration, in which the biodigester is dimensioned and the technical configuration is defined in coherence with the feeding strategy; (3) operational control and monitoring, based on tracking temperature (T), pH, and electrical conductivity (EC) as process stability variables, and biogas production as the integrated system response; (4) integrated economic and environmental assessment, where energy performance, greenhouse gas (GHG) balance, and economic indicators are quantified under comparable criteria; and (5) decision-making, validation, and feedback, in which system performance is evaluated against technical, economic, and environmental criteria, and design assumptions and parameters are adjusted when necessary.

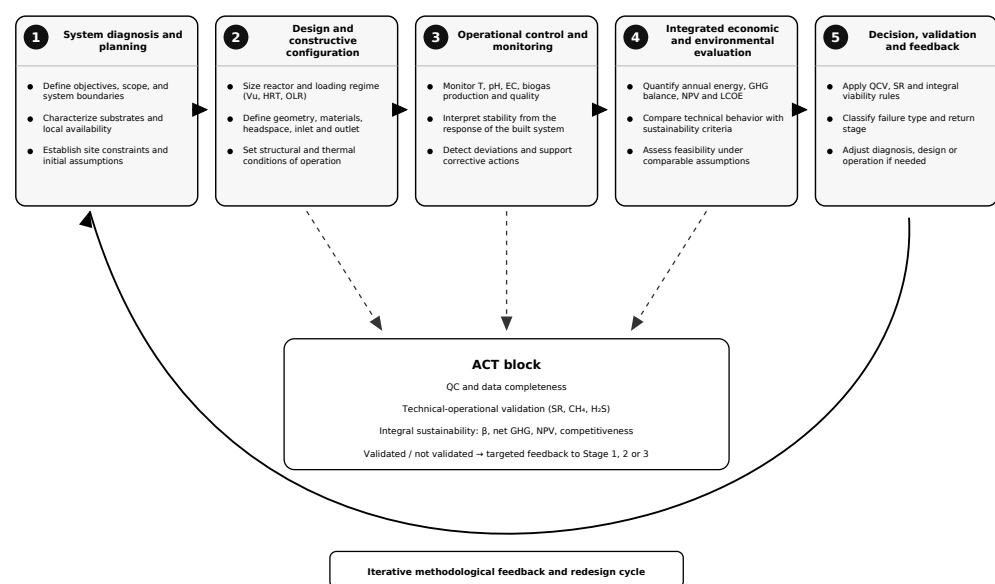


Figure 1. Methodology for small-scale biodigesters.

The framework is exercised on a pilot biodigester sited in Lurín District, Lima, Peru (Supplementary Figure S1), whose substrates, design, and monitoring are described from Section 3 onward.

2.1. Integrated Methodological Framework

The framework presented in this section is the methodological abstraction of a three-stage research trajectory of the authors that began with the Chillón compact biodigester [37] and continued with the Huaycán prototype with active pH–EC control [28]. During the development of the third stage of this trajectory at Lurín, the authors recognized that a common methodological architecture connected the three cases—system diagnosis, structural design, operational monitoring, integrated evaluation, and decisional closure with feedback—and proceeded to formalize this architecture as a replicable framework for small-scale anaerobic biodigesters. The present manuscript reports the formalization of that framework. Chillón and Huaycán are therefore the formative cases that empirically grounded the framework’s components, while Lurín is the methodologically independent test set on which the framework’s discriminatory capacity is verified. This distinction—between cases that contributed to the framework’s construction and the case that tests it—is fundamental to the epistemic structure of the manuscript and is maintained throughout the subsequent sections.

An integrated methodological framework is defined here as a structured, sequential, and reproducible set of analytical and operational stages that: (i) connects design decisions with operational outcomes and sustainability verification through explicit traceability; (ii) establishes quantitative acceptance/rejection criteria at each stage; and (iii) incorporates a formal feedback mechanism that identifies the specific stage requiring correction when the system fails to meet validation thresholds. Unlike modular assessment approaches, an integrated framework does not permit isolated interpretation of design, operation, or sustainability indicators; rather, each indicator is meaningful only within the context established by preceding stages.

The five stages are detailed individually in Sections 2.2–2.6; in brief, each stage has a single methodological purpose and conditions the next: diagnosis fixes the problem boundaries and substrates (E1); design fixes the physical operating regime (E2); monitoring reads the built system as a state estimator rather than a mere set of set-points (E3); the integrated assessment converts that verified performance into economic and climate indicators (E4); and the ACT closure issues a reproducible validated/not-validated verdict with stage-specific feedback (E5).

The integration of design, operation, and sustainability dimensions is materialized throughout all stages of the framework, ensuring that none of these dimensions is analyzed in isolation. The replicability of the approach is guaranteed through the clear definition of stages, the types of analyses associated with each, and the interaction logic between them, allowing its application to different small-scale anaerobic biogas production systems, regardless of the type of waste or specific biogas production configuration.

2.2. Stage 1: System Diagnosis and Planning

The diagnosis and planning stage aimed to define the biogas production system to be evaluated and to establish the initial criteria that guided the design and operation of the biogas production system. In this stage, the small-scale system was delimited, the evaluation objectives were defined, and the physical and functional boundaries of the analysis were established.

Substrate selection was carried out considering local availability, representativeness, and feasibility for use in decentralized systems, defining their role within the process either as the primary substrate or as part of a codigestion strategy. This selection allowed the initial conditions of the system to be established and anticipated their influence on design decisions and on the operational stability of the anaerobic process.

Initial planning criteria were established, including preliminary operational assumptions and technical system constraints, which were used as reference points for design decisions and for the subsequent interpretation of biogas production performance. These criteria were not defined as optimal values, but rather as initial working conditions within the proposed methodological framework.

2.3. Stage 2: System Design and Construction

In this stage, the design and construction of the small-scale anaerobic biogas production system were carried out based on the explicit definition of geometric, hydraulic, structural, and energetic variables, as well as the equations governing its configuration and physical operation. The objective was to establish a structurally coherent system whose operating conditions were determined from the design stage.

Overall, the design and construction of the biogas production system were based on the explicit definition of structural, hydraulic, and energetic variables, all supported by analytical relationships and design equations. The variables considered included the useful and total reactor volume, filling fraction, hydraulic retention time, applied organic loading rate, daily mass of volatile solids fed, available volume for biogas accumulation, internal pressure,

reactor geometry, structural configuration of inlets and outlets, airtightness conditions, and the thermal inertia of the system. These variables and equations defined the physical framework of the biodigester and established the structural limits within which operational dynamics and biogas production were subsequently evaluated.

2.3.1. Useful Reactor Volume (V_u)

The useful volume of the biodigester was determined following the hydraulic design principles established in [28,37–39], which relate the daily feeding flow rate and hydraulic retention time through the fundamental equations governing reactor sizing (Equations (1)–(4)):

$$V_u = Q_d \cdot \text{HRT} \quad (1)$$

$$V_T = \frac{V_u}{f_u} \quad (2)$$

$$f_u = \frac{V_u}{V_T} \quad (3)$$

$$\text{HRT} = \frac{V_u}{Q_d} \quad (4)$$

where V_u is the useful reactor volume [m^3], V_T the total biodigester volume [m^3], Q_d the daily feeding flow rate [$\text{m}^3 \text{d}^{-1}$], HRT the hydraulic retention time [d], and f_u the filling fraction [-].

2.3.2. Applied Organic Loading Rate (OLR)

The applied volumetric organic loading rate was defined as (Equation (5)) [28]:

$$\text{OLR} = \frac{VS_{in}}{V_u} \quad (5)$$

where OLR is the applied organic loading rate [$\text{kg}_{\text{VS}} \text{m}^{-3} \text{d}^{-1}$], VS_{in} the daily mass of volatile solids fed [$\text{kg}_{\text{VS}} \text{d}^{-1}$], and V_u the useful reactor volume [m^3].

2.3.3. Daily Mass of Volatile Solids Fed (VS_{in})

The daily mass of volatile solids fed was calculated as (Equation (6)) [39]:

$$VS_{in} = Q_d \cdot VS \quad (6)$$

where VS_{in} is the daily mass of volatile solids fed [$\text{kg}_{\text{VS}} \text{d}^{-1}$], Q_d the daily feeding flow rate [$\text{m}^3 \text{d}^{-1}$], and VS the volatile solids concentration of the substrate [$\text{kg}_{\text{VS}} \text{m}^{-3}$].

2.3.4. Available Volume for Biogas Accumulation (V_g)

The volume available for gas storage (Equation (7)) was defined as [37]:

$$V_g = V_T - V_u \quad (7)$$

where V_g is the available volume for biogas accumulation [m^3], V_T the total biodigester volume [m^3], and V_u the useful reactor volume [m^3].

2.3.5. Internal Pressure Associated with Biogas Storage

The operating pressure of biogas in low-pressure systems is quantified by manometry (water column) as (Equation (8)), equivalent to [39]:

$$P_g = \rho_w g \Delta h \quad (8)$$

where P_g is the gauge pressure of the biogas [Pa], ρ_w the water density [kg m^{-3}], g the gravitational acceleration [m s^{-2}], and Δh the height difference in the manometer [m].

2.3.6. Reactor Geometry

Assuming a cylindrical geometry for the reactor (Equation (9)) [37]:

$$V_T = \frac{\pi D^2}{4} H \quad (9)$$

where V_T is the total biodigester volume [m^3], D the internal reactor diameter [m], and H the effective reactor height [m].

2.3.7. Structural Configuration of Inlets and Outlets (Slope/Inclination)

The hydraulic inclination of the conduit (inlet or outlet) is expressed as (Equation (10)) [28]:

$$\tan(\theta) = \frac{\Delta h}{L} \quad (10)$$

where θ is the conduit inclination angle [$^\circ$], Δh the height difference between ends [m], and L the conduit length [m].

2.3.8. Sealing Conditions

Tightness is verified through a pressure drop test over an interval Δt (typically 24 h). The fractional leakage rate of the system is defined as (Equation (11)):

$$\eta_{\text{fug}} = \frac{V_g}{V_{\text{bg},d}} \frac{\Delta P_{\text{abs}}}{\Delta t} \frac{T_{\text{std}}}{T_{\text{int}}} \frac{1}{P_{\text{std}}} \quad (11)$$

where η_{fug} is the fractional leakage rate [–] (referred to daily production), V_g the gas headspace volume [m^3], $V_{\text{bg},d}$ the daily biogas production [$\text{m}^3 \text{d}^{-1}$], ΔP_{abs} the absolute pressure drop over the interval [Pa], Δt the test interval [d] (e.g., 1 day), T_{int} the internal gas temperature [K], T_{std} the standard temperature [K], and P_{std} the standard pressure [Pa].

The absolute pressure drop is calculated as (Equation (12)):

$$\Delta P_{\text{abs}} = P_{\text{abs},0} - P_{\text{abs},t} \quad (12)$$

Recommended minimum operational criterion: $\eta_{\text{fug}} \leq 0.05$ (losses equivalent to $\leq 5\%$ of daily production).

2.3.9. Thermal Inertia of the System

Passive thermal stability (e.g., burial, surrounding thermal mass) is represented using a lumped-parameter model (Equation (13)):

$$C_{\text{th}} \frac{dT_{\text{int}}}{dt} = UA(T_{\text{ext}} - T_{\text{int}}) + Q_{\text{gen}} \quad (13)$$

where C_{th} is the effective thermal capacity of the system [J K^{-1}], T_{int} the internal digester temperature [$^\circ\text{C}$ or K], T_{ext} the external (ambient/soil) temperature [$^\circ\text{C}$ or K], UA the overall heat transfer coefficient [W K^{-1}], and Q_{gen} the net heat generation/consumption of the process [W].

The thermal time constant τ_{th} represents the time required for the system to reach approximately 63% of its final temperature difference after a step change in conditions. It quantifies the system's thermal inertia and transient response, given by (Equation (14)):

$$\tau_{th} = \frac{C_{th}}{UA} \quad (14)$$

2.4. Stage 3: Operational Control and System Monitoring

The Operational Control and Monitoring Stage is aimed at evaluating the response of the designed and constructed biodigester through a control scheme based on the systematic tracking of key operational variables. This stage does not modify the structural conditions of the system; rather, it enables interpretation of its dynamic behavior, verification of anaerobic process stability, and timely detection of operational deviations.

In order to ensure the stability of the anaerobic process and allow early detection of operational deviations, the methodological framework establishes a systematic monitoring scheme for key variables selected for their capacity to reflect the physicochemical, biological, and energetic state of the biodigester. Table 1 summarizes the operational variables to be controlled, the monitoring frequency, and the reference operational ranges defined from experimental evidence obtained in studies conducted under this framework. These ranges constitute validated operational windows used as criteria for assessing system stability and the coherence between the structural design of the biodigester and its operational performance.

Table 1. Monitoring frequency and two-level operational criteria for small-scale biodigesters.

Variable	Frequency	Minimum Validation Criterion	Desirable Benchmark
pH	Daily	6.8–7.2	6.9–7.1
EC	Daily	5600–7500 $\mu\text{S}/\text{cm}$ (ampliated tolerance)	6200–6300 $\mu\text{S}/\text{cm}$ (strict benchmark from [28] under active NaHCO_3 control)
Temperature	Daily	20–24 $^{\circ}\text{C}$ and $\Delta T < \pm 1^{\circ}\text{C day}^{-1}$	21–23 $^{\circ}\text{C}$ under low fluctuation
Daily biogas production	Daily	No collapse or sustained drop	Case-specific performance benchmark
CH_4 in biogas (%)	Weekly	$\geq 50\%$	$> 60\%$
H_2S	Weekly	< 10 ppm	< 5 ppm

The strict benchmark window for pH (6.92–6.97) and EC (6200–6300 $\mu\text{S}/\text{cm}$) is traceable exclusively to the Huaycán case [28], where active NaHCO_3 dosing was implemented. The Chillón case [37] did not incorporate EC as a monitoring variable; therefore, the EC benchmark column reflects the formalization developed in [28] rather than a combined reference. The minimum validation criterion (ampliated tolerance window) is consistent with general literature on small-scale anaerobic digestion under passive operation.

Methane content is interpreted here using a two-level criterion: $\text{CH}_4 \geq 50\%$ is adopted as the minimum acceptable threshold for technical validation under real small-scale operating conditions, whereas $\text{CH}_4 > 60\%$ is retained as a desirable operational benchmark associated with higher gas quality and process efficiency. These criteria are context-dependent and should not be interpreted as universal limits outside the boundary conditions of the present framework.

The operational ranges reported in this table were derived from empirical evidence obtained under the specific conditions of this study (co-digestion of bovine manure and organic MSW fraction, coastal subtropical climate, unheated buried reactor at Lurin, Peru). These ranges are context-dependent and should not be applied as universal thresholds. Transferability to other substrates, inoculation conditions, OLR/HRT regimes, or climatic contexts requires local parameterization or justified benchmarking, as discussed in Section 4.2.

In order to operationalize biodigester control and transform variable monitoring into a systematic diagnostic and decision-making mechanism, the methodological framework incorporates an operational diagnostic and intervention matrix. Supplementary Table S1 establishes the relationship between the main operational deviations detectable through key variable monitoring, their technical interpretation, and the methodological actions required to restore system stability. This matrix enables a structured and reproducible response to process disturbances, facilitating operational management of the biodigester without modifying its structural configuration and ensuring coherence between design, operation, and the system's energetic performance.

To ensure the replicability of the operational control scheme and facilitate the implementation of the methodological framework in small-scale anaerobic biodigesters, reference measurement equipment is defined for monitoring key operational variables. Supplementary Table S2 presents the types of instruments recommended for each variable, prioritizing criteria of robustness, low cost, commercial availability, and ease of field use, without restricting the use to specific brands or models.

