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Systematic Review

Process Resilience, Microbial Adaptation, and Integrated Bioresource Recovery for Circular Bioeconomy Applications: A Systematic Review

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Abstract

With increasing global energy demand and the need to mitigate climate change, anaerobic digestion (AD) has emerged as a promising waste-to-energy technology that produces renewable biogas and supports sustainable waste management. However, the operation of AD systems under extreme environmental and operational conditions, including temperature extremes, salinity, ammonia toxicity, pH fluctuations, organic overloading, water scarcity, and emerging contaminants, threatens process stability and methane production. This systematic review aims to synthesize current evidence on the resilience of anaerobic digestion systems under extreme conditions, with particular emphasis on microbial adaptation mechanisms, process stability, and opportunities for bioresource recovery. Findings from the reviewed literature indicate that physiological adaptation, syntrophic interactions, direct interspecies electron transfer, and microbial community restructuring are key mechanisms that enhance system resilience. The review further identifies resource-recovery pathways, including biomethane upgrading, nutrient recycling, digestate valorization, volatile fatty acid production, biohydrogen generation, and carbon recovery, as important strategies for improving the sustainability of AD systems within circular bioeconomy frameworks. Drawing on the synthesized evidence, the paper proposes a conceptual resilience framework linking environmental stressors, microbial adaptation, engineering interventions, process management, and resource recovery. The review concludes by highlighting priority research areas, including synthetic microbial consortia, digital monitoring technologies, climate-resilient digester design, and artificial intelligence-based optimization, to advance sustainable renewable energy production and circular bioeconomy development.

Keywords: anaerobic digestion; process resilience; methane production; bioresource recovery; circular economy

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1. Introduction

Growing global populations, urbanization, industrialization, and climate change are increasing the generation of biodegradable waste while intensifying the demand for low-carbon energy and efficient resource utilization [1,2]. Anaerobic digestion (AD) provides an important solution by converting organic waste into renewable biogas and nutrient-rich digestate while supporting waste treatment, greenhouse gas mitigation, and nutrient recycling [3]. However, the performance of AD systems depends on complex microbial communities that are sensitive to temperature fluctuations, salinity, ammonia toxicity, pH instability, organic overloading, emerging contaminants, and feedstock variability. These

stressors can destabilize biological processes, reduce methane yields, and compromise long-term operational performance [4].

The challenge of maintaining stable AD performance has become increasingly important under climate change conditions, where extreme temperatures, water scarcity, flooding, and changing biomass characteristics introduce additional operational uncertainties [5]. In response, recent technological advances have expanded opportunities to improve process resilience. Developments in metagenomics, metabolomics, microbial network analysis, bioelectrochemical systems, conductive materials, artificial intelligence (AI), machine learning, Internet of Things (IoT)-based monitoring, digital twins, and advanced process-control technologies are improving the understanding and management of stressed AD systems [6]. These emerging technologies provide new opportunities to detect disturbances, predict system failures, optimize operational conditions, and enhance resource recovery, thereby supporting more resilient and adaptive AD processes.

Despite these advances, existing knowledge remains fragmented. Previous review studies have largely focused on individual aspects of anaerobic digestion, including microbial community dynamics, ammonia inhibition, salinity stress, reactor engineering, biomethane enhancement, process optimization, or resource-recovery pathways [7]. While these studies have substantially improved understanding within their respective domains, they generally examine resilience-related factors independently [8]. Consequently, limited attention has been paid to how environmental stressors, microbial adaptation mechanisms, engineering interventions, intelligent process management approaches, and resource-recovery pathways interact to influence overall system resilience.

This represents a critical knowledge gap because resilience in AD systems emerges from the interaction of biological, technological, operational, and resource-management dimensions rather than from any single factor in isolation [7,8]. As AD systems are increasingly expected to operate under variable climatic conditions while contributing to circular bioeconomy objectives, a more integrated understanding of resilience is required. To date, no recent systematic review has comprehensively synthesized these interconnected dimensions within a single resilience-oriented framework.

Therefore, this systematic review addresses this gap by synthesizing evidence from 98 peer-reviewed studies published between 2022 and 2025. The review aims to develop an integrated understanding of how anaerobic digestion systems respond and adapt to environmental and operational disturbances while maintaining process stability and maximizing resource recovery. Specifically, the review seeks to achieve the following:

RQ1: Identify the major environmental and operational stressors affecting anaerobic digestion performance.

RQ2: Examine microbial adaptation mechanisms that promote process resilience under stress.

RQ3: Evaluate engineering and intelligent process-management strategies that enhance resilience and recovery.

RQ4: Assess how resilient anaerobic digestion systems contribute to integrated bioresource recovery and circular bioeconomy objectives.

The systematic synthesis is organized according to these research questions. First, the review identifies key environmental and operational stressors (RQ1). Second, it examines microbial adaptation and resilience mechanisms reported under stressed conditions (RQ2). Third, it evaluates engineering interventions and emerging intelligent management technologies designed to improve system stability and recovery (RQ3). Finally, it assesses the contribution of resilient AD systems to biomethane production, nutrient recovery, digestate valorization, carbon recovery, and broader circular bioeconomy objectives (RQ4).