2.5. Stage 4: Integrated Economic and Environmental Evaluation

Stage 4 is the integrated economic and environmental assessment that feeds the decision block (the formal decision is issued in Stage 5). In this stage, environmental and economic impacts derived from the structural, hydraulic, and energetic design established in Stage 2 are integrally quantified, whose operational parameters were experimentally verified in Stage 3 and territorially defined in Stage 1.

The objective of this stage is not to optimize the system, but to evaluate whether the biodigester, under the previously established conditions, simultaneously meets the minimum criteria of environmental sustainability and economic viability.

The evaluation is based on indicators directly derived from the structural variables:

$$\{V_u, HRT, OLR, VS_{in}\}.$$

Therefore, any result obtained in this stage is a direct consequence of the decisions made in the previous stages.

2.5.1. Annual Energy Production

Annual energy production (Equation (15)) represents the effective capacity of the biodigester to transform the fed organic matter into useful energy. This indicator integrates the volume of biogas produced, the methane fraction, and the calorific value of the generated fuel. Its estimation allows direct linkage between the hydraulic design (HRT , OLR , useful volume) and the real annual energy performance of the system:

$$E_a = V_{bg,d} f_{CH_4} PCI_{CH_4} 365 \quad (15)$$

where E_a is the annual energy generated [$kWh a^{-1}$], $V_{bg,d}$ is the daily volume of biogas produced [$m^3 d^{-1}$], f_{CH_4} is the volumetric methane fraction [-], and PCI_{CH_4} is the lower heating value of methane [$kWh m^{-3}$].

Minimum energy coverage.

The generated energy must represent a significant fraction of the local energy demand defined in Stage 1 (Equation (16)):

$$\beta = \frac{E_a}{E_{dem}} \quad (16)$$

where E_{dem} is the local annual energy demand [kWh a^{-1}] and β is the relative energy coverage [-].

2.5.2. Avoided Emissions Through Energy Substitution

Climate mitigation occurs when the generated energy replaces conventional sources with higher carbon intensity (Equation (17)):

$$GEI_{\text{ev}} = E_a EF_{\text{sub}} \quad (17)$$

where GEI_{ev} represents avoided emissions [$\text{kgCO}_2\text{eq a}^{-1}$] and EF_{sub} is the emission factor of the substituted fuel [$\text{kgCO}_2\text{eq kWh}^{-1}$].

2.5.3. Fugitive Emissions

Methane losses (Equation (18)) must be deducted from the gross benefit due to their high global warming potential:

$$GEI_{\text{fug}} = V_{\text{bg},d} f_{\text{CH}_4} \eta_{\text{fug}} GWP_{\text{CH}_4} 365 \quad (18)$$

where η_{fug} is the leakage rate [-] and GWP_{CH_4} is the global warming potential of methane expressed on a volumetric basis [$\text{kgCO}_2\text{eq m}^{-3}$], obtained as $GWP_{\text{CH}_4,\text{vol}} = \rho_{\text{CH}_4} \times GWP_{\text{CH}_4,\text{mass}} = 0.716 \times 28 \approx 20.05 \text{ kgCO}_2\text{eq m}^{-3}$ at standard temperature and pressure (STP, 273.15 K, 101.325 kPa), where $\rho_{\text{CH}_4} = 0.716 \text{ kg m}^{-3}$ is the density of methane at STP and $GWP_{\text{CH}_4,\text{mass}} = 28$ is the 100-year global warming potential of methane on a mass basis (IPCC AR5, without climate-carbon feedbacks).

2.5.4. Net Environmental Balance

The real climate impact is obtained by subtracting fugitive emissions from the gross benefit (Equation (19)):

$$GEI_{\text{net}} = GEI_{\text{ev}} - GEI_{\text{fug}} \quad (19)$$

2.5.5. Net Present Value (NPV)

NPV (Equation (20)) integrates investment, benefits, and updated costs over the project lifetime:

$$NPV = -C_{\text{inv}} + \sum_{t=1}^n \frac{F_t}{(1+r)^t} \quad (20)$$

2.5.6. Levelized Cost of Energy (LCOE)

LCOE allows comparison of the biodigester with energy alternatives under a homogeneous criterion (Equation (21)):

$$LCOE = \frac{C_{\text{inv}} + \sum_{t=1}^n \frac{C_{\text{op},t}}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (21)$$

To facilitate comparison, the dimensionless ratio is defined as (Equation (22)):

$$\phi = \frac{LCOE}{P_{\text{energy}}} \quad (22)$$

The threshold values applied to the integrated assessment indicators, used to classify each scenario's performance, are reported in Supplementary Table S10.

2.5.7. Sensitivity Analysis

Since the indicators depend on structural parameters, sensitivity is evaluated with respect to each variable (Equation (23)):

$$S_x = \frac{\partial I}{\partial x} \cdot \frac{x}{I} \quad (23)$$

where S_x is the dimensionless sensitivity of indicator I (e.g., E_a , GEI_{net} , NPV) to a relative change in the input parameter x (e.g., $V_{bg,d}$, f_{CH_4} , η_{fug} , prices, or the discount rate r).

2.5.8. Integral Viability Condition

Sustainability requires simultaneous compliance with environmental, economic, competitiveness, and energy-coverage criteria; the formal definition of the integral viability condition Ω is given in Equation (27) of Stage 5. The iterative nature of the methodological framework is formally closed when the operational filter (Equation (28)) and the integral verification (Equation (29)) are simultaneously satisfied.

2.6. Stage 5: Integral Validation and Framework Feedback (ACT)

Stage 5 constitutes the decisional closure of the methodological framework and verifies, using reproducible criteria, whether the evaluated biodigester can be considered technically stable and integrally sustainable (energy–environment–economy) under the conditions defined in Stages 1–4. This stage transforms the obtained results into a formal decision (*validated/not validated*) and, in case of non-compliance, activates a feedback mechanism that explicitly indicates which stage to return to (operation, design, or diagnosis) and which variables must be adjusted.

2.6.1. Data Consolidation and Quality Control (QC)

To avoid validations based on incomplete or biased records, a minimum level of quality control is required.

Minimum temporal coverage.

The evaluated period must cover at least one complete retention cycle (Equation (24)):

$$T_{eval} \geq HRT \quad (24)$$

Monitoring completeness.

The percentage of effectively measured records relative to the monitoring plan (Table 1, Stage 3) is calculated as (Equation (25)):

$$C_{data} = \frac{N_{reg,real}}{N_{reg,plan}} \quad (25)$$

It is required that $C_{data} \geq 0.90$ (90%) for the validation to be considered methodologically acceptable.

2.6.2. Technical–Operational Validation (Design–Operation Consistency)

In this sub-stage, it is validated whether the biodigester operated within the operational windows (Stage 3) and whether its dynamics are consistent with the structural design (Stage 2). An operational stability index is defined as (Equation (26)):

$$SR = \frac{N_{d,stable}}{N_{d,total}} \quad (26)$$

A day is considered stable if it simultaneously meets:

- pH within the operational window;
- EC within the operational window;
- temperature within the defined stability criterion;
- daily production without collapse;
- no evidence of persistent leakage (anomalous drops associated with pressure/hermeticity).

The minimum stability criterion requires $SR \geq 0.75$, as values below 75% indicate systems operationally dominated by disturbances—transforming from “stable” to merely “fault-tolerant,” which invalidates the control framework. Additionally, weekly CH_4 must exceed Stage 3 thresholds and H_2S must remain below defined risk levels. Failure in any criterion disqualifies the system from technical-operational validation, regardless of theoretical profitability.

2.6.3. Integral Sustainability Validation (Energy–Environment–Economy)

With operation validated, integral viability is evaluated using the indicators from Stage 4. The decision is expressed as a joint condition (Equation (27)):

$$\Omega = (GEI_{\text{net}} > 0) \wedge (NPV > 0) \wedge (\phi < 1) \wedge (\beta \geq 0.10) \quad (27)$$

where GEI_{net} is the net environmental balance, NPV the discounted profitability, ϕ the relative competitiveness of the LCOE, and β the minimum energy coverage with territorial impact.

The system is considered integrally sustainable only if Ω is true. The final decision applies two mandatory filters without ambiguity:

- (1) Operational validation requires (Equation (28)):

$$(C_{\text{data}} \geq 0.90) \wedge (SR \geq 0.75) \wedge (CH_4 \text{ complies}) \wedge (H_2S \text{ complies}) \quad (28)$$

- (2) Integral verification requires (Equation (29)):

$$\Omega = \text{true} \quad (29)$$

The framework is validated only if both conditions are simultaneously satisfied; it is not validated if either fails.

2.6.4. Feedback (Correction Path and Return Stage)

When the system does not validate, feedback is not generic; the type of failure is classified and the correct stage is revisited.

- (A) Operational failure (return to Stage 3).

Typical condition: $C_{\text{data}} \geq 0.90$ but $SR < 0.75$ and/or pH–EC–T deviations with correct infrastructure.

Actions: adjustment of feeding regime, fractionation, dilution, recirculation, alkalization/ionic adjustment rules, condensate control, induced mixing routine.

- (B) Structural failure (return to Stage 2).

Typical condition: recurrent collapses due to physical limitations (insufficient headspace, persistent leaks, HRT/OLR incompatible with the real substrate, hydraulic inlet–outlet problems).

Actions: structural redesign (increase reactor volume or headspace fraction, modify inlet/outlet geometry, enhance burial depth or insulation, replace fittings/seals to restore hermeticity, reconfigure hydraulic profile to ensure self-cleaning slopes).

- (C) Diagnostic/planning failure (return to Stage 1).

Typical condition: $\beta < 0.10$ due to misestimated demand, insufficient real substrate availability, or logistical/social constraints preventing the operational regime.

Actions: redefine system boundaries, territorial objective, functional unit, residue availability, and energy demand.

2.6.5. Mandatory Outputs of Stage 5 (Minimum Report)

To ensure replicability, Stage 5 must explicitly produce and report:

- C_{data} and SR for the evaluated period;
- Gas quality compliance (CH_4 , H_2S);
- β , GEI_{net} , NPV , ϕ , and the boolean value of Ω ;
- Final decision (*validated/not validated*);
- If not validated: type of failure (A/B/C), return stage, and adjusted variables.

Integral sustainability is assessed through the joint environmental, economic, and competitiveness indicators derived from Stage 4. The coverage factor β is retained as part of the generic framework when a quantitative territorial energy-demand baseline (E_{dem}) has been explicitly defined in Stage 1. However, in the Lurín pilot application no quantified E_{dem} was established during diagnosis; therefore, β is reported as not applicable for this case and Ω is not used as the discriminant criterion for the final decision. Under these conditions, the ACT conclusion for Lurín rests on Filter 1, which already fails due to insufficient technical–operational stability ($SR < 0.75$).

To improve readability and keep the main manuscript focused on the scientific logic of the framework, detailed operational intervention matrices, instrumentation specifications, and extended auxiliary calculations are provided in the Supplementary Material. The main text retains only the equations, criteria, and summaries that are strictly required to understand and reproduce the ACT decision logic.

3. Results

In this section, the five-stage integrated methodology for the design and operational control of small-scale biodigesters is validated. It is conceived as a replicable and decisional (not descriptive) procedure that connects territorial conditions, design decisions, operational performance, and environmental–economic impact. Validation is executed in two complementary layers. First, a retrospective layer that reconstructs the formative contributions of two previously published cases of the same research program—Chillón [37] (compact buried design, univariate predictive model for pH and temperature, $R^2 = 0.98$ over a 30-day monitoring horizon) and Huaycán [28] (active pH–EC control with stoichiometric NaHCO_3 dosing, multivariable predictive model with linear, quadratic and interaction terms, $R^2 = 0.78$ with $\text{MAPE} = 2.7\%$ over approximately four months of monitoring)—and identifies the empirical evidence each case provided to the construction of the E1–E5 framework. Second, a prospective layer in which the framework, once formalized, is tested on the Lurín dataset (200 L prototype under codigestion of bovine manure and the organic fraction of municipal solid waste), whose original research objective was independent of the framework's criteria. The Lurín dataset therefore functions as a methodological test set: the framework was not trained on it, and the decision yielded by the ACT block constitutes evidence of discriminatory capacity rather than confirmation of an a priori construction. The results are reported following the sequence of the framework, and at each stage the outputs from Lurín are contrasted with the operational windows formalized in [28] and with the structural-predictive baseline established in [37]. The study site is located in Lurín District (Lima, Peru; Supplementary Figure S1).

3.1. Stage 1: System Diagnosis and Planning

The diagnostic stage aimed to establish the technical and energy needs that justified the implementation of the pilot system, as well as to define the structural and operational boundaries under which the anaerobic digestion process would be evaluated.

The preliminary analysis identified a critical gap: the absence of local experimental data to estimate the real methanogenic potential of the residues generated at the slaughterhouse. Although the availability of bovine manure was constant and quantifiable, there was no in situ energy characterization to support the sizing of a biodigester at operational scale. This uncertainty prevented the formulation of evidence-based technical proposals.

During the diagnosis and planning phase, physicochemical characterization of the substrates selected for co-digestion in Lurín (bovine manure and the organic fraction of MSW) was performed. This baseline enables two methodological decisions that govern system performance: (i) design (Stage 2), because TS–VS and C/N determine VS_{in} , OLR, HRT, and therefore hydraulic sizing and useful volume under a defined feeding regime; and (ii) operational control (Stage 3), because the stoichiometry and organic load associated with this characterization condition the expected stability window of acid–base and ionic equilibrium reflected in (pH–EC), as well as the observable energy response (biogas production under real variability).

As shown in Table 2, the manure–MSW characterization provides the basis for defining mixing scenarios evaluated during the diagnosis phase (Stage 1), integrating: (i) the C/N balance of the mixture as a biochemical stability criterion; (ii) the daily input volatile solids load (VS_{in}) as a design–operation variable governing OLR; and (iii) the daily biogas and methane (CH_4) potential as an upper bound of energy performance under the adopted conversion assumptions. This information establishes a quantitative planning window that supports the selection of a target mixture with traceability toward hydraulic design (Stage 2) and operational control (Stage 3). Methane potential is estimated from biogas potential using the corresponding assumed CH_4 fraction.

Table 2. Physicochemical properties and co-digestion scenarios of cattle manure and MSW (Lurín).

(a) Physicochemical Properties						
Parameter		Unit	Cattle Manure		MSW (Lurín)	
Carbon (C)		%	32.60		26.99	
Hydrogen (H)		%	4.80		4.50	
Oxygen (O)		%	44.02		49.97	
Nitrogen (N)		%	0.96		1.31	
Sulfur (S)		%	0.60		0.20	
Total solids (TS)		%	22.51		8.28	
Volatile solids (VS)		%	18.69		6.88	
(b) Co-Digestion Scenarios						
Manure/MSW (%)	C/N	VS_{in} (kgVS/d)	Biogas (L/d)	CH_4 (L/d)	CH_4 Yield (L CH_4 /kgVS)	Comment
100/0	34.13	0.364	109–146	60–80	165–220	Max VS_{in} ; N limitation risk
70/30	28.86	0.296	89–119	49–65	166–220	Selected: optimal C/N– VS_{in}
50/50	26.08	0.251	75–100	41–55	163–219	Intermediate reference
30/70	23.95	0.205	62–82	34–45	166–220	Min VS_{in} ; low C/N

For each scenario, the specific methane potential (penultimate column) is obtained as the daily CH_4 range divided by VS_{in} ; the selected 70/30 mixture sustains 166–220 L CH_4 kgVS^{−1}, the theoretical target is later contrasted with the field value measured in Stage 3.