The novelty of this review lies not merely in discussing these topics individually but in integrating them into a single Integrated Resilience Framework. Unlike previous reviews that focus on discrete resilience components, this framework conceptualizes AD resilience as a dynamic, interconnected process that links environmental stressors, microbial adaptation, engineering interventions, AI-enabled monitoring and control, process recovery, and circular resource valorization. By connecting these previously fragmented research domains, the framework provides a holistic perspective on the design and operation of resilient anaerobic digestion systems that sustain performance under increasingly variable environmental conditions.

Collectively, this review provides a comprehensive and systematic perspective on the resilience of anaerobic digestion, offering researchers, practitioners, and policymakers a conceptual foundation for developing robust, adaptive, and resource-efficient AD systems that support renewable energy production, sustainable waste management, and the development of a circular bioeconomy.

2. Literature Review

2.1. Circular Bioeconomy and Resource Recovery

The circular bioeconomy seeks to replace fossil-based resource consumption with renewable biological resources while promoting recycling, reuse, and valorization of waste streams [8]. Unlike the conventional linear model, circular bioeconomy systems aim to keep materials and nutrients circulating within production–consumption cycles for as long as possible. Carmona et al. [9] asserted that bioresource recovery has evolved from simple waste treatment toward integrated systems capable of recovering water, nutrients, energy, and high-value products. Wastewater treatment plants are increasingly being transformed into resource recovery facilities that generate biogas, reclaimed water, fertilizers, and biomaterials.

Similarly, recent advances in biotechnology have enabled conversion of agricultural residues, food waste, industrial by-products, and municipal waste into biofuels, bioplastics, biofertilizers, and specialty chemicals. Such innovations contribute significantly to environmental sustainability and resource efficiency.

2.2. Process Resilience in Biological Systems

Process resilience has become a major focus in environmental biotechnology because biological treatment systems frequently encounter operational disturbances [10]. Resilience encompasses resistance, recovery capacity, adaptability, and long-term stability. Resilient biological reactors can absorb shocks without significant loss of performance. Factors affecting resilience include microbial diversity, operational parameters, environmental fluctuations, and reactor configuration. Studies indicate that systems with higher microbial diversity generally exhibit greater stability because functional redundancy allows different microbial groups to compensate when dominant populations are stressed [11,12]. Advanced monitoring systems involving omics technologies, machine learning, and artificial intelligence are increasingly used to predict disturbances and enhance system resilience through proactive interventions.

2.3. Microbial Adaptation and Community Dynamics

Microbial adaptation is a fundamental determinant of anaerobic digestion (AD) resilience because microorganisms must continuously adjust their physiological, genetic, and ecological functions in response to changing environmental conditions. Rather than functioning as passive responders to disturbance, AD microorganisms can adapt through mechanisms such as horizontal gene transfer, mutation, metabolic flexibility, quorum sens-

ing, and syntrophic interactions, enabling microbial communities to maintain functional stability under stress [3,13]. These mechanisms allow microbial populations to redistribute metabolic functions and sustain critical biochemical pathways despite fluctuations in temperature, substrate availability, pH, ammonia concentration, and other operating conditions. Therefore, microbial adaptability should be considered a core biological mechanism underpinning the resilience of AD systems.

This adaptive capacity is further strengthened by engineered microbial consortia, which provide a stronger basis for process resilience than reliance on individual microbial strains. Through metabolic cooperation and division of labour, consortium members perform complementary functions and can compensate for the inhibition or loss of particular populations [14,15]. Such functional complementarity has enabled engineered microbial communities to achieve improved performance in pollutant degradation, nutrient recovery, and bioresource conversion [16,17]. Consequently, microbial diversity should not be viewed merely as an ecological characteristic; it represents an important functional asset that can increase the stability and adaptability of AD processes.

Functional redundancy provides an additional resilience mechanism because different microorganisms may perform similar ecological functions, allowing alternative populations to compensate when dominant species are suppressed by environmental disturbances [18,19]. This redundancy creates a biological buffer that can reduce the impact of disturbances and facilitate recovery of microbial functions. In AD systems, maintaining diverse and functionally complementary microbial communities is therefore particularly important because disturbances affecting one functional group can potentially be mitigated by other populations within the consortium.

Moreover, genomic and transcriptomic studies increasingly demonstrate that microbial communities can actively regulate their metabolic functions in response to environmental stress. Adaptive microorganisms can modify metabolic pathways and gene expression to maintain nutrient removal and substrate conversion efficiencies under adverse temperatures and changing substrate concentrations [3,19]. This evidence challenges the view that process stability depends primarily on maintaining constant operating conditions. Instead, it suggests that enhancing the adaptive capacity of microbial communities can provide AD systems with greater tolerance to unavoidable environmental and operational variability.

Accordingly, microbial adaptation, functional redundancy, and engineered consortia should be regarded as strategic components of resilient AD design rather than solely as natural biological responses [4]. Integrating microbial ecology, genomic knowledge, and engineered consortia into process design could enable AD systems to withstand disturbances, recover more rapidly, and sustain biogas production and resource-recovery performance under increasingly variable operating conditions. This integration is particularly important for advancing AD from a process optimized for stable laboratory conditions toward a more robust technology capable of supporting circular bioeconomy and low-carbon development objectives.

2.4. Integrated Bioresource Recovery Technologies

Integrated bioresource recovery combines biological, chemical, and physical processes to extract multiple resources from waste streams. Major approaches include the following:

Anaerobic Digestion:

Anaerobic digestion converts organic waste into methane-rich biogas while producing digestate that can be further processed for nutrient recovery. It is regarded as a cornerstone technology for implementing the circular bioeconomy.

Fundamentals of Anaerobic Digestion:

Anaerobic digestion consists of four interconnected biological stages:

- Hydrolysis;
- Acidogenesis;
- Acetogenesis;
- Methanogenesis.

Each stage depends upon specialized microbial consortia that cooperate through syntrophic interactions. Hydrolytic bacteria initially degrade complex carbohydrates, proteins, and lipids into soluble substrates. Acidogenic microorganisms convert these products into volatile fatty acids (VFAs), hydrogen, and carbon dioxide. Acetogenic bacteria subsequently produce acetate and hydrogen that serve as substrates for methanogenic archaea responsible for methane production [20]. Successful digestion requires balanced microbial interactions, stable pH (6.8–7.5), adequate alkalinity, suitable carbon-to-nitrogen ratios, sufficient trace elements, and optimal hydraulic retention times [21].

Nutrient Recovery:

Technologies such as struvite precipitation, ammonia stripping, membrane separation, and algal assimilation recover nitrogen and phosphorus from waste streams [22–24]. These recovered nutrients can be reused as fertilizers, reducing dependence on synthetic fertilizers.

Algal-Bacterial Biorefineries:

Microalgae-based systems simultaneously treat wastewater, capture carbon dioxide, recover nutrients, and produce biomass suitable for biofuel and bioproduct generation.

Smart Integrated Biorefineries:

Integrated biorefinery concepts combine fermentation, anaerobic digestion, hydrothermal processes, algae cultivation, and nutrient recovery to achieve near-zero waste production while maximizing product diversification.

2.5. Extreme Conditions Affecting Anaerobic Digestion

2.5.1. Low-Temperature Digestion

Psychrophilic digestion (<20 °C) is increasingly important in northern climates and mountainous regions.

Low temperatures reduce the following:

- Enzymatic activity;
- Hydrolysis rates;
- Microbial growth;
- Methane production.

Methane yields may decrease by 30–60% compared with mesophilic digestion [22]. Recent studies demonstrate that psychrophilic microbial communities gradually adapt by enriching cold-tolerant Methanoculleus and Methanogenium species that can maintain methane production during prolonged low-temperature exposure [23].

2.5.2. Thermophilic Conditions

Thermophilic digestion (>55 °C) accelerates degradation kinetics while improving pathogen destruction.

Advantages include the following:

- Shorter retention times;
- Enhanced biogas production;
- Improved solids destruction.

However, thermophilic systems exhibit increased sensitivity to ammonia toxicity and organic overload due to reduced microbial diversity [24].

2.5.3. High Ammonia Concentrations

Protein-rich feedstocks frequently generate ammonia concentrations exceeding inhibitory thresholds.

Free ammonia penetrates microbial cell membranes, disrupting intracellular pH regulation and enzyme activity.

Methanogenic archaea are particularly susceptible.

Adaptation mechanisms include the following:

- Microbial acclimation;
- Bioaugmentation;
- Trace element supplementation;
- Co-digestion with carbon-rich substrates.

Recent metagenomic studies demonstrate enrichment of hydrogenotrophic methanogens capable of tolerating ammonia concentrations exceeding 5 g NH_4^+-N/L [25].

3. Materials and Methods

3.1. Review Design and Protocol

This study employed a systematic review methodology to evaluate contemporary research on process resilience, microbial adaptation, engineering interventions, and integrated bioresource recovery in anaerobic digestion (AD) systems operating under environmental and operational stress conditions [18]. The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure transparency, consistency, and reproducibility throughout the review process.

A review protocol was developed prior to the literature search and is provided in the Supplementary Material (Supplementary File S2). The protocol specified the review objectives, research questions, search strategy, eligibility criteria, screening procedures, data extraction framework, quality appraisal criteria, and synthesis approach [26]. Although the review was not registered in an external registry, the protocol was used to ensure methodological consistency throughout all stages of the review.

The review was guided by the following research questions:

RQ1: What are the major environmental and operational stressors affecting the stability and performance of anaerobic digestion system?

RQ2: How do microbial communities adapt and maintain functional stability under extreme and variable conditions?

RQ3: What engineering and intelligent process-management strategies can enhance the resilience and recovery of anaerobic digestion systems?

RQ4: How can resilient anaerobic digestion systems support integrated resource recovery and advance circular bioeconomy objectives?

The systematic review process consisted of five sequential stages: (i) formulation of research questions, (ii) systematic literature searching, (iii) study screening and selection, (iv) quality appraisal and data extraction, and (v) thematic synthesis and framework development.