A clear trade-off is observed: as the percentage of MSW increases, the C/N ratio decreases from 34.13 (100/0) to 23.95 (30/70), approaching the range typically favorable for co-digestion; however, simultaneously VS_{in} declines (0.364→0.205 kgVS/d) and, consequently, the daily biogas and CH_4 potential decreases (109–146→62–82 L/d and 60–80→34–45 L/d, respectively). Under this balance, 70% manure–30% MSW emerges as a “hinge” scenario: it places the mixture at C/N = 28.86 (chemically more compatible with acid–base stability and lower risk of N limitation) without excessively penalizing the effective organic load (VS_{in} = 0.296 kgVS/d), sustaining a potential of 89–119 L/d of biogas and 49–65 L/d of CH_4 . In contrast, 100% manure maximizes potential but with a high C/N (tendency toward N limitation and slower kinetics), whereas >50% MSW pushes C/N to lower values with marked loss of VS_{in} and energy potential. Among the evaluated scenarios, the 70% manure/30% MSW combination was selected as the target mixture because it achieves a C/N ratio of 28.86—within the range considered favorable for co-digestion stability (25–30)—while maintaining a VS_{in} of 0.296 kgVS/d sufficient to sustain a theoretical biogas potential of 89–119 L/d and a CH_4 potential of 49–65 L/d. This corresponds to an estimated specific methane yield of approximately 165–220 $LCH_4/kgVS$ under theoretical conversion assumptions, which must be verified experimentally in Stage 3.

Scenarios with higher MSW fractions (>50%) were excluded due to excessive C/N reduction and substantial VS_{in} loss, while 100% manure, despite maximizing theoretical potential, presents a C/N of 34.13 with associated risk of nitrogen limitation and slower methanogenic kinetics. In summary, the table does not “choose” aesthetically; it delimits a design window ($\approx$ 60–80% manure) where C/N and VS_{in} remain within a usable regime and establishes biogas/ CH_4 ranges that must be coherent with pH–EC–T control under real operation.

Consequently, the need to implement a small-scale pilot system was defined as a diagnostic tool, whose purpose was not to maximize biogas production but to characterize the real behavior of the substrate under site-specific environmental conditions. This decision responded to a staged methodological approach in which experimental quantification precedes definitive design.

The system was delimited as a decentralized pilot unit with a nominal capacity of 200 L. Under the same filling criterion adopted for the prototype family (f_u = 0.70), the corresponding useful liquid volume is 140 L and the available headspace volume is 60 L. The reactor was therefore operated at 70% liquid filling and 30% free gas-storage volume, preserving the same design logic used in the baseline compact prototype. Substrate selection was based on sustained local availability and representativeness within small-scale agro-livestock systems. Bovine manure was defined as the primary substrate, while household organic waste fulfilled a co-digestion function aimed at improving the C/N ratio and process stability.

Initial operational assumptions included a hydraulic retention time of 15 days, continuous operation without external energy input, and a thermal regime dependent on environmental conditions. These parameters were not defined as optimized values, but as baseline conditions within the proposed methodological framework, allowing subsequent evaluation of the deviation between expected performance and observed behavior.

The physical and functional boundaries of the analysis included reactor volume, passive biogas storage, and exclusion of active thermal control systems. In this way, the system was conceived as a representative model of real operation in coastal rural environments, ensuring that the obtained results reflected practical conditions rather than artificially controlled scenarios.

This stage consolidated the structural baseline of the study, establishing the framework under which design, performance, and feasibility evaluations were developed in subsequent stages.

3.2. Stage 2: Design and Structural Configuration of the Biodigester

Stage 2 defines the Reference Structural Configuration (RSC) of the biodigester, understood as the set of geometric and hydraulic decisions that establish the physical framework of the system and, therefore, delimit its operating regime. In this stage, structural variables and their design relationships are formalized (for example, V_u , V_T , f_u , V_g , HRT , VS_{in} , OLR , and reactor geometry). As a consistency verification of the framework, this stage incorporates a retrospective comparative analysis of the baseline studies [28,37,40] and the applied case (Lurín, 200 L).

The comparison between the 1100 L reference biodigesters and the 200 L Lurín prototype is not intended as a performance equivalence but as a structural transferability verification. Both systems fall within the small-scale definition adopted in this study ($V_T < 10 \text{ m}^3$).

The purpose of Table 3 is to verify whether the framework's Stage 2 dimensionless invariants remain consistent across the 5.5:1 volume ratio between the reference and pilot systems.

Table 3. Structural parameters and scaling of the biodigester systems.

Structural Variable	Montevideo [40]	Chillón [37]	Huaycán [28]	Lurín (200 L)	Structural Function
Total volume (V_T)	1100 L	1100 L	1100 L	200 L	Scale (5.5:1)
Filling fraction (f_u)	0.70	0.70	0.70	0.70	Volumetric invariant
Useful volume ($V_u = f_u \cdot V_T$)	770 L	770 L	770 L	140 L	Derived scaling
Burial depth	—	1.10 m	1.10 m	$\approx 1.0 \text{ m}$	Passive thermal inertia
Inlet/outlet angle	$38^\circ/40^\circ$	$45^\circ/45^\circ$	$45^\circ/40^\circ$	$45^\circ/40^\circ$	Self-cleaning
D_{in}/D_{out} ratio	2	2	2	2	Hydraulic inv.
A_{in}/A_{out} ratio	4	4	4	4	Hydraulic inv.
Gas storage	HS 30%	HS 30%	HS 30%	HS 30%	Config. inv.

3.2.1. Structural Invariants and Scaling Analysis

Table 3 compares the Stage 2 structural variables of the three 1100 L reference biodigesters [28,37,40] and the 200 L Lurín prototype.

Table 3 confirms that the four reactors constitute a single geometric family: the dimensionless invariants that govern the physical operating regime—filling fraction ($f_u = 0.70$), headspace fraction (30%), and the conveyance hierarchy ($D_{in}/D_{out} = 2$, $A_{in}/A_{out} = 4$)—are preserved across the full 5.5:1 volume range, so the dominant inter-case difference is scale rather than geometric logic. Only two parameters vary in a structurally meaningful way: the outlet elevation (0.50–0.75 m), which sets the effective working level and the headspace margin under foam or expansion events, and the conveyance angles ($45^\circ/45^\circ$ in Chillón versus $45^\circ/40^\circ$ in Huaycán and Lurín), which modulate gravitational self-cleaning. The expected physical consequence of the scale reduction—lower thermal and hydraulic inertia and hence higher sensitivity to load and temperature disturbances—is precisely the property that Stage 3 monitoring quantifies and that the ACT stability ratio (SR) ultimately captures.

Figure 2 shows the structural configuration of the Lurín prototype biodigester (200 L) in cross-sectional view, highlighting the geometric variables governing its hydraulic operation: filling fraction (headspace), relative inlet and outlet depths with respect to the base,

angles of the feeding and discharge lines, and main lengths/projections. This representation is used as the basis for parameterizing the system and ensuring traceability between the design and the variables compared in Table 3.

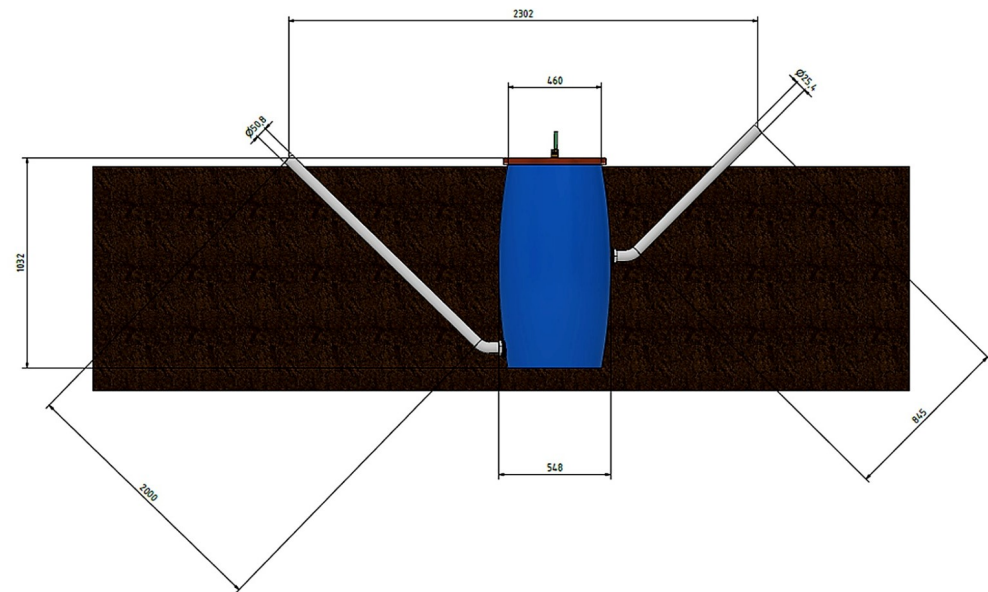


Figure 2. Structural configuration of the Lurín biodigester (200 L): cross-sectional view and reference geometric parameters. Lurín District, Lima, Peru.

Figure 2 consolidates Stage 2 by fully defining the physical object of the study: total and useful volume, filling fraction, and internal configuration governing gravitational flow and effective retention. With this geometric traceability, subsequent operational results (pH, EC, biogas production, and composition) are interpreted as a response of the anaerobic process rather than as an effect of dimensional ambiguities. Consequently, comparison with reference systems and replication of the design are supported by equivalent structural parameters (e.g., f_u , V_g/V_T , elevation ratios), enabling Stage 3 to function as a quantitative verification of stability under an explicit design.

3.2.2. Formative Cases of the Framework: Empirical Contributions from Chillón and Huaycán

Chillón [37] is the formative case that established the structural and predictive foundation of the framework. The Chillón study formalized the compact buried geometry ($f_u = 0.70$, headspace 30%, burial depth 1.10 m) that defines the geometric family adopted in this work, and developed a regression models with $R^2 = 0.98$ (OLS for continuous pH and temperature outputs) and pseudo- R^2 (McFadden) = 0.895 (multinomial logistic model for operational state classification) over a monitoring horizon of 30 days for pH and temperature and 16 days for biogas production, achieving stable production of 250.5 ± 9.36 L/day under codigestion of 70% bovine manure and 30% agricultural residues at HRT = 20 days and a stable mesophilic regime ($T = 25\text{--}35^\circ\text{C}$; $28\text{--}32^\circ\text{C}$ during methanogenesis). Although Chillón satisfied operational stability under the variables it monitored (pH, T) and provided a complete integrated evaluation in a complementary techno-economic and life cycle assessment ($Ea = 584.6$ kWh/a, $GEI_{\text{net}} = 109.2$ kgCO₂eq/a, NPV positive under co-product scenario), electrical conductivity was not incorporated as a control variable—a limitation explicitly recognized in the subsequent Huaycán study [28]. Therefore, Chillón contributes to the E1–E5 framework the structural-predictive component (Stages 1–2 and the univariate component of Stage 3) but does not provide evidence on the multivariable stability index (SR) as defined here, since EC was unavailable.

Huaycán [28] is the formative case that established the active operational control component of the framework. The Huaycán study elevated pH and EC to coupled first-order control. Table 4 highlights key design parameters, operational windows, and outcomes across the three studies, evidencing the framework’s discriminatory capacity on previously unseen data.

Table 4. Research-program trajectory and specific contribution of each case to the construction of the E1–E5 framework with ACT block: Chillón [37] (formative case—structural and predictive contribution), Huaycán [28] (formative case—active operational control contribution with quantitative benchmarks), and Lurín (methodologically independent prospective test).

Dimension	Chillón [37]	Huaycán [28]	Lurín (This Study)
Epistemological role	Formative case—structural-predictive contribution	Formative case—active operational control contribution	Methodologically independent prospective test
VT/Vu (filling fraction)	1100 L/770 L (fu = 0.70)	1100 L/770 L (fu = 0.70)	200 L/140 L (fu = 0.70)
Codigestion	70% bovine + 30% agricultural residues	70% bovine + 30% guinea pig manure	70% bovine + 30% organic fraction MSW
HRT	20 d	≈20 d	15 d
Thermal regime	25–35 °C (28–32 °C methanogenesis, mesophilic)	25–32 °C (controlled mesophilic)	18.4–22.3 °C (psychrophilic-mesophilic)
pH operational window	≈7.0 (no active control)	6.92–6.97 (active target)	6.71–7.32 (drift, no active control)
EC window (μS/cm)	Not reported	6200–6300 (active target with NaHCO ₃)	5800–9810 (~89% outside benchmark)
NaHCO ₃ intervention	Not applied	0.3–0.4 kg/d × 3–4 d (stoichiometric)	Not applied (research design choice)
Monitoring horizon	30 d (pH/T) + 16 d (biogas)	≈4 months (March–July 2025)	15 d (1 HRT cycle)
Predictive model (R ² /r)	0.98/not reported	0.78/0.89 (multivariable, interactions)	n.s. (n = 15)
Biogas production (L/d)	250.5 ± 9.36	370–462 (peak)	96.9 ± 12.3

The framework’s ACT block is genuinely applied only to Lurín, which serves as the methodologically independent test set. In contrast, Chillón and Huaycán are formative cases whose datasets informed the construction of the framework; therefore, applying the ACT block retrospectively to them would introduce methodological circularity and is explicitly avoided. Additionally, electrical conductivity (EC) was not reported in [37], and thus the operational EC benchmark is exclusively traceable to [28]. Finally, the decision in the Lurín case not to apply NaHCO₃ intervention responds to the original research objective—namely, the characterization of prototype behavior at reduced scale under an independent analytical perspective—rather than to an omission of the active control regime established in [28]. This methodological independence is precisely what enables Lurín to function as a clean and unbiased test set.

3.3. Stage 3: Operational Control and System Monitoring

The experimental campaign at Lurín was organized in two sequential monitoring phases, both conducted on the same prototype under identical structural and feeding

conditions. (i) Phase 1—Pre-ACT physicochemical monitoring (27 days from system start-up). During this phase, pH, electrical conductivity, and temperature were measured daily to characterize the physicochemical trajectory of the system from inoculation through the first hydraulic retention cycle and the subsequent stabilization period. Biogas production was not yet measured during this phase. (ii) Phase 2—ACT validation campaign (15 days, 9–25 June 2025, post first-HRT). After the system had completed the pre-ACT stabilization period, joint daily monitoring of temperature, pH, electrical conductivity, and biogas production was conducted during one additional complete HRT cycle. CH₄ and H₂S were measured weekly during this phase.. This sequential design ensures that the stability index SR is computed on a stabilized operating regime rather than on the start-up transient, thereby attributing observed instability to operational dynamics under normal conditions and not to inoculum acclimation.

Field operational control of the biodigester under real feeding variability and environmental conditions is reported. The analysis is based on daily monitoring of *T*, pH, and EC as control variables representing, respectively, the kinetic regime of the process (*T*) and the acid–base and ionic state of the digestate (pH–EC), which are direct determinants of methanogenic stability. Their dynamics are contrasted with a reference window (benchmark) derived from the previously validated cases in Chillón and Huaycán, used as an operational criterion to identify deviations and stability margins.

Table 5 consolidates the 15-day daily field record of the Lurín biodigester, integrating temperature (*T*), pH, and EC as physicochemical descriptors of digestate status, together with daily biogas production as the system’s energetic response. The “operational status” classifies each day according to its proximity to the observed stability window, allowing identification of production peaks when the system remains near favorable conditions (pH ≈ 6.9–7.1 and *T* ≈ 20–22 °C) and declines when thermal deviations (<20 °C), acidification (pH < 6.8), or abrupt EC increases occur. This dataset constitutes the quantitative starting point for subsequent analysis, as it establishes the empirical basis to: (i) contrast performance against benchmarks, (ii) justify operational adjustments, and (iii) model the relationship between physicochemical stability and biogas yield.