3.2. Search Strategy

A comprehensive literature search was conducted across five scientific databases: Scopus, Web of Science Core Collection, ScienceDirect, PubMed, and Google Scholar. These databases were selected because of their extensive coverage of environmental engineering, biotechnology, microbiology, renewable energy, and waste management research.

The literature search was conducted between 10 and 15 July 2025, with all searches completed on 15 July 2025. Only studies published between January 2022 and June 2025 were considered for inclusion in order to capture the most recent developments in AD resilience and resource recovery.

The primary search string was as follows:

("anaerobic digestion" OR "anaerobic digester" OR biomethane OR biogas)
AND
(resilience OR stability OR adaptation OR acclimation OR recovery)
AND
(microbial OR microbiome OR methanogen* OR syntroph*)
AND
(stress OR ammonia OR salinity OR temperature OR "organic loading"
OR contaminant* OR drought)
AND
("resource recovery" OR digestate OR nutrient* OR
"volatile fatty acid*" OR hydrogen OR "circular bioeconomy").

Database-specific modifications were implemented to account for differences in indexing systems, search fields, and query functionalities.

3.3. Eligibility Criteria

Studies were considered eligible for inclusion if they met the following criteria:

Inclusion Criteria:

- Investigated anaerobic digestion or anaerobic co-digestion systems;
- Examined process resilience, stability, microbial adaptation, or stress-response mechanisms;
- Assessed environmental or operational stressors affecting AD performance;
- Evaluated biological, engineering, operational, or digital interventions intended to improve system robustness;
- Reported methane production, process-performance indicators, or bioresource-recovery outcomes;
- Were published in peer-reviewed journals;
- Were published between January 2022 and June 2025;
- Were available as full-text articles in English.

Exclusion Criteria:

- Focused exclusively on aerobic treatment systems;
- Did not address AD resilience, adaptation, stress response, or process performance;
- Were conference abstracts, editorials, opinion papers, commentaries, or non-peer-reviewed publications;
- Provided insufficient methodological information;
- Were duplicate records;
- Were unrelated to anaerobic digestion processes.

3.4. Screening and Study Selection

All records identified through database searching were exported into reference-management software (Mendeley v1.69.5) for organization and duplicate removal. Screening and study selection were conducted in accordance with the PRISMA 2020 framework. The screening process was performed in two stages. First, titles and abstracts were assessed against the predefined eligibility criteria. Articles considered potentially relevant proceeded to a full-text review. Full-text articles were then independently evaluated by two reviewers to determine final eligibility. Any disagreements regarding study inclusion were resolved

through discussion and consensus. Where necessary, a third reviewer was consulted to resolve unresolved discrepancies. The initial database search identified 275 records. After removing 50 duplicate records, 225 unique studies remained for title and abstract screening. Following screening, 50 studies were excluded for failing to meet the eligibility criteria. The remaining 175 articles underwent full-text assessment. During full-text review, 77 studies were excluded due to insufficient relevance to the review objectives, inadequate methodological reporting, lack of resilience-related outcomes, or failure to report process performance or resource recovery indicators. Consequently, 98 studies met all inclusion criteria and were included in the final synthesis.

The study-selection process is summarized in the PRISMA flow diagram (Figure 1).

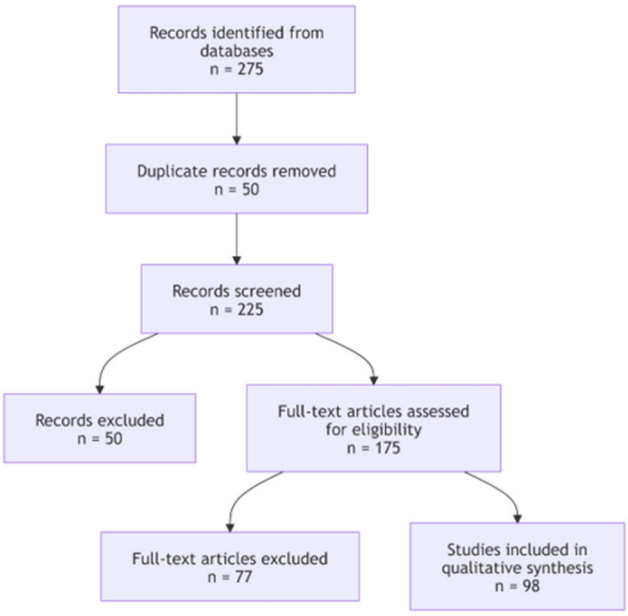


Figure 1. PRISMA 2020 flow diagram illustrating the identification, screening, eligibility assessment, and inclusion of studies.

3.5. Quality Assessment

To evaluate the methodological quality of the included studies, each article was independently assessed using a structured quality appraisal framework adapted from established systematic review guidelines. The assessment considered the clarity of study objectives, the adequacy of the experimental design, the appropriateness of the analytical methods, the completeness of data reporting, and the validity of the conclusions. Each criterion was assigned a score, and the cumulative score was used to classify studies as high, moderate, or low quality.

The quality assessment served two purposes. First, it enabled a systematic evaluation of the reliability of the evidence included in this review. Second, it informed the interpretation of findings during data synthesis. Greater emphasis was placed on conclusions supported by multiple high-quality studies, while findings derived primarily from moderate-quality studies were interpreted with appropriate caution. Although no study was excluded solely on the basis of quality score, the appraisal process provided an important contextual framework for assessing the strength and consistency of the available evidence.

Each study was evaluated using the following criteria:

- Clearly stated research objectives;
- Appropriate experimental design;
- Adequate feedstock characterization;
- Clear reporting of operating conditions;

- Inclusion of suitable controls or baseline comparisons;
- Appropriate monitoring of process-performance indicators;
- Adequate statistical analysis and reporting;
- Sufficient methodological detail to permit reproducibility;
- Clear reporting of microbial analyses (where applicable);
- Transparent presentation of results and conclusions.

Each criterion was scored on a binary basis (0 = No, 1 = Yes), resulting in a maximum quality score of 10.

Studies were classified as follows:

- High quality: 8–10 points.
- Moderate quality: 5–7 points.
- Low quality: 0–4 points.

The quality assessment results for all 98 studies are reported in Supplementary File S1. Studies were not excluded solely on the basis of methodological quality. However, quality scores were considered when interpreting the evidence. Findings consistently supported by high-quality studies were given greater weight during synthesis, whereas conclusions derived primarily from moderate- or low-quality studies were interpreted more cautiously and identified as areas requiring additional research.

3.6. Data Extraction

Data were extracted from all eligible studies using a standardized extraction template developed specifically for this review. The extraction process was designed to facilitate comparison across studies and support thematic synthesis.

The following information was collected:

- Publication year;
- Country of study;
- Feedstock type;
- Reactor configuration;
- Experimental scale (laboratory, pilot, or full scale);
- Operating temperature;
- Organic loading rate (OLR);
- Hydraulic retention time (HRT);
- pH conditions;
- Type of environmental or operational stressor;
- Stress intensity and duration;
- Microbial adaptation mechanisms;
- Intervention strategy employed;
- Methane-production response;
- Process-resilience indicators;
- Resource-recovery outcomes;
- Key findings;
- Study limitations.

3.7. Data Synthesis and Analysis

Substantial heterogeneity was observed across the included studies in feedstock characteristics, reactor configurations, operational conditions, stressor severity, microbial analyses, intervention strategies, and reported performance indicators. Consequently, a formal quantitative meta-analysis was deemed inappropriate because pooling fundamen-

tally different experimental systems could introduce bias and undermine the validity of aggregated estimates.

Instead, a structured thematic synthesis approach was adopted. The included studies were categorized according to the four research questions and five major thematic areas.

Theme 1: Environmental and Operational Stressors (RQ1)

This theme examined the impacts of ammonia toxicity, salinity, temperature extremes, pH instability, organic overloading, emerging contaminants, water scarcity, and other environmental disturbances on AD performance and stability.

Theme 2: Microbial Adaptation and Community Restructuring (RQ2)

This theme focused on microbial acclimation processes, syntrophic interactions, methanogenic adaptation, direct interspecies electron transfer (DIET), and mechanisms of microbial community restructuring associated with resilience under stressed conditions.

Theme 3: Engineering and Biological Interventions (RQ3)

This theme explored engineering and biological approaches to improving resilience, including co-digestion, bioaugmentation, addition of conductive materials, pretreatment technologies, operational optimization, and reactor design modifications.

Theme 4: Intelligent Monitoring and Predictive Control (RQ3)

This theme evaluated emerging technologies, including sensor systems, machine learning, artificial intelligence, digital twins, and predictive-control platforms for real-time monitoring and mitigation of process disturbances.

Theme 5: Integrated Bioresource Recovery (RQ4)

This theme assessed opportunities for resource valorization beyond methane production, including digestate utilization, nutrient recycling, volatile fatty acid production, hydrogen generation, carbon recovery, and circular bioeconomy applications.

Because quantitative outcome measures were reported inconsistently across studies, no formal meta-analysis or pooled effect-size calculations were performed. Instead, quantitative findings were synthesized descriptively and reported as ranges, comparative trends, and representative study-level outcomes within each thematic category. This approach preserved the contextual differences among AD systems while enabling identification of recurring resilience mechanisms, intervention strategies, and resource-recovery pathways.

The synthesized evidence from these thematic areas was subsequently integrated to develop an Integrated Resilience Framework linking environmental stressors, microbial adaptation, engineering interventions, intelligent process management, and circular bioresource-recovery pathways in anaerobic digestion systems.

4. Results

4.1. Characteristics and Thematic Distribution of the Included Evidence

The included studies collectively examined the relationship between microbial adaptation, environmental disturbance, process resilience, and resource recovery across anaerobic digestion (AD) and other biological resource recovery systems. The evidence was thematically synthesized according to the principal stressors investigated, microbial responses, adaptation mechanisms, process-performance outcomes, and resource-recovery pathways. The synthesis identified four closely related dimensions of resilience: physiological adaptation, microbial community restructuring, syntrophic cooperation and direct interspecies electron transfer (DIET). These mechanisms were reported across studies investigating temperature variation, ammonia toxicity, pH disturbances, salinity, organic overloading, volatile fatty acid (VFA) accumulation, and toxic contaminants.