Table 5. Operational monitoring in Lurín over one HRT cycle (2025-06-09 to 2025-06-25, *n* = 15 days): T–pH–EC and daily biogas production under real conditions. The campaign-average specific methane yield was 177.4 L CH₄ kgVS^{−1} at a mean methane fraction of 54.2%.

Day	<i>T</i> (°C)	pH	EC (μS/cm)	Operational Status	Biogas (L/d)
1	20.4	7.31	6153	Transitional	95.1
2	19.4	7.32	5895	Low temperature	88.6
3	20.0	7.23	5800	Transitional	92.3
4	20.1	7.16	6821	Stable window	108.8
5	22.3	7.25	6902	Transitional	104.7
6	21.4	6.95	7410	Stable window	115.0
7	20.5	6.84	7545	Stable window	111.6
8	18.4	7.00	7571	Low temperature	92.4
9	20.9	7.01	7772	Stable window	112.2
10	20.5	7.06	7316	Stable window	111.0
11	18.4	7.09	7557	Low temperature	86.7
12	18.4	7.11	7571	Low temperature	85.9
13	20.5	6.71	9235	Acidification risk	83.8
14	21.2	6.72	9810	Acidification risk	79.0
15	21.3	7.08	9093	High ionic strength	86.2
Mean ± SD	20.25 ± 1.17	7.05 ± 0.19	7497 ± 1168	—	96.9 ± 12.3

Biogas composition (CH₄ and H₂S) was monitored weekly during the Phase 2 ACT campaign using a Geotech GA5000 portable gas analyzer (QED Environmental Systems, Coventry, United Kingdom) (NDIR for CH₄, ±1%; electrochemical sensor for H₂S, ±5%, LOD ≈ 1 ppm). Two effective measurements were obtained over the 15-day period.

The 15-day Phase 2 ACT validation campaign covers exactly one complete HRT cycle following the 27-day Phase 1 pre-ACT stabilization period, satisfying the minimum temporal criterion ($T_{eval} \geq HRT$) defined in the QC block (Equation (24)). The sequential design ensures that the SR index is computed on a regime that is no longer dominated by start-up transients. While this duration meets the framework's internal validation requirements, it represents a limitation for statistical generalization, as discussed in Section 4.2. The daily variation in operational status is not a data artifact but a scientifically informative result: it reveals that the system does not achieve steady-state operation under real feeding and environmental variability, transitioning between stable (Days 4, 6, 7, 9, 10), transitional (Days 1, 3, 5), low temperature (Days 2, 8, 11, 12), acidification risk (Days 13, 14), and high ionic strength (Day 15) states within a single retention cycle. This transient behavior is quantified by the stability ratio $SR = 5/15 = 0.33$, which falls below the required threshold ($SR \geq 0.75$) and directly triggers the 'not validated' decision in Stage 5, prescribing Type A feedback for ionic strength management and thermal buffering improvement.

Figure 3 documents EC operational control in Lurín and its direct comparison with the Chillón–Huaycán benchmark window, used here as a reference for ionic stability in small-scale biogas digesters.

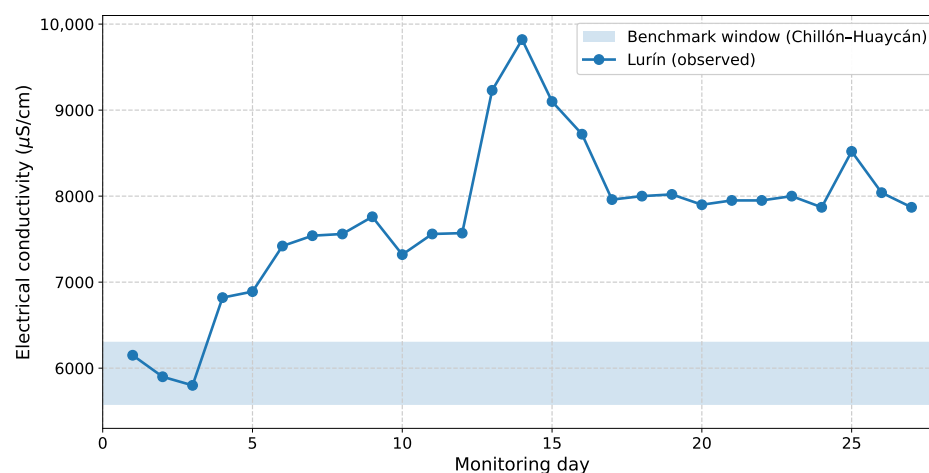


Figure 3. Electrical Conductivity (EC) monitoring in Lurín vs. benchmark operating window (Chillón–Huaycán). Phase 1: pre-ACT physicochemical monitoring ($n = 27$ days from system start-up); biogas production was not measured during this phase.

The key result is that Lurín operates predominantly above the benchmark EC window—a shift in the ionic-strength regime rather than a measurement detail: this regime governs both the buffering capacity against acidogenic pulses and the risk of osmotic stress on methanogenic archaea, so EC behaves as a state descriptor that explains why systems with similar pH can yield different biogas performance. Replicability therefore requires anchoring the process to a verifiable ionic corridor, not only maintaining pH. This dataset ($n = 27$) is the basis for Figures 4–6 and provide the descriptive context for ionic and acid–base drift analysis under the start-up regime.

Figure 4 shows the temporal profile of digestate pH measured in the field in Lurín and its contrast with a reference window (benchmark) derived from validated Chillón and Huaycán cases (pH 6.8–7.2), used as an operational stability criterion for anaerobic digestion. In the pre-ACT physicochemical dataset (Phase 1, $n = 27$), 18/27 (66.7%) of pH measurements fell within the benchmark, while 3/27 (11.1%) dropped below 6.8 (episodes compatible with transient loss of buffering capacity during start-up acclimation and risk of methanogenic inhibition due to VFA accumulation) and 6/27 (22.2%) exceeded 7.2 (relative over-alkalinization that does not provide intrinsic kinetic gain and must be interpreted

alongside ionic dynamics). These percentages characterize pH dynamics during the start-up and stabilization period and are not used as inputs for the SR computation, which is restricted to the Phase 2 dataset ($n = 15$).

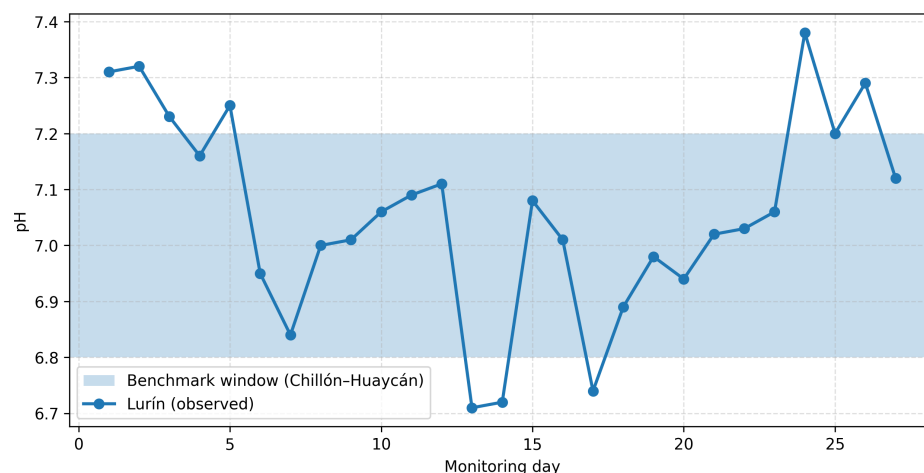


Figure 4. Digestate pH monitoring in the small-scale Lurín biodigester compared with the reference operating window [28,39]. Phase 1: pre-ACT physicochemical monitoring ($n = 27$ days from system start-up); biogas production was not measured during this phase.

In control terms, this result is not interpreted as isolated “good/bad pH,” but as evidence that system stability in Lurín depends on maintaining the acid–base balance within the reference window and completing the diagnosis with EC, since pH and ionic strength jointly govern consortium resilience under real feeding variability.

Figure 5 presents the observed temperature time series and contrasts it with a reference window (benchmark) constructed from previously validated cases (Chillón–Huaycán), used here as a comparative criterion to identify periods when the system operates under thermal conditions analogous to those reported as stable in small-scale biodigesters.

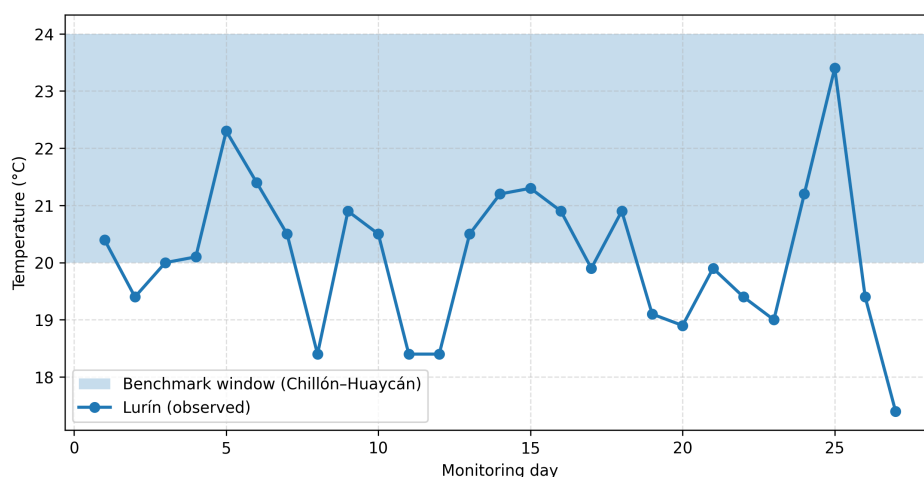


Figure 5. Temperature monitoring in the small-scale Lurín biodigester compared with the reference operating window [28,39]. Phase 1: pre-ACT physicochemical monitoring ($n = 27$ days from system start-up); biogas production was not measured during this phase.

The combined record ($T = 20.25 \pm 1.17$ °C, $\text{pH} = 7.05 \pm 0.19$, $\text{EC} = 7497 \pm 1168$ $\mu\text{S cm}^{-1}$; Table 5) indicates partially limited thermal kinetics with marked ionic accumulation: sub-optimal temperature lowers hydrolysis and acetogenesis rates and hence methanogenesis, so without active heating T acts as a limiting driver of stability and yield.

The temporal co-evolution of daily biogas production with digestate pH and with EC is provided in Supplementary Figure S2 and Figure S3, respectively: biogas peaks concentrate when pH remains near neutrality ($\approx 6.9\text{--}7.2$) and EC stays moderate ($\approx 6.0\text{--}7.8\text{ mS cm}^{-1}$), whereas acidification or a sustained EC rise toward $9\text{--}10\text{ mS cm}^{-1}$ coincides with lower and more variable production, consistent with methanogenic kinetics limited by transient acidification and ionic accumulation; EC thus operates as an early indicator of system drift.

Figures 3–5 and Supplementary Figures S2 and S3 report single daily field readings (one measurement per variable per day); error bars are therefore not applicable to individual points, and the associated metrological uncertainty is the instrument accuracy specified in Supplementary Table S2 (pH ± 0.02 ; EC $\pm 1\%$; $T \pm 0.5^\circ\text{C}$; biogas volume $\pm 2\text{--}5\%$). The quantitative statistical treatment of the Phase 2 campaign—means, standard deviations, coefficients of variation, bootstrap confidence intervals, and Pearson correlations—is consolidated in Table 6.

The Lurín reactor delivered an average daily biogas production of 96.9 L d^{-1} with a mean methane fraction of 54.2%, yielding a daily methane flow of $52.5\text{ L CH}_4\text{ d}^{-1}$. Referred to the daily volatile-solids load of the selected 70% manure/30% MSW scenario ($VS_{in} = 0.296\text{ kgVS d}^{-1}$), the experimental specific yield is $177.4\text{ L CH}_4\text{ kgVS}^{-1}$ ($327.4\text{ L biogas kgVS}^{-1}$). The most favorable operational window—pH $\approx 6.9\text{--}7.1$ with EC $\approx 6000\text{--}7500\text{ }\mu\text{S cm}^{-1}$ —corresponded to peak production days; outside this window, yield dropped consistently with the methanogenic kinetic interpretation.

The experimental results indicate that the Lurín reactor did not merely approach the theoretical window defined in Stage 1, but achieved an explicit field-based methane yield of $177.4\text{ L CH}_4/\text{kgVS}$ under the monitored semi-continuous operating regime, with an applied organic loading rate of $OLR = 2.11\text{ kgVS m}^{-3}\text{ d}^{-1}$ (calculated as $VS_{in}/V_u = 0.296/0.140$) and $HRT = 15\text{ d}$. This OLR falls within the typical range reported for small-scale unheated co-digestion prototypes operating on bovine manure and MSW-derived substrates.

The response surface uses pH and EC as dual predictors of biogas yield because they are the two actively manageable state variables under minimal field instrumentation—an operator adjusts pH through load management, buffering, or dilution, and EC through dilution or purging—whereas temperature in an unheated buried reactor is quasi-exogenous and cannot be modulated, so it adds no actionable control information; moreover, with $n = 15$ observations a three-predictor surface would risk overfitting. The pH–EC pair is therefore the minimal operational control set with the highest practical relevance for field decision-making without active thermal control. This selection is a deliberate design choice rather than an omission: laboratory descriptors such as chemical oxygen demand (COD) and volatile fatty acids (VFA) require reagents and bench analysis that are seldom feasible under the resource-limited, minimal-instrumentation field conditions the framework targets, and requiring them would contradict its transferability premise. We acknowledge that EC alone is an aggregate descriptor that does not separate protective alkalinity from inhibitory salinity; this dual role is precisely why EC must be read jointly with pH and, in future work, complemented by easily measurable redox descriptors. Accordingly, a minimal causal-diagnostic module (VFA/alkalinity, COD/VS, oxidation–reduction potential, and ionic balance) is identified in Sections 4.2 and 4.3 as the priority extension for resolving failure mechanisms.

Figure 6 shows the resulting response surface of daily biogas yield over the pH–EC plane, visualizing the high-performance region and the sensitivity to acid–base and ionic deviations; temperature, HRT, OLR, and VS load were retained in the predictive model and sensitivity analysis but not in the graphical surface.

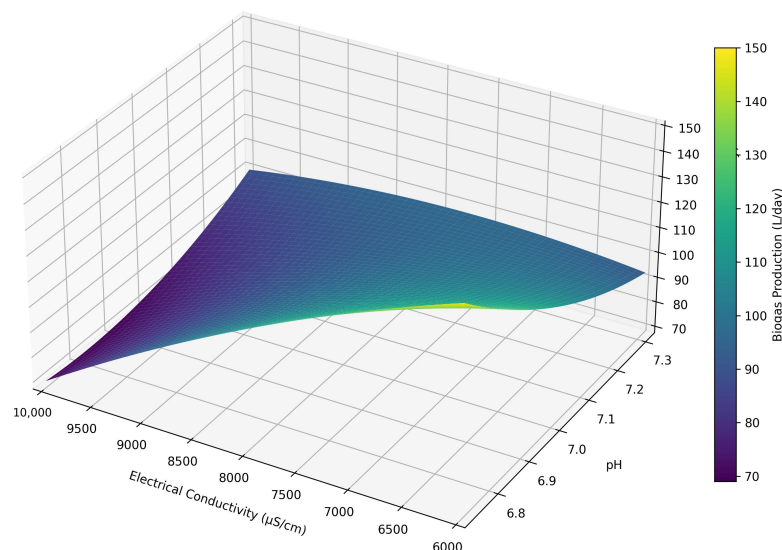


Figure 6. Response surface of biogas production [L d^{-1}] as a function of pH [–] and electrical conductivity (EC) [$\mu\text{S cm}^{-1}$]: Lurín case (Phase 2 dataset, $n = 15$).