The studies differed considerably in experimental conditions, substrate characteristics, reactor configurations, operating temperatures, disturbance intensity and duration, and analytical approaches. Consequently, direct comparison of reported performance values

was not possible for all studies. The evidence was therefore synthesized according to recurring relationships and mechanisms rather than treating all reported outcomes as directly comparable.

To strengthen the systematic synthesis, the included studies were compared according to the environmental stressor investigated, microbial response, adaptation mechanism, process-performance response and resulting resilience outcome (Table 1). Rather than treating microbial adaptation and process resilience as independent concepts, the synthesis examined the relationships reported across the evidence base. This comparison identified recurring patterns involving physiological adaptation, syntrophic cooperation, direct interspecies electron transfer (DIET), and microbial community restructuring. The evidence also showed that the magnitude and direction of responses varied according to disturbance intensity, exposure duration, substrate characteristics, reactor configuration and microbial acclimation. Consequently, the findings were synthesized thematically while avoiding direct quantitative comparison where experimental conditions were not sufficiently comparable.

Overall, the evidence indicates that process resilience is strongly associated with microbial communities' capacity to maintain essential metabolic functions during disturbance and to restore process performance following stress. The reviewed studies further demonstrate that resilience is an emergent property of microbial communities rather than a characteristic of individual microorganisms.

4.2. Environmental Stressors and Their Effects on Process Performance

The included studies identified temperature variation, ammonia toxicity, pH fluctuations, organic overloading, VFA accumulation, salinity and toxic contaminants as major disturbances affecting AD performance. Across the evidence base, these stressors were associated with changes in microbial activity and community composition and, depending on disturbance severity, reductions in methane production, substrate degradation and process stability.

Temperature was one of the most frequently investigated disturbances [26]. Low-temperature conditions generally reduced hydrolysis, microbial growth and metabolic conversion rates, resulting in lower methane productivity. In contrast, thermophilic operation increased biochemical reaction rates but could also increase sensitivity to ammonia inhibition and other disturbances [27]. Several studies reported substantial reductions in methane production under prolonged low-temperature conditions, with reported reductions reaching approximately 30–60% in some experimental settings. The magnitude of the response varied according to substrate characteristics, microbial acclimation, reactor configuration and duration of exposure.

Ammonia toxicity was particularly prominent in studies involving manure, poultry litter, protein-rich substrates and food waste [22]. Elevated ammonia concentrations affected methanogenic activity, altered microbial community structure and were frequently associated with VFA accumulation and reduced methane production [28]. The evidence consistently indicated that acetoclastic methanogens were more sensitive to ammonia stress than several hydrogenotrophic methanogenic groups. Under prolonged ammonia exposure, several studies observed a relative increase in hydrogenotrophic methanogenesis, indicating a shift in metabolic pathways that contributed to continued methane production under inhibitory conditions.

Table 1. Evidence synthesis of microbial adaptation, environmental stressors, and process resilience.

Environmental Stressor	Reported Microbial Response	Principal Adaptation Mechanism	Observed Process Response	Resilience Outcome	Representative Evidence
Temperature variation	Changes in microbial growth rates, enzyme activity and community composition; enrichment of temperature-tolerant populations	Physiological adaptation; community restructuring	Reduced hydrolysis and methane production under low temperatures; increased instability under some thermophilic conditions	Adapted communities maintained or more rapidly restored methane production	Refs. [18,22,26–29]
Ammonia toxicity	Suppression of sensitive acetoclastic methanogens and increased relative importance of hydrogenotrophic methanogens	Community restructuring; syntrophic acetate oxidation; physiological adaptation	Reduced methanogenesis, increased VFA accumulation and altered methane pathways	Maintenance of methane production through alternative metabolic pathways	Refs. [18,22,26–39]
pH disturbance	Altered microbial activity and relative abundance of sensitive taxa	Physiological adaptation; community restructuring; syntrophic cooperation	Reduced substrate conversion and methane production under severe disturbance	Recovery following restoration of favourable pH conditions	Refs. [39–55]
Organic overloading	Increased acidogenic activity and disruption of balance between fermenters and methanogens	Syntrophic adaptation; community restructuring	VFA accumulation, reduced methane production and process instability	Recovery through microbial acclimation and improved substrate conversion	Refs. [55–69]
VFA accumulation	Inhibition of methanogenic populations and changes in microbial interactions	Syntrophic cooperation; physiological adaptation	Reduced methane formation and prolonged recovery	Enhanced VFA conversion following restoration of microbial balance	Refs. [55–69]
Salinity stress	Selection for salt-tolerant microorganisms and changes in microbial activity	Osmotic regulation; physiological adaptation; community restructuring	Reduced microbial growth and substrate conversion at elevated salinity	Persistence of selected tolerant populations and partial process recovery	Refs. [51–73]
Toxic contaminants	Suppression of sensitive populations and enrichment of tolerant microorganisms	Physiological adaptation; community restructuring	Reduced enzymatic activity, substrate degradation and methane production	Recovery following adaptation or reduction in contaminant exposure	Refs. [73–76]
Conductive-material supplementation	Increased representation/activity of microorganisms associated with extracellular electron transfer	DIET enhancement	Improved electron transfer and substrate conversion	Faster recovery and improved methane production under selected stress conditions	Refs. [74–76]
Co-digestion	Improved microbial balance through complementary substrates and dilution of inhibitors	Community adaptation; syntrophic cooperation	Improved nutrient balance and methane production	Greater operational stability under variable feedstock conditions	Refs. [77–81]
Bioaugmentation	Introduction or enrichment of functional microbial populations	Microbial inoculation; functional replacement	Faster restoration of impaired metabolic functions	Shorter recovery periods under selected disturbances	Refs. [77–84]
Feedstock pretreatment	Increased substrate accessibility and biodegradability	Process adaptation rather than direct microbial adaptation	Improved hydrolysis and substrate conversion	Reduced process stress associated with recalcitrant substrates	Refs. [78–85]
Advanced monitoring and AI	Early identification of microbial/process instability indicators	Adaptive process control	Earlier detection of pH, VFA and methane deviations	Potential prevention or mitigation of severe process failure	Refs. [85–94]

Organic overloading and associated VFA accumulation represented another important source of process instability. Excessive organic loading increased acid production and could

exceed the capacity of methanogenic populations to convert intermediates efficiently. The resulting accumulation of VFAs was associated with declining methane production and prolonged recovery periods. The severity of this response depended on loading rate, substrate composition, buffering capacity and the previous acclimation of the microbial community.

Salinity and toxic contaminants also affected microbial activity and substrate conversion. Increased salinity imposed osmotic stress and altered microbial growth, while inhibitory compounds affected enzymatic activity and the abundance of sensitive microbial populations [29]. These effects were particularly evident in studies involving industrial wastewater, municipal waste streams and other substrates containing potentially inhibitory compounds.

Importantly, the evidence indicates that these stressors should not be considered independently. Several studies reported simultaneous or sequential disturbances, in which one stressor increased the sensitivity of the microbial community to another. The combined effects of temperature variation, ammonia accumulation, organic overloading and pH instability were therefore associated with more pronounced reductions in process performance than isolated disturbances.

4.3. Microbial Adaptation Mechanisms

The synthesis identified four principal microbial adaptation mechanisms associated with process resilience: physiological adaptation, syntrophic cooperation, DIET and microbial community restructuring. Although the relative importance of these mechanisms varied among studies, the evidence indicates that they operate interactively rather than independently.

4.3.1. Physiological Adaptation

Physiological adaptation represented an immediate microbial response to environmental disturbance. Studies examining ammonia, temperature, salinity and pH stress reported changes in microbial metabolism and cellular regulation that enabled microorganisms to maintain cellular homeostasis under adverse conditions [30].

Reported responses included modification of membrane composition, regulation of enzyme activity, production of stress-response proteins, osmotic regulation and synthesis of protective intracellular or extracellular compounds [31]. These responses enabled stress-tolerant microorganisms to remain metabolically active despite changes in their surrounding environment.

Hydrogenotrophic methanogens were repeatedly identified as important contributors to resilience under ammonia stress. Their relative tolerance compared with acetoclastic methanogens enabled methane production to continue when the latter pathway was inhibited [32]. Similarly, microorganisms exposed to temperature or salinity fluctuations exhibited physiological adjustments that reduced cellular damage and supported continued metabolic activity.

The evidence therefore suggests that physiological adaptation is particularly important during the initial phase of disturbance, when microorganisms must rapidly respond to changing environmental conditions before longer-term changes in community composition occur.

4.3.2. Syntrophic Cooperation

Syntrophic interactions emerged as an important mechanism for maintaining metabolic flux under stressful conditions. Anaerobic digestion depends on metabolic interactions among fermentative bacteria, acetogenic organisms and methanogenic archaea. Efficient removal of metabolic intermediates by syntrophic partners prevents the accumulation of compounds that could inhibit upstream microbial populations.

Several studies reported increased importance of syntrophic acetate-oxidizing bacteria (SAOB) and hydrogenotrophic methanogens under elevated ammonia conditions. When acetoclastic methanogenesis was inhibited, acetate oxidation through the SAO pathway provided an alternative route for acetate conversion [33]. Hydrogen and carbon dioxide generated through this pathway were subsequently utilized by hydrogenotrophic methanogens for methane production.

This transition illustrates how microbial cooperation can compensate for the loss or reduced activity of sensitive functional groups. Studies reporting stronger syntrophic interactions generally associated these communities with lower accumulation of metabolic intermediates, greater methane stability and improved recovery following disturbance.

4.3.3. Direct Interspecies Electron Transfer

DIET was identified in the included evidence as an additional mechanism capable of strengthening metabolic cooperation between microorganisms. Unlike hydrogen- or formate-mediated interspecies electron transfer, DIET enables direct electron transfer between microbial partners via conductive structures or materials.

Several studies investigated the role of conductive materials, including biochar, magnetite, activated carbon and granular activated carbon [34]. Their addition was generally associated with improved electron transfer, enhanced substrate conversion and improved methane production under selected stress conditions.

The evidence further indicated increased representation of DIET-associated microbial groups, particularly members of *Geobacter* and *Methanosarcina*, in systems where DIET was enhanced [35]. Conductive materials appeared to reduce electron-transfer limitations and thereby support syntrophic metabolism during periods of organic overloading, ammonia stress or pH disturbance.

However, the reported effects were not uniform across all systems. Differences in conductive material properties, dosage, substrate composition, reactor conditions and microbial community structure affected the magnitude of the response. DIET should therefore be interpreted as a context-dependent resilience mechanism rather than a universally applicable intervention.

4.3.4. Microbial Community Restructuring

The included studies consistently indicated that environmental disturbance can alter microbial community composition. Sensitive populations declined under severe stress, whereas microorganisms with greater physiological tolerance or metabolic flexibility increased in relative abundance.

Ammonia exposure provided the clearest example of this process. Several studies reported a reduction in acetoclastic methanogens, including *Methanosaeta*, accompanied by increased representation of hydrogenotrophic methanogens such as *Methanoculleus* and *Methanobacterium*. Increased representation of syntrophic acetate-oxidizing bacteria was also reported under conditions in which acetoclastic methanogenesis was inhibited.

Although disturbance sometimes resulted in an immediate decline in microbial diversity, the persistence of function was supported by functional redundancy within the microbial community [35]. Different taxa could perform overlapping ecological functions, allowing essential biochemical pathways to continue despite the loss or suppression of particular populations.

The evidence therefore suggests that resilience is more closely related to functional organization and adaptive capacity than to taxonomic diversity alone. Community restructuring can act as an ecological filtering process through which disturbance selects microbial populations better suited to the altered operating environment.

4.4. Relationship Between Microbial Adaptation and Process Resilience

Across the included studies, microbial adaptation was consistently associated with the ability of biological treatment systems to maintain or recover process performance following disturbance. Resilience was expressed through resistance to performance deterioration during stress and through recovery after the disturbance was removed or reduced.

Systems containing previously acclimated or stress-adapted microbial communities generally demonstrated greater stability when exposed to changes in temperature, substrate composition, organic loading and inhibitory compounds [36]. In contrast, systems containing microbial communities with limited exposure or adaptation to the imposed stress frequently exhibited sharper reductions in methane production and longer recovery periods.

The evidence indicates that resilience results from the interaction of several mechanisms. Physiological adaptation provides an immediate response to stress; syntrophic cooperation maintains metabolic exchange; DIET can improve electron-transfer efficiency; and community restructuring allows stress-tolerant populations to replace sensitive functional groups [37]. These processes collectively support the continuation of carbon conversion and methane formation during disturbance.

The relationship can therefore be conceptualized as a sequence of interconnected responses:

Environmental disturbance → physiological stress response → microbial interaction and metabolic adjustment → community restructuring → maintenance or recovery of process function.

The reviewed evidence suggests that the effectiveness of this response depends on disturbance intensity, exposure duration, microbial acclimation, substrate characteristics and operating conditions.

4.5. Resilience and Process Performance

Resilience was reflected in several measurable process-performance indicators, including methane production, volatile solids removal, substrate conversion, VFA accumulation and recovery time. Studies involving acclimated or stress-adapted microbial communities generally reported greater maintenance of these indicators during disturbance.

Methane production was the most frequently reported performance indicator. Reduced methane yields were commonly observed following temperature shocks, ammonia accumulation, organic overloading and other inhibitory conditions [38]. However, systems containing adapted microbial communities were often able to maintain methane production or recover more rapidly after the disturbance.

VFA accumulation provided an additional indicator of process instability. Excessive accumulation generally indicated an imbalance between acid-producing and methane-producing populations [39]. Stronger syntrophic interactions and adaptation of methanogenic populations were associated with more effective VFA conversion and improved restoration of methane production.

The evidence also suggests that recovery time provides an important complementary measure of resilience. Two systems may experience similar reductions in methane production but differ substantially in their ability to restore normal operation [40]. Consequently, resilience assessment should consider both the magnitude of performance loss and the rate of recovery following disturbance.

4.6. Resilience-Enhancing Operational Strategies

The reviewed studies identified several engineering and operational strategies for improving resilience. These included co-digestion, bioaugmentation, feedstock pretreat-

ment, reactor design modifications, conductive-material supplementation and advanced process monitoring.

Co-digestion was frequently reported as an effective approach because combining complementary feedstocks can improve nutrient balance, dilute inhibitory compounds and stabilize substrate availability [41]. Studies involving manure, crop residues, food waste and agro-industrial residues demonstrated that appropriate feedstock combinations can improve methane production while reducing the effects of individual substrate limitations.

Bioaugmentation provided another strategy for restoring impaired microbial communities. The introduction of specialized microorganisms was investigated under conditions including ammonia inhibition, low temperature and organic overloading [42]. The reported outcomes suggest that bioaugmentation can accelerate recovery in selected systems, although successful implementation depends on compatibility between introduced microorganisms and the resident microbial community.

Pretreatment was used to increase substrate biodegradability and reduce limitations associated