This dataset ($n = 15$) is reported in Table 6 and constitutes the exclusive basis for the operational stability index SR computation, the Pearson correlation analysis (Table 6), the response surface (Figure 6), and the integrated ACT decision (Stage 5)

Table 6 summarizes the descriptive statistics and bivariate Pearson correlations between operational variables and daily biogas production. None of the individual correlations reach statistical significance at $\alpha = 0.05$ with the available sample size ($n = 15$), which reflects the limited statistical power of a single-HRT monitoring campaign rather than the absence of functional relationships.

The direction of associations is consistent with mechanistic expectations: temperature shows a positive trend ($r = 0.377$), suggesting kinetic enhancement at higher temperatures within the observed mesophilic-psychrophilic range; pH exhibits a weak positive association ($r = 0.096$), indicating that the relatively narrow pH range observed (6.71–7.32) may not generate sufficient contrast to detect a strong linear effect; and EC shows a negative trend ($r = -0.354$), consistent with the expected inhibitory effect of ionic accumulation on methanogenic activity.

These results reinforce the framework's rationale for using multivariable stability criteria (SR, which require simultaneous compliance of pH, EC, T, and production) rather than single-variable regression thresholds for operational classification, since individual variable effects may be masked by interactions and limited sample size.

Table 6. Descriptive statistics and Pearson correlations between operational variables and daily biogas production. 95% confidence intervals computed via percentile bootstrap (10,000 iterations); $n = 15$.

Variable	Mean $\pm$ SD	Range	CV (%)	r (Pearson)	95% CI (Bootstrap)	p -Value
Temperature ($^{\circ}\text{C}$)	20.25 $\pm$ 1.17	18.4–22.3	5.8	+0.377	[−0.043, +0.767]	0.167 (n.s.)
pH	7.05 $\pm$ 0.19	6.71–7.32	2.7	+0.096	[−0.577, +0.557]	0.734 (n.s.)
EC ($\mu\text{S/cm}$)	7497 $\pm$ 1168	5800–9810	15.6	−0.354	[−0.720, +0.267]	0.195 (n.s.)
Biogas (L/d)	96.9 $\pm$ 12.3	79.0–115.0	12.7	—	—	—

n.s. = not significant at $\alpha = 0.05$. Correlations are bivariate Pearson r between each variable and daily biogas production (L/d).

Although none of the bivariate Pearson correlations reaches statistical significance at $\alpha = 0.05$ ($p = 0.167, 0.734, 0.195$ for T , pH, EC, respectively), the point estimates are directionally consistent with mechanistic expectations: positive r for T (kinetic enhancement

at higher temperatures within the observed mesophilic–psychrophilic range), negligible r for pH (the narrow observed range 6.71–7.32 limits contrast), and negative r for EC (compatible with ionic-strength inhibition of methanogenic activity). These descriptive trends warrant verification with extended monitoring (3–4 HRT cycles) before mechanistic conclusions can be drawn statistically.

The surface reveals a clear gradient: maximum production concentrates in a narrow “operational zone” where pH remains close to neutrality (≈ 6.9 – 7.1) and EC stays at moderate values (≈ 6.0 – 7.5 mS/cm). As EC increases toward the higher range (≈ 9 – 10 mS/cm), production drops markedly, even if pH remains acceptable, indicating that ionic strength/salinity acts as an independent limiting factor. In parallel, pH deviations away from the neutral range reduce performance even with controlled EC, demonstrating pH–EC interaction: pH control without ionic control does not guarantee energy stability. From a control perspective, the figure justifies using pH–EC as a paired decision variable set to maintain the process within the high-performance region and prevent transitions toward lower-production states.

3.4. Stage 4: Integrated Economic and Environmental Assessment

This stage frames biodigester sustainability as a quantifiable and comparable criterion, integrating within a single methodological block energy performance, economic viability, and the climate balance associated with real system operation. Unlike ex post evaluations disconnected from design, the indicators here are calculated using as a basis: (i) the structural decisions defined in Stage 2 (e.g., V_u , filling fraction, HRT, OLR, and storage configuration), (ii) the operational parameters measured in Stage 3 (daily biogas production, CH_4 fraction, pH–EC–T stability, and tightness condition), and (iii) the contextual assumptions established in Stage 1 (energy substitution scenario, evaluation horizon, and local use/valorization conditions).

The purpose is not to “optimize” the system, but to verify whether, under the already defined real regime, the biodigester simultaneously meets minimum criteria of: (a) territorial energy impact (coverage), (b) net climate mitigation (avoided minus fugitive emissions), and (c) economic performance (NPV and competitiveness relative to local energy). To ensure traceability, the assessment is structured into three coupled modules: (1) annual useful energy from biogas and its methane content; (2) system economics (CAPEX, OPEX, revenues/savings, NPV, LCOE), explicitly incorporating coproduct (biofertilizer) treatment as either an equivalent substitution credit or alternative scenario; and (3) climate balance through energy substitution and methane leakage penalty.

Finally, this stage includes a sensitivity analysis to identify dominant parameters (biogas production, f_{CH_4} , leakage rate, prices/values, and discount rate) and culminates in an integrated feasibility condition that directly feeds Stage 5, activating feedback toward Stages 1–3 if defined thresholds are not met.

Table 7 presents the base economic and techno-energy parameters used to construct the integrated assessment for the Lurín case in Stage 4. It consolidates, in a traceable manner: (i) project financial assumptions (CAPEX, lifetime, and discount rate), (ii) measured operational variables governing energy generation (daily biogas production and CH_4 fraction), and (iii) economic valuation factors of system products (biogas and biofertilizer), together with annual operation and maintenance costs. These values constitute the minimum input set required to estimate annual energy, net cash flows, NPV, and LCOE within a unified comparison framework, ensuring coherence between observed experimental performance and the economic quantification of the system.

Table 7. Base economic parameters for integrated assessment (Lurín case).

Item	Symbol	Value	Unit
Initial investment (CAPEX)	(C_{inv})	148.68	USD
System lifetime	(n)	10	years
Discount rate	(r)	0.10	–
Daily biogas production	($V_{bg,d}$)	0.0969	m ³ /d
CH ₄ fraction (for energy/GHG) ¹	(f_{CH_4})	0.58	–
CH ₄ energy content (LHV)	(PCI_{CH_4})	9.97	kWh/m ³
Daily biofertilizer production (≈flow)	(Q_d)	9.8	L/d
Biogas value (market reference)	–	3.288	USD/m ³
Biofertilizer unit value (economic equivalent)	–	0.676	USD/L
Annual O&M costs	(C_{op})	25.0	USD/a

¹ $f_{CH_4} = 0.58$ is the planning-stage design value used to report nominal capacity; the field-measured fraction in Stage 3 was $f_{CH_4,exp} = 0.542$. Because E_a and GEI_{net} are both linear in f_{CH_4} , substituting the measured value lowers each by the same factor (a 6.5% reduction), without altering the sign or the directional conclusions of the assessment.

The $f_{CH_4} = 0.58$ value corresponds to the planning-stage assumption defined in Stage 1 for hydraulic sizing and preliminary energy estimation. The field-measured value during Phase 2 ($0.542 \pm [SD]$) was used to verify operational compliance in Stage 3 (Table 1, CH₄ ≥ 50% criterion) but the planning-stage assumption was retained in Stage 4 indicator computations for traceability with the original design hypothesis. A sensitivity analysis based on the measured value yields a 6.5% reduction in both E_a and GEI_{net} (both indicators are linear in f_{CH_4}), with the directional conclusions of the integrated assessment remaining unchanged.

Biofertilizer unit value derived from equivalent NPK content valuation based on regional wholesale prices for liquid organic fertilizers and commercial digestate extracts marketed in coastal Lima (March 2025 reference period), adopted as the central estimate in the absence of a formalized local market for small-scale anaerobic-digestion co-products. Given that this parameter dominates total revenue (>95%), a three-scenario sensitivity analysis is reported in Supplementary Table S8.

Values represent theoretical upper-bound estimates of daily biogas and methane potential, calculated from substrate elemental composition and VS content under assumed conversion efficiencies. These are planning-stage projections (Stage 1), not experimentally measured yields. Actual production under real conditions is verified in Stage 3. Methane potential is estimated from biogas potential using the corresponding assumed CH₄ fraction.

The valuation uses two unit prices (Table 7): a biogas market reference of 3.288 USD m^{−3} and a biofertilizer equivalent value of 0.676 USD L^{−1}. Annual revenues follow as biogas = $V_{bg,d} \times 365 \times 3.288 = 116.30 \text{ USD a}^{-1}$ and biofertilizer = $Q_d \times 365 \times 0.676 = 2418.05 \text{ USD a}^{-1}$. Under the co-product valorization scenario (Scenario A: biogas + biofertilizer monetization), the system generates 2534.4 USD a^{−1} in total revenue (116.30 USD a^{−1} from biogas; 2418.05 USD a^{−1} from biofertilizer). Subtracting annual O&M costs of 25 USD a^{−1}, the net annual cash flow is 2509.35 USD a^{−1}, leading to NPV (10 a, $r = 10\%$) ≈ 15,269 USD and a simple payback of approximately 21.6 days. In this scenario, the net LCOE becomes negative (≈−11.4 USD/kWh) because the coproduct dominates the economic balance. Under the energy-only scenario (Scenario B: biogas alone, without biofertilizer credit), annual revenue equals 116.30 USD a^{−1}; the net cash flow drops to ≈91.30 USD a^{−1}, with payback of ≈1.63 years and energy LCOE ≈ 0.24 USD kWh^{−1}. The economic conclusion is therefore strongly conditioned by the biofertilizer valorization assumption, which dominates total revenue (>95%). The complete itemized calculation, including the discounted cash flows, is reported in Supplementary Table S3.

To quantify the net climate performance of the biodigester, an annual GHG balance was estimated based on the two dominant terms in small-scale systems with energy use

of biogas: (i) avoided emissions from the substitution of LPG as the reference fossil fuel ($EF_{\text{sub}} = 0.227 \text{ kgCO}_2\text{eq/kWh}$, IPCC AR6 default for residential LPG combustion), calculated from the annual useful energy E_a ; and (ii) fugitive emissions associated with CH_4 leakage, parameterized through the leakage rate η_{fug} and the GWP_{100} of methane. Supplementary Table S4 consolidates the baseline parameters and constants used in the calculation.

Under baseline assumptions, energy substitution avoids $46.4 \text{ kgCO}_2\text{eq a}^{-1}$ while CH_4 fugitive losses introduce $8.2 \text{ kgCO}_2\text{eq a}^{-1}$, yielding a net positive balance of $GEI_{\text{net}} = 38.2 \text{ kgCO}_2\text{eq a}^{-1}$. Methane leakage therefore consumes approximately 18% of the gross mitigation benefit, identifying η_{fug} as the dominant lever for environmental performance improvement. The detailed parameter table and full computation are reported in Supplementary Table S4.

Stage 4 consolidates the decision-oriented evaluation of the framework by translating the verified technical performance (Stage 3) and the design conditions defined in Stage 2 into quantifiable criteria of economic viability and climate sustainability under the contextual assumptions of Stage 1. From an environmental perspective, the system presents a positive net mitigation outcome ($GEI_{\text{net}} = 38.2 \text{ kgCO}_2\text{eq a}^{-1}$), since avoided emissions from energy substitution exceed the fugitive methane losses; the biodigester therefore operates as a net mitigator under the adopted leakage assumption.

From an economic standpoint, interpretation must be separated into two scenarios: Scenario A (co-product: biogas + digestate valorization), where the biofertilizer credit dominates total revenue (net annual cash flow $\approx 2509.35 \text{ USD a}^{-1}$) and explains the extremely short payback (~ 22 days); this is a co-product-driven return, not an energy return, and is therefore highly sensitive to digestate price stability, logistics, and marketable volume; and

Scenario B (energy only: biogas alone, without biofertilizer credit), where cash flow depends exclusively on the value of the produced biogas (annual revenue $\approx 116.30 \text{ USD a}^{-1}$) minus O&M, so the return is governed by biogas productivity and energy price.

Consequently, although the reported NPV is positive within the evaluated horizon, the robustness of the economic conclusion depends critically on (i) the real valorization of the digestate (price, demand, logistics, and marketable volume) [41] and (ii) the stability of daily biogas yield under operational variability. Analogously, the robustness of the climate balance is strongly conditioned by the methane leakage rate (η_{fug}) and by the emission factor of the substituted fuel (EF_{sub}), which control the sign and magnitude of GEI_{net} . Therefore, Stage 4 can be formally closed by stating that the case satisfies the minimum environmental condition ($GEI_{\text{net}} > 0$), while economic viability remains scenario-dependent (pure energy vs. co-product). It is recommended to explicitly state the decision rule and to report, even in compact form, a first-order sensitivity analysis (biofertilizer price, $V_{\text{bg},d}$, CAPEX/O&M, η_{fug} , and EF_{sub}) to ensure that the decision does not hinge on a single dominant assumption.

3.5. Stage 5: Integral Validation and Framework Feedback (ACT)

With the technical–operational results already verified (pH–EC–T control and daily production) and the integrated economic–environmental assessment closed, the next step is to finalize the Lurín case decision under reproducible and non-subjective criteria. To this end, two sequential filters are applied: first, a minimum data quality control to ensure temporal coverage and monitoring completeness; second, a technical–operational validation that quantifies stability through SR and simultaneously requires compliance with gas quality criteria (CH_4 , H_2S). Only if these filters are satisfied is integral feasibility assessed through the joint condition Ω (environment–economy–competitiveness–coverage). Collectively, this ACT block transforms the previously computed indicators into a single

output (validated/not validated) and, when applicable, explicitly identifies the feedback route toward the stage that must be corrected.

Supplementary Table S5 consolidates the full ACT verification as an auditable dashboard in which each entry derives explicitly from the monitoring campaign (Stage 3), the structural configuration (Stage 2), or the economic–environmental modules (Stage 4), and no indicator is interpreted in isolation but only as part of the joint acceptance condition. Quality control—sufficient temporal coverage ($T_{eval} \geq HRT$) and completeness ($C_{data} \geq 0.90$)—operates as a mandatory filter that prevents spurious validation from short or incomplete campaigns, while the multivariable stability index SR , complemented by the CH_4 and H_2S criteria, quantifies operational controllability rather than mere production and guards against declaring stability from volumetric output alone.

With the purpose of applying the formal decision rule (ACT) of the methodological framework, Table 8 summarizes—in a compact and verifiable format—the calculated indicators and their acceptance thresholds, organized according to the three validation filters: (i) data quality control (QC), (ii) technical–operational validation through the stability index SR and gas quality, and (iii) integrated sustainability verification (environment–economy–competitiveness). This synthesis does not describe the system; it subjects it to a decision test in which each criterion is evaluated against an explicit threshold, allowing a reproducible conclusion as to whether the Lurín case validates the framework, and precisely identifying the stage to which the process must return in case of non-compliance.

Table 8. Summary of Stage 5 (ACT) criteria and compliance verification (Lurín case).

Block	Indicator	Value (Lurín)	Threshold/Rule	Status
QC	Temporal coverage (T_{eval} vs. HRT)	15 d Phase 2 (after 27 d Phase 1 stabilization) vs. HRT = 15 d	$T_{eval} \geq HRT$	Compliant
QC	Completeness (C_{data})	1.000 (64/64)	≥ 0.90	Compliant
Operation	Stability ratio (SR)	0.33	≥ 0.75	Non-compliant
Gas	CH_4	54.2%	$\geq 50\%$ minimum	Compliant
Gas	H_2S	0 ppm	< 10 ppm	Compliant
Environment	GEI_{net}	38.2 kgCO ₂ e/a	> 0	Compliant
Economy	NPV (biogas only)	≈412 USD	> 0	Compliant
Economy	NPV (biogas + biofertilizer)	≈15,269 USD	> 0	Compliant
Competitiveness	ϕ	N/A	P_{energy} not defined in Stage 1	Not applicable
Coverage	β	N/A	No E_{dem} defined in Stage 1	Not applicable
Integral condition	Ω	Not assessed for this pilot case	β unavailable	Not applicable
Decision	Final ACT decision	Not validated (Type A)	Filter 1 fails because $SR < 0.75$	Final

$C_{data} = 64/64 = 1.000$, where $N_{reg,plan} = (4 \text{ daily variables} \times 15 \text{ days of Phase 2}) + (2 \text{ weekly gas variables} \times 2 \text{ weeks}) = 64$. All planned records were effectively obtained: the 60 daily measurements of T , pH, EC and biogas, and the four weekly gas analyses (two CH_4 and two H_2S). The 60 daily values are reported in Table 5 and the gas analyses in Supplementary Table S7. The ACT validation is computed exclusively on the Phase 2 dataset; the Phase 1 pre-ACT physicochemical record ($n = 27$) is used only for descriptive characterization (Figures 3–5).

The integral sustainability condition Ω cannot be evaluated for the Lurín case because two of its constituent indicators (β and ϕ) require Stage 1 inputs (E_{dem} and P_{energy} , respectively) that were not formally defined during the original research design, since the Lurín study was conceived to characterize prototype behavior at reduced scale rather than to evaluate territorial energy substitution. The ACT decision for Lurín therefore rests entirely on Filter 1 (technical–operational validation), which already fails due to insufficient stability ($SR = 0.33 < 0.75$). This dependency of Ω on Stage 1 parameters is itself a methodological finding: it shows that integral sustainability verification cannot proceed without complete diagnostic-stage inputs, reinforcing the framework’s sequential logic.

The application of ACT reveals a methodologically clean result: the Lurín case does not validate the framework, and it does so for a dominant and quantifiable reason: technical–operational stability. First, the system passes the data quality filter, simultaneously meeting the minimum temporal coverage requirement ($T_{\text{eval}} \geq HRT$) and completeness threshold ($C_{\text{data}} \geq 0.90$); therefore, the conclusion is not based on weak records but on a sufficient observational basis. However, when evaluating design–operation consistency, the stability index results in $SR = 0.33$ (5 stable days out of 15), well below the threshold $SR \geq 0.75$. This implies that system performance is operationally dominated by perturbations and state transitions (ionic drift and thermal/acidogenic episodes). Thus, although periods of good performance may exist, the required stability standard to declare the system “controlled” under the framework is not achieved. In parallel, gas quality may be acceptable for domestic use (minimum CH_4 and H_2S thresholds within limits), but this compliance does not compensate for failure to meet the structuring ACT criterion: multivariable daily stability that validates operational control.

Second, the integrated evaluation shows conditionally positive signals: the net climate balance remains positive ($GEI_{\text{net}} > 0$), and economic indicators may be favorable, especially under the co-product valorization scenario; however, ACT is designed precisely to prevent the classic error in small projects—concluding economic or environmental viability under unstable operation. In other words, in Lurín there may be net mitigation and “on-paper” profitability, but the operational evidence indicates that the system does not yet operate within a sufficiently stable regime to sustain those metrics in a robust and replicable manner.

Consequently, the final decision is “Not validated,” and the feedback is classified as an operational failure (Type A): the appropriate return is to Stage 3, adjusting the control regime (primarily ionic strength/EC management, handling of thermal variability, and prevention of acidification episodes) until SR exceeds 0.75 without deteriorating gas quality. Only once sustained stability is demonstrated can the economic and environmental indicators of Stage 4 be interpreted as attributes of the design–operation configuration rather than as results sensitive to a short monitoring campaign. In this way, the framework does not “penalize” the case study; it uses it as intended—to issue an unambiguous decision and clearly indicate what must be corrected and where within the methodological cycle.

4. Discussion

In this section, the available evidence is contrasted with the methodological coverage required to implement and verify small-scale biodigesters in a reproducible manner; aggregate stage-level coverage statistics are summarized in Table 9. Although the literature is extensive, its contribution is often concentrated on isolated modules (technology/substrate selection, design and sizing, operation/O&M and process optimization, or economic/environmental assessment), which limits traceability between design decisions, operational performance, and sustainability verified through explicit criteria. The mean CH_4 fraction was $54.2 \pm 2.1\%$ (range 52.7–55.7%), and H_2S concentration was below the instrumental detection limit (<1 ppm) in all measurements, conservatively reported as 0 ppm in Table 9. Individual measurement values are reported in Supplementary Table S7.

Table 9. Coverage and focus of studies across methodological stages ($n = 48$).

Stage	N (of 48)	Coverage	Main Focus
E1—Diagnosis and planning	24/48	50.0%	Technology/substrate selection and territorial delimitation
E2—Design and configuration	10/48	20.8%	Sizing, geometry, and materials
E3—Operation, monitoring, and control	29/48	60.4%	Process parameters, stability, and interventions
E4—Economic/environmental assessment	19/48	39.6%	TEA/LCA/GHG balance
E5—Decision and formal feedback	1/48	2.1%	Quantitative decision closure and feedback

To make this contrast verifiable, the synthesis is organized as a stage-based mapping (E1–E5); the complete reference-by-reference coding is provided in Supplementary Table S6, and the aggregate pattern is summarized in Table 9. In this classification: E1 = diagnosis and initial decision (context, technology/substrate); E2 = design and configuration (sizing, geometry, materials); E3 = operation, monitoring, and control (O&M, stability, improvement interventions); E4 = economic and environmental evaluation; E5 = decision validation and feedback. Each reference is coded according to the presence of an explicit framework, the stages covered, and the type of contribution (procedure, evidence/benchmark, or thematic support).

The E1–E5 classification was defined a priori as a structured analytical instrument to evaluate methodological coverage across the literature. Each reference was independently coded by two authors according to explicit stage definitions, and discrepancies were resolved through consensus discussion. The mapping is therefore a reproducible analytical tool designed to quantify coverage patterns, not a post hoc construction intended to validate the proposed framework.

Based on the E1–E5 stage mapping (Supplementary Table S6; $N = 48$), the literature shows a marked concentration in E3 (operation/monitoring/control; 60.4%) and E4 (economic/environmental assessment; 39.6%), indicating that most research prioritizes (i) process performance optimization through operational parameters, stability, kinetics, and improvement interventions (e.g., co-digestion, additives, trace elements, or nanomaterials) [42–54], and (ii) quantification of feasibility and sustainability through economic and environmental assessments (TEA/LCA, scenario analysis, indicators) [55–66]. In contrast, E1 (diagnosis/initial decision; 50.0%) [67–74] and E2 (design/configuration; 20.8%) [75–79] show partial coverage, and the most critical methodological finding is the near-total absence of E5 (decision validation and explicit feedback; 2.1%, a single study [80]). This indicates that, despite abundant experimental and scenario-based evaluation evidence, a reproducible closure based on data quality control, stability criteria, and explicit acceptance/rejection rules with stage feedback is rarely formalized.

In terms of methodological continuity, although 16.7% of the references cover ≥ 3 stages, only 4.2% cover ≥ 4 stages, and just 2.1% cover the full E1–E5 cycle. This pattern confirms that the state of the art is dominated by modular contributions: partial frameworks (14.6%) and studies without an explicit framework (83.3%), with relevant disconnects such as E4 without E3 (25.0%) and E1 without E2 (39.6%), limiting traceability between selection decisions, system configuration, operational performance, and verifiable sustainability.

4.1. Discriminatory Power and Comparative Advantages of the Integrated Framework

The principal advantage of the E1–E5 framework lies in its capacity to prevent a class of error that is prevalent in fragmented evaluations: declaring system viability based on favorable economic or environmental indicators without verifying operational stability. In the Lurín case, the system exhibits positive net GHG mitigation ($GEI_{net} = 38.2 \text{ kgCO}_2\text{eq/a}$) and positive NPV under the co-product scenario ($\sim 15,269 \text{ USD}$); energy competitiveness (ϕ) cannot be evaluated because P_{energy} was not defined in Stage 1, and the integral indicators that can be computed remain favorable. Under conventional modular assessment—as practiced by the majority of the mapped literature (35.4% cover E4 without any formal decision closure)—these indicators would support a conclusion of viability. However, the ACT block reveals that operational stability is critically insufficient ($SR = 0.33 < 0.75$), meaning that the economic and environmental metrics are artifacts of short-term favorable episodes rather than attributes of a robust design–operation configuration.

This discriminatory capacity distinguishes the proposed framework from prior approaches. Kulkarni et al. [81] reported positive TEA/LCA outcomes for small-scale biodi-

gesters in low- and middle-income countries without quantifying operational stability or establishing formal acceptance/rejection criteria, so their conclusions could not distinguish genuinely stable systems from those that merely performed well during the evaluation period. Eftaxias et al. [27] conducted a techno-economic assessment for animal-husbandry biogas plants without feedback to design stages when economic thresholds were not met, yielding a one-directional evaluation without corrective capacity. Villarroel-Schneider et al. [19] estimated GHG reductions for Latin American dairy farms from assumed rather than measured operational parameters, which the present framework requires through Stage 3 monitoring before permitting Stage 4 conclusions. Mendiola-Rodriguez and Ricardez-Sandoval [80] integrated design and control through deep reinforcement learning, but focused on computational optimization rather than reproducible decisional closure for resource-limited field contexts with minimal instrumentation.

The framework also enables targeted corrective action rather than generic optimization recommendations. By classifying failure as Type A (operational: return to E3), Type B (structural: return to E2), or Type C (diagnostic/planning: return to E1), it reduces trial-and-error cycles and focuses limited resources on the binding constraint: in the Lurín case, the Type A classification identifies ionic-strength management (EC control through dilution/purging) and thermal buffering as the primary intervention targets, avoiding unnecessary structural modifications or system redesign. The explicit QC requirements ($C_{\text{data}} \geq 0.90$, $T_{\text{eval}} \geq \text{HRT}$) further prevent a common small-scale error—drawing conclusions from incomplete or biased monitoring campaigns—since none of the 48 mapped references reported data-completeness metrics or minimum temporal-coverage criteria as preconditions for their conclusions.

The ACT decision criteria are applied comparatively to the three cases of the research program in Supplementary Table S9, with explicit acknowledgment of their asymmetric epistemic status (in Chillón, EC was not measured, so SR cannot be fully computed; in Huaycán, the strict EC window was derived from the case itself). Three lessons emerge. First, the framework does not produce false positives on the formative cases: Chillón and Huaycán, when evaluated under criteria independent of their own derivation (tolerance windows, integral indicators), comply consistently. Second, the framework correctly identifies the operational instability of Lurín that fragmented modular assessments would have missed. Third, the dependency of Ω on Stage 1 inputs (E_{dem} , P_{energy}) is common to all three cases, indicating that the integral filter requires diagnostic-stage parameterization that was not the original objective in any of them. This asymmetry is not a weakness concealed in the analysis but an explicit constraint that the bidirectional verification identified as a priority for future work (Section 4.3) is designed to address.

Crucially, the discriminatory test is clean because Lurín did not participate in the framework's construction: its criteria were formalized after data collection, and the active NaHCO_3 control of Huaycán was deliberately not applied. The coexistence of severe operational instability ($SR = 0.33$) with simultaneously positive integral indicators is precisely the configuration that fragmented modular evaluation fails to detect. The failure is mechanistically traceable to the formative evidence: EC remained outside the Huaycán-derived window (6200–6300 $\mu\text{S}/\text{cm}$) for $\approx 89\%$ of the campaign, and the psychrophilic–mesophilic temperature (18.4–22.3 °C) contrasts with the stable mesophilic regime (28–32 °C) of the larger-scale cases. The 27-day Phase 1 stabilization preceding the 15-day ACT campaign ensures that $SR = 0.33$ reflects regime-level dynamics rather than start-up transients.

4.2. Limitations of the Integrated Methodological Framework

Measurement validity. The framework depends on the metrological quality of its control variables (pH, EC, T , tightness, biogas flow, $\text{CH}_4\text{--H}_2\text{S}$); the QC criteria do not correct

systematic biases (miscalibration, sensor drift, sampling error), which under minimal instrumentation may propagate into false positives or negatives at the decision stage.

Context-specific thresholds. The operational windows of Table 1 (pH 6.8–7.2, EC 5600–6300 $\mu\text{S}/\text{cm}$, T 20–24 $^{\circ}\text{C}$) were established for this study’s substrate, inoculum, and climate and are not transferable without validation to other substrates, thermal regimes, or actively controlled systems. The internal logic holds regardless of values, but the numerical windows must be recalibrated per context—a threshold-regionalization procedure identified as priority future work.

Temporal coverage. The single HRT cycle (15 days) satisfies the minimum QC criterion ($T_{\text{eval}} \geq \text{HRT}$) but does not capture seasonal variability or slow-onset phenomena (trace-element depletion, recalcitrant VFA accumulation, alkalinity loss); the resulting SR reflects short-term controllability rather than long-term robustness, and the $n = 15$ correlations did not reach significance ($\alpha = 0.05$). Evaluation periods of 3–4 HRT cycles (45–60 days) are recommended. This does not invalidate the framework—the ACT logic correctly returns “not validated” with targeted feedback—but it constrains the generalizability of the specific SR value.

Construct validity. Aggregated stability indices synthesize multivariable conditions into a single judgment but do not identify failure mechanisms (VFA accumulation, free-ammonia inhibition, sulfides, trace-metal toxicity, foaming, mass-transfer limits); consistent compliance classification therefore still requires complementary diagnostic modules (VFA/alkalinity, TAN/FAN, COD/VS, ionic balance) not always feasible at small scale.

Model validity. Stage E4 is structurally sensitive to system boundaries (gate-to-gate vs. cradle-to-gate), emission factors, substitution assumptions, discount rate, local prices, and leakage rate, so two implementations with similar operation may reach opposite viability conclusions; without standardized, transparent inventories, inter-study comparability is limited.

Uncertainty treatment. The explicit decision rules do not guarantee robustness near thresholds (region of indifference), where measurement and TEA/LCA uncertainty can reverse the sign of NPV or net GHG without real design changes; global sensitivity analysis (Sobol/Morris) and/or Monte Carlo simulation should complement the Boolean logic so that decisions are expressed as probabilities of compliance.

Technological heterogeneity. Generalizing to other digester types (tubular, fixed-dome, CSTR, batch; buried or not; with or without agitation) is non-trivial because hydrodynamics and transfer dynamics alter the meaning of “stable production”, the “operational window”, and T_{eval} , so portability requires adapting the derived variables and stability criteria to each technology.

Socio-institutional dimensions. Non-technical variables (maintenance capacity, spare-part availability, training, incentives) govern long-term functionality; although addressed qualitatively in E1, they are not formalized in E5 as acceptance conditions, so a technically viable system may still fail in real operation through governance gaps.

Digestate quality. The framework does not include a full digestate-quality module (salinity, sodium, metals, pathogens, phytotoxicity), which conditions agronomic applicability and real economic value; its absence risks overestimating economic benefits or underestimating environmental impacts.

Asymmetric testing. The framework was constructed from the Chillón [37] and Huaycán [28] evidence and prospectively validated only on the unstable Lurín case (a true negative); it has not yet been applied to a system under active pH–EC control to confirm that it also returns a positive ACT decision (a true positive). Closing this falsification loop bidirectionally is the priority verification identified in Section 4.3.

4.3. Future Research Directions

The limitations identified above define a structured agenda for refining and transferring the framework. First and foremost, the framework requires prospective validation on a case study that implements active operational control (pH–EC management through stoichiometric NaHCO_3 dosing or an equivalent regime) under its own quantitative criteria, in order to close the falsification loop bidirectionally: beyond demonstrating that the framework correctly rejects an unstable system (as shown in Lurín), it must also be shown that it issues a positive ACT decision when the system operates within stable windows. Only the conjunction of a true negative (Lurín) and a true positive (a demonstrably stable case) establishes discriminatory capacity in both directions.

Beyond this priority, the most relevant future directions are the following. First, the development of formal threshold-regionalization procedures that adapt the operational windows (pH, EC, temperature, gas quality) to different substrates, inoculation sources, thermal regimes, and climatic contexts through preliminary benchmarking campaigns, preserving the framework's internal logic while restoring external validity. Second, because anaerobic digestion is governed by many interacting factors and small-scale field campaigns rarely yield datasets large enough for conventional statistical inference, the decision stage can be strengthened with artificial-intelligence algorithms that remain reliable with limited data (e.g., Bayesian or regularized machine-learning models), rather than relying solely on data-intensive probabilistic formulations; a bounded uncertainty check near threshold values can nonetheless be retained. Third, feedback should be coupled with a minimal causal diagnostic module (e.g., VFA/alkalinity, TAN/FAN, sulfides, oxidation–reduction potential (ORP), and ionic balance) that translates non-compliance into verifiable corrective actions, thereby reducing trial-and-error cycles during operation. ORP is prioritized because it is inexpensive and field-measurable and, unlike EC, discriminates the redox state of the medium, helping resolve the buffering-versus-salinity ambiguity of conductivity-only monitoring. Fourth, extended monitoring over at least three to four HRT cycles (45–60 days) is required to capture seasonal variability and slow-onset phenomena (trace-element depletion, recalcitrant VFA accumulation, progressive alkalinity loss) and to confer statistical power on the correlation and stability analyses. Finally, the formal integration of digestate quality (salinity, sodium, metals, pathogens, phytotoxicity) and socio-institutional adoption factors into the decision rule would extend the framework from technical validation toward full sustainability and real-world durability.

5. Conclusions

This study formalized an integrated five-stage methodological framework (E1 diagnosis–planning, E2 design–configuration, E3 operational control–monitoring, E4 economic–environmental assessment, and E5 decision–validation with feedback) that establishes explicit traceability between design decisions, operational performance, and verified sustainability for small-scale anaerobic biodigesters. The framework's novelty lies in its ACT (Acceptance–Control–Traceability) decision block, which converts modular monitoring and assessment outputs into a single reproducible verdict through three sequential filters: data completeness ($C_{\text{data}} \geq 0.90$), multivariable operational stability ($SR \geq 0.75$), and integral sustainability (Ω).

A stage-coded mapping of 48 references confirmed the modular nature of the state of the art: operation/monitoring (E3, 60.4%) and economic–environmental assessment (E4, 39.6%) dominate, whereas a formal decision closure with feedback (E5) is present in only 2.1% of the corpus (a single study). This near-total absence of reproducible decisional closure is precisely the gap the framework addresses.

Applied prospectively to a methodologically independent 200 L co-digestion prototype in Lurín, the framework yielded $C_{\text{data}} = 1.000$ but $SR = 0.33$, classifying the system as not validated with a Type A (operational) failure, despite a positive net climate balance ($GEI_{\text{net}} = 38.2 \text{ kgCO}_2\text{eq/a}$) and a positive NPV under the co-product scenario. The integral condition Ω could not be evaluated because the Stage 1 territorial inputs (E_{dem} , P_{energy}) were not defined, which is itself a methodological finding regarding the framework's sequential dependencies. The prescribed feedback (return to Stage 3 for ionic-strength and thermal management) demonstrates that the framework not only issues a verdict but localizes the corrective action.

Chillón and Huaycán served as formative cases that empirically grounded the framework's components, and Lurín contributed a methodologically independent test set whose original research objective did not require replication of the Huaycán active control regime. On this independent case, the framework correctly rejected a system that fragmented modular evaluation would have classified as viable—a class of false positives that modular assessments fail to prevent. We note that this establishes the framework's ability to detect failure; demonstrating that it also recognizes a genuinely stable system (the complementary direction of the falsification loop) remains the priority verification identified in Section 4.3.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriengineering8070285/s1>. Table S1: Operational diagnostic and intervention matrix; Table S2: Recommended field instrumentation for key variables; Table S3: Itemized economic computation and discounted cash flows; Table S4: Baseline parameters and constants for the GHG balance; Table S5: ACT decision dashboard (full criteria and compliance); Table S6: Complete reference-by-reference E1–E5 stage coding ($N = 48$); Table S7: Weekly biogas composition measurements (CH_4 , H_2S); Table S8: Three-scenario sensitivity analysis of the biofertilizer unit price; Table S9: Comparative application of the ACT decision block to the three cases of the research program. Figure S1: Geographic location of the experimental biodigester site; Figure S2: Daily biogas production and pH in Lurín (Phase 2); Figure S3: Daily biogas production and EC in Lurín (Phase 2); Table S10: Decision thresholds and detailed classification criteria for the integrated assessment.

Author Contributions: Conceptualization, R.A.M.V. and Y.C.A.; methodology, Y.C.A. and R.J.B.; software, L.A.I.C. and J.R.-R.; validation, Y.C.A., R.J.B. and P.Y.S.-C.; formal analysis, R.A.M.V. and Y.C.A.; investigation, R.A.M.V.; resources, J.R.-R. and J.B.R.-O.; data curation, L.A.I.C.; writing—original draft preparation, R.A.M.V. and Y.C.A.; writing—review and editing, Y.C.A., R.J.B., L.A.I.C., P.Y.S.-C., J.B.R.-O. and J.R.-R.; visualization, L.A.I.C.; supervision, Y.C.A. and J.R.-R.; project administration, Y.C.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding authors.

Acknowledgments: The authors thank the Universidad Tecnológica del Perú, the Universidad de Cienfuegos, and the Universidad Autónoma de Querétaro for institutional support during the development of this research.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations and Nomenclature

The following abbreviations and symbols are used in this manuscript:

AD	Anaerobic digestion
ACT	Acceptance–Control–Traceability (decision block)
HRT	Hydraulic retention time
OLR	Organic loading rate
TS/VS	Total solids/Volatile solids
MSW	Municipal solid waste
GHG	Greenhouse gas
TEA/LCA	Techno-economic analysis/Life-cycle assessment
LHV	Lower heating value
QC	Quality control
RSC	Reference structural configuration
LOD	Limit of detection
STP	Standard temperature and pressure
ORP	Oxidation–reduction potential
V_u, V_T, V_g	Useful/total/gas-storage volume [m^3]
f_u	Filling fraction [–]
Q_d	Daily feeding flow rate [$\text{m}^3 \text{d}^{-1}$]
VS_{in}	Daily volatile solids fed [$\text{kg}_{VS} \text{d}^{-1}$]
E_a	Annual useful energy [kWh a^{-1}]
η_{fug}	Fractional leakage rate [–]
GWP_{CH_4}	Global warming potential of CH_4
$\text{GEI}_{ev/fug/net}$	Avoided/fugitive/net GHG [$\text{kgCO}_2\text{eq a}^{-1}$]
NPV, LCOE	Net present value/Levelized cost of energy
ϕ, β	Competitiveness/energy-coverage ratio [–]
C_{data}, SR	Data completeness/Stability ratio [–]
Ω	Integral sustainability condition (boolean)
E_{dem}, P_{energy}	Local energy demand/energy price

References

- Gómez Montoya, J.P.; Castillo Alvarez, Y.; Fernandes De Magalhães, R.; Henrique Lermen, F. A thermo-economic analysis of a circular economy model for biomass in South America producing biofertilizers and biogas from municipal solid waste. *Renew. Energy* **2024**, *225*, 120254. <https://doi.org/10.1016/j.renene.2024.120254>.
- Chojnacka, K. Valorization of biorefinery residues for sustainable fertilizer production: A comprehensive review. *Biomass Convers. Biorefinery* **2023**, *13*, 14359–14388. <https://doi.org/10.1007/s13399-023-04639-2>.
- Leong, Y.K.; Chang, J.S. Valorization of fruit wastes for circular bioeconomy: Current advances, challenges, and opportunities. *Bioresour. Technol.* **2022**, *359*, 127459. <https://doi.org/10.1016/j.biortech.2022.127459>.
- Chitaka, T.Y.; Schenck, C. Developing country imperatives in the circular bioeconomy: A review of the South African case. *Environ. Dev.* **2023**, *45*, 100812. <https://doi.org/10.1016/j.envdev.2023.100812>.
- Keerthana Devi, M.; Manikandan, S.; Oviyapriya, M.; Selvaraj, M.; Assiri, M.A.; Vickram, S.; Subbaiya, R.; Karmegam, N.; Ravindran, B.; Chang, S.; et al. Recent advances in biogas production using Agro-Industrial Waste: A comprehensive review outlook of Techno-Economic analysis. *Bioresour. Technol.* **2022**, *363*, 127871. <https://doi.org/10.1016/j.biortech.2022.127871>.
- Obileke, K.; Makaka, G.; Nwokolo, N. Recent Advancements in Anaerobic Digestion and Gasification Technology. *Appl. Sci.* **2023**, *13*, 5597. <https://doi.org/10.3390/app13095597>.
- Saravanan, A.; Kumar, P.S.; Nhung, T.C.; Ramesh, B.; Srinivasan, S.; Rangasamy, G. A review on biological methodologies in municipal solid waste management and landfilling: Resource and energy recovery. *Chemosphere* **2022**, *309*, 136630.
- Morales-Polo, C. A Review on Anaerobic Digestate as a Biofertilizer: Characteristics, Production, and Environmental Impacts from a Life Cycle Assessment Perspective. *Appl. Sci.* **2025**, *15*, 8635. <https://doi.org/10.3390/app15158635>.
- Romio, C.; Ward, A.J.; Møller, H.B. Characterization and valorization of biogas digestate and derived organic fertilizer products from separation processes. *Front. Sustain. Food Syst.* **2024**, *8*, 1415508. <https://doi.org/10.3389/fsufs.2024.1415508>.
- Rodríguez-Jiménez, L.M.; Pérez-Vidal, A.; Torres-Lozada, P. Research trends and strategies for the improvement of anaerobic digestion of food waste in psychrophilic temperatures conditions. *Heliyon* **2022**, *8*, e11174. <https://doi.org/10.1016/j.heliyon.2022.e11174>.

11. Archana, K.; Viskram, A.; Senthil Kumar, P.; Manikandan, S.; Saravanan, A.; Natrayan, L. A review on recent technological breakthroughs in anaerobic digestion of organic biowaste for biogas generation: Challenges towards sustainable development goals. *Fuel* **2024**, *358*, 130298. <https://doi.org/10.1016/j.fuel.2023.130298>.
12. Awasthi, M.K.; Sindhu, R.; Sirohi, R.; Kumar, V.; Ahluwalia, V.; Binod, P.; Juneja, A.; Kumar, D.; Yan, B.; Sarsaiya, S.; et al. Agricultural waste biorefinery development towards circular bioeconomy. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112122.
13. Uzorka, A.; Wonyanya, M. Design and performance evaluation of small-scale biogas digesters using locally available materials in rural Uganda. *Renew. Energy* **2025**, *246*, 122994. <https://doi.org/10.1016/j.renene.2025.122994>.
14. Tolessa, A. Current status and future prospects of small-scale household biodigesters in Sub-Saharan Africa. *J. Energy* **2024**, *2024*, 5596028.
15. Bruun, S.; Jensen, L.S.; Khanh Vu, V.T.; Sommer, S. Small-scale household biogas digesters: An option for global warming mitigation or a potential climate bomb? *Renew. Sustain. Energy Rev.* **2014**, *33*, 736–741. <https://doi.org/10.1016/j.rser.2014.02.033>.
16. Batstone, D.J.; Keller, J.; Angelidaki, I.; Kalyuzhnyi, S.V.; Pavlostathis, S.G.; Rozzi, A.; Sanders, W.; Siegrist, H.; Vavilin, V.A. The IWA anaerobic digestion model no 1 (ADM1). *Water Sci. Technol.* **2002**, *45*, 65–73.
17. Angelidaki, I.; Ellegaard, L.; Ahring, B.K. A comprehensive model of anaerobic bioconversion of complex substrates to biogas. *Biotechnol. Bioeng.* **1999**, *63*, 363–372.
18. Wang, S.; Wu, Y. Hyperthermophilic composting technology for organic solid waste treatment: Recent research advances and trends. *Processes* **2021**, *9*, 675.
19. Villarroel-Schneider, J.; Höglund-Isaksson, L.; Mainali, B.; Martí-Herrero, J.; Cardozo, E.; Malmquist, A.; Martin, A. Energy self-sufficiency and greenhouse gas emission reductions in Latin American dairy farms through massive implementation of biogas-based solutions. *Energy Convers. Manag.* **2022**, *261*, 115670. <https://doi.org/10.1016/j.enconman.2022.115670>.
20. Saha, C.K.; Khatun, M.L.; Nime, J.; Kirtania, K.; Alam, M.M. Co-Digestion-Based Circular Bio-Economy to Improve Biomethane Generation and Production of Nutrient-Enriched Digestate in Bangladesh. *Sustainability* **2024**, *16*, 104. <https://doi.org/10.3390/su16010104>.
21. Wasajja, H.; Al-Muraisy, S.A.A.; Piaggio, A.L.; Ceron-Chafla, P.; Aravind, P.V.; Spanjers, H.; van Lier, J.B.; Lindeboom, R.E.F. Improvement of Biogas Quality and Quantity for Small-Scale Biogas-Electricity Generation Application in off-Grid Settings: A Field-Based Study. *Energies* **2021**, *14*, 3088. <https://doi.org/10.3390/en14113088>.
22. Castillo Alvarez, Y.; Cordero Noa, J.J.; Quispe Soto, G.V.; Jiménez Borges, R. Efficiency and Sustainability in Industrial Biogas Plants: Bibliometric Review of Key Operating Parameters and Emerging Process Metrics. *Sci* **2026**, *8*, 71.
23. Chettri, D.; Verma, A.K.; Ghosh, S.; Verma, A.K. Biogas from lignocellulosic feedstock: Current status and challenges. *Environ. Sci. Pollut. Res.* **2024**, *31*, 1–26.
24. Sharma, B.; Suthar, S. Enriched biogas and biofertilizer production from Eichhornia weed biomass in cow dung biochar-amended anaerobic digestion system. *Environ. Technol. Innov.* **2021**, *21*, 101201. <https://doi.org/10.1016/j.eti.2020.101201>.
25. Nyika, J.; Dinka, M.; Adediran, A.A. Recycling Plant Biomass and Life Cycle Assessment in Circular Economy Systems. In *Plant Biomass Derived Materials*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2024; Chapter 21, pp. 557–574. <https://doi.org/10.1002/9783527839032.ch21>.
26. Castillo Alvarez, Y.; Jiménez Borges, R.; Alfonso-Francia, G.; Rodríguez Pérez, B.; Patiño Vidal, C.D.; Iturralde Carrera, L.A.; Rodríguez-Reséndiz, J. Transition to a Circular Bioeconomy in the Sugar Agro-Industry: Predictive Modeling to Estimate the Energy Potential of By-Products. *Technologies* **2025**, *13*, 238. <https://doi.org/10.3390/technologies13060238>.
27. Eftaxias, A.; Kolokotroni, I.; Michailidis, C.; Charitidis, P.; Diamantis, V. Techno-Economic Assessment of Anaerobic Digestion Technology for Small- and Medium-Sized Animal Husbandry Enterprises. *Appl. Sci.* **2024**, *14*, 4957. <https://doi.org/10.3390/app14114957>.
28. Camacho Alvarez, D.G.; Chávez García, J.A.; Castillo Alvarez, Y.; Jiménez Borges, R. Sustainable Valorization of Bovine–Guinea Pig Waste: Co-Optimization of pH and EC in Biodigesters. *Recycling* **2025**, *10*, 190.
29. Luo, T.; Khoshnevisan, B.; Huang, R.; Chen, Q.; Mei, Z.; Pan, J.; Liu, H. Analysis of revolution in decentralized biogas facilities caused by transition in Chinese rural areas. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110133. <https://doi.org/10.1016/j.rser.2020.110133>.
30. Hayyat, U.; Khan, M.U.; Sultan, M.; Zahid, U.; Bhat, S.A.; Muzamil, M. A Review on Dry Anaerobic Digestion: Existing Technologies, Performance Factors, Challenges, and Recommendations. *Methane* **2024**, *3*, 33–52. <https://doi.org/10.3390/methane3010003>.
31. Castillo-Leon, N.Y.; Tarazona-Romero, B.E.; Carvajal Gamarra, M.E.; Acosta-Cardenas, O.A.; Quizena-Fernandez, Y.P.; Alarcon-Guerrero, M.Y. Evaluation of the anaerobic digestion process for low and micro-scale biogas production: A review. In *Proceedings of the IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2024; Volume 1299, p. 012008. <https://doi.org/10.1088/1757-899X/1299/1/012008>.
32. Sawatdeenarunat, C.; Surendra, K.; Takara, D.; Oechsner, H.; Khanal, S.K. Anaerobic digestion of lignocellulosic biomass: Challenges and opportunities. *Bioresour. Technol.* **2015**, *178*, 178–186. <https://doi.org/10.1016/j.biortech.2014.09.103>.

33. Kusmiyati, K.; Wijaya, D.K.; Hartono, B.R.; Shidik, G.F.; Fudholi, A. Harnessing the power of cow dung: Exploring the environmental, energy, and economic potential of biogas production in Indonesia. *Results Eng.* **2023**, *20*, 101431.
34. Ben Khedher, N.; Lattieff, F.A.; Mahdi, J.M.; Ghanim, M.S.; Majdi, H.S.; Jweeg, M.J.; Baazaoui, N. Modeling of biogas production and biodegradability of date palm fruit wastes with different moisture contents. *J. Clean. Prod.* **2022**, *375*, 134103. <https://doi.org/10.1016/j.jclepro.2022.134103>.
35. Issahaku, M.; Derkyi, N.S.A.; Kemausuor, F. A systematic review of the design considerations for the operation and maintenance of small-scale biogas digesters. *Heliyon* **2024**, *10*, e24019.
36. Shehata, M.; Elsayed, Y.; Mohamed, A.; Ismail, M.; Walker, M.; Ibrahim, I. Biogas production from different food waste using small-scale floating-drum-type anaerobic digester. *Bioprocess Biosyst. Eng.* **2026**, *49*, 69–80. <https://doi.org/10.1007/s00449-025-03239-w>.
37. Pinares Buendía, J.S.; Samaniego Nolasco, J.A.; Patiño Vidal, C.D.; Carhuancho Leon, F.M.; Rodríguez Rodríguez, B.; Jiménez Borges, R.; Castillo Alvarez, Y. Economic and environmental evaluation of a small-scale biogas plant: Case study in the Chillon Valley, Peru. In Proceedings of the 23rd LACCEI International Multi-Conference for Engineering, Education, and Technology, Mexico City, Mexico, 16–18 July 2025.
38. Alvarez, Y.C.; Yanes, J.P.M.; Borges, R.J.; Vidal, C.D.P. Design proposal of an industrial biodigester of filter-cake for the generation of electrical energy [Propuesta de diseño De un biodigestor industrial de cachaza para la generación de energía eléctrica]. *Univ. Soc.* **2021**, *13*, 74–80.
39. Alvarez, Y.C.; Borges, R.J.; Vidal, C.D.P.; Leon, F.M.C.; Buendia, J.S.P.; Nolasco, J.A.S. Design improvements and best practices in small-scale biodigesters for sustainable biogas production: A case study in the chillon valley, Perú. *Energies* **2025**, *18*, 338.
40. Camacho Alvarez, D.G.; Chávez García, J.A.; Lama Bustinza, J.C.; Rodríguez Rodríguez, B.; Castillo Alvarez, Y.; Jiménez Borges, R. Improved biogas production by anaerobic co-digestion of whey and bovine manure: A case study in Montevideo-Peru. In Proceedings of the 23rd LACCEI International Multi-Conference for Engineering, Education, and Technology, Mexico City, Mexico, 16–18 July 2025.
41. Gómez-Montoya, J.P.; Castillo-Alvarez, Y.; Ortiz-Dongo, L.F.; Solórzano, R.; Patiño-Agudelo, A.D.; Luna-delRisco, M.; Arrieta-Gonzalez, C.E. Improvement and Maturation of Liquid Biofertilizers in Series-Connected Biodigesters: Comparative Analysis of Guinea Pig Manure and Vermicompost Leachate. *Sci* **2025**, *7*, 161.
42. Dikshit, P.K.; Padhi, S.K.; Pattanaik, L.; Khan, A.; Ranjan, A.; Sadhu, S. A critical review on nanotechnological advancement in biogas production from organic waste. *Biomass Convers. Biorefinery* **2025**, *15*, 26737–26759.
43. Workie, E.; Kumar, V.; Bhatnagar, A.; He, Y.; Dai, Y.; Tong, Y.W.; Peng, Y.; Zhang, J.; Fu, C. Advancing the bioconversion process of food waste into methane: A systematic review. *Waste Manag.* **2023**, *156*, 187–197.
44. Khalid, A.; Arshad, M.; Anjum, M.; Mahmood, T.; Dawson, L. The anaerobic digestion of solid organic waste. *Waste Manag.* **2011**, *31*, 1737–1744.
45. Zhu, J.; Fei, X.; Yin, K. Assessment of waste-to-energy conversion technologies for biomass waste under different shared socioeconomic pathways. *Energy Environ. Sustain.* **2025**, *1*, 100021.
46. Madondo, N.; Rathilal, S.; Tetteh, E.; Bakare, B. *Application of Metallic Additives in Anaerobic Digestion for Improving the Metabolic Activity*; Pilares D'Elegância, Lda: Odivelas, Portugal, 2022; p. 26.
47. Wang, K.; Yun, S.; Xing, T.; Li, B.; Abbas, Y.; Liu, X. Binary and ternary trace elements to enhance anaerobic digestion of cattle manure: Focusing on kinetic models for biogas production and digestate utilization. *Bioresour. Technol.* **2021**, *323*, 124571.
48. Cabrita, T.M.; Santos, M.T. Biochemical methane potential assays for organic wastes as an anaerobic digestion feedstock. *Sustainability* **2023**, *15*, 11573.
49. Hasan, S.; Alam, M.; Akter, A.; Uddin, I.; Khaled, M.; Rahman, H. Biogas production from cafeteria waste by anaerobic digestion. In *Proceedings of the BIO Web of Conferences*; EDP Sciences: Les Ulis, France, 2023; Volume 62, p. 03001.
50. Hakimi, M.; Manogaran, M.D.; Shamsuddin, R.; Johari, S.A.M.; Hassan, M.A.M.; Soehartanto, T. Co-anaerobic digestion of sawdust and chicken manure with plant herbs: Biogas generation and kinetic study. *Heliyon* **2023**, *9*, e17096.
51. Mancilla-Leytón, J.M.; Fernández-Rodríguez, M.J.; De la Lama-Calvente, D.; Borja, R. Evaluation of batch mesophilic anaerobic digestion of waste Euro banknotes for methane Production: Preliminary studies and kinetic approach. *Waste Manag.* **2024**, *173*, 22–28.
52. Garusinghe, G.D.A.U.; Perera, B.A.K.S.; Weerapperuma, U.S. Integrating Circular Economy Principles in Modular Construction to Enhance Sustainability. *Sustainability* **2023**, *15*, 11730. <https://doi.org/10.3390/su15151730>.
53. Chekol, F. Climbing up the ladder: The functionality of household level bio-digester's in rural Ethiopia. *Cogent Eng.* **2024**, *11*, 2399736.
54. Afridi, Z.U.R.; Qammar, N.W. Technical challenges and optimization of biogas plants. *ChemBioEng Rev.* **2020**, *7*, 119–129.
55. Oliveira, L.S.; Oliveira, D.S.; Bezerra, B.S.; Pereira, B.S.; Battistelle, R.A.G. Environmental analysis of organic waste treatment focusing on composting scenarios. *J. Clean. Prod.* **2017**, *155*, 229–237.

56. Thomsen, M.; Romeo, D.; Caro, D.; Seghetta, M.; Cong, R.G. Environmental-economic analysis of integrated organic waste and wastewater management systems: A case study from Aarhus City (Denmark). *Sustainability* **2018**, *10*, 3742.
57. Piechota, G.; Unpaprom, Y.; Dong, C.D.; Kumar, G. Recent advances in biowaste management towards sustainable environment. *Bioresour. Technol.* **2023**, *368*, 128326.
58. Khan, A.; Niazi, M.B.K.; Ansar, R.; Jahan, Z.; Javaid, F.; Ahmad, R.; Anjum, H.; Ibrahim, M.; Bokhari, A. Thermochemical conversion of agricultural waste to hydrogen, methane, and biofuels: A review. *Fuel* **2023**, *351*, 128947.
59. Yasar, A.; Nazir, S.; Rasheed, R.; Tabinda, A.B.; Nazar, M. Economic review of different designs of biogas plants at household level in Pakistan. *Renew. Sustain. Energy Rev.* **2017**, *74*, 221–229.
60. Raza, S.T.; Feyissa, A.; Li, R.; Rene, E.R.; Ali, Z.; Iqbal, H.; Sahito, Z.A.; Chen, Z. Emerging technology effects on combined agricultural and eco-vermicompost. *J. Environ. Manag.* **2024**, *352*, 120056. <https://doi.org/10.1016/j.jenvman.2024.120056>.
61. Luo, T.; Zhu, N.; Shen, F.; Long, E.; Long, Y.; Chen, X.; Mei, Z. A case study assessment of the suitability of small-scale biogas plants to the dispersed agricultural structure of China. *Waste Biomass Valorizat.* **2016**, *7*, 1131–1139.
62. Xu, C.; Chen, W.; Hong, J. Life-cycle environmental and economic assessment of sewage sludge treatment in China. *J. Clean. Prod.* **2014**, *67*, 79–87.
63. Belinska, S.; Bielik, P.; Adamičková, I.; Husárová, P.; Onyshko, S.; Belinska, Y. Assessment of environmental and economic-financial feasibility of biogas plants for agricultural waste treatment. *Sustainability* **2024**, *16*, 2740.
64. Ibarra-Esparza, F.E.; González-López, M.E.; Ibarra-Esparza, J.; Lara-Topete, G.O.; Senés-Guerrero, C.; Cansdale, A.; Forrester, S.; Chong, J.P.; Gradilla-Hernández, M.S. Implementation of anaerobic digestion for valorizing the organic fraction of municipal solid waste in developing countries: Technical insights from a systematic review. *J. Environ. Manag.* **2023**, *347*, 118993.
65. Simsek, S.; Uslu, S. Investigation of the impacts of gasoline, biogas and LPG fuels on engine performance and exhaust emissions in different throttle positions on SI engine. *Fuel* **2020**, *279*, 118528.
66. Benyahya, Y.; Fail, A.; Alali, A.; Sadik, M. Recovery of household waste by generation of biogas as energy and compost as bio-fertilizer—A review. *Processes* **2021**, *10*, 81.
67. Mapantsela, Y.; Mukumba, P.; Obileke, K.; Lethole, N. Portable biogas digester: A review. *Gases* **2024**, *4*, 205–223.
68. Triantaphyllou, E. Multi-criteria decision making methods. In *Multi-Criteria Decision Making Methods: A Comparative Study*; Springer: Berlin/Heidelberg, Germany, 2000; pp. 5–21.
69. Fadhli, M.R.; Uttunggadewa, S.; Hadiani, R.; Pudjaprasetya, S.R. Optimization model for multi-products multi-periods multi-suppliers raw-material selection and composition, and order quantity problem with one-year minimum order quantity contract. *MethodsX* **2023**, *11*, 102350. <https://doi.org/10.1016/j.mex.2023.102350>.
70. Nevzorova, T.; Kutcherov, V. Barriers to the wider implementation of biogas as a source of energy: A state-of-the-art review. *Energy Strategy Rev.* **2019**, *26*, 100414.
71. Balmes, J.R.; Holm, S.M.; McCormack, M.C.; Hansel, N.N.; Gerald, L.B.; Krishnan, J.A. Cooking with Natural Gas: Just the Facts, Please. *Am. J. Respir. Crit. Care Med.* **2023**, *207*, 996–997. <https://doi.org/10.1164/rccm.202302-0278VP>.
72. Chaudhury, A.H.; Ahammed, S. Diffusion of biogas technology: A community based approach. *Khulna Univ. Stud.* **2000**, *2*, 7–22.
73. Shukor, J.A.; Omar, M.F.; Kasim, M.M.; Jamaludin, M.H.; Naim, M.A. Assessment of composting technologies for organic waste management. *Int. J. Technol.* **2018**, *9*, 1579–1587.
74. Rolker, H.; Eisler, M.; Cardenas, L.; Deeney, M.; Takahashi, T. Food waste interventions in low-and-middle-income countries: A systematic literature review. *Resour. Conserv. Recycl.* **2022**, *186*, 106534.
75. Gotlih, J. *Design and Optimization of Manufacturing Systems*; MDPI: Basel, Switzerland, 2025.
76. Kocak-Enturk, E.; Yetilmezsoy, K.; Ozturk, M. A small-scale biogas digester model for hen manure treatment: evaluation and suggestions. *Fresenius Environ. Bull.* **2007**, *16*, 804.
77. Nkoi, B.; Lebele-Alawa, B.T.; Odobeatu, B. Design and fabrication of a modified portable biogas digester for renewable cooking-gas production. *Eur. J. Eng. Technol. Res.* **2018**, *3*, 21–29.
78. Maina, G.; Mohammed, U.; Tolba, I.B. Conceptual Design of a System to Facilitate Production of Methane Through Anaerobic Digestion of Organic Material. *Eur. J. Eng. Technol. Res.* **2022**, *7*, 5–11.
79. Jyothilakshmi, R.; Prakash, S. Design, fabrication and experimentation of a small scale anaerobic biodigester for domestic biodegradable solid waste with energy recovery and sizing calculations. *Procedia Environ. Sci.* **2016**, *35*, 749–755.
80. Mendiola-Rodriguez, T.A.; Ricardez-Sandoval, L.A. Integration of design and control for renewable energy systems with an application to anaerobic digestion: A deep deterministic policy gradient framework. *Energy* **2023**, *274*, 127212.
81. Kulkarni, I.; Zang, J.W.; Leandro, W.M.; Parikh, P.; Adler, I.; Da Fonseca-Zang, W.A.; Campos, L.C. Closed-loop biodigesters on small-scale farms in low-and middle-income countries: A review. *Water* **2021**, *13*, 2744.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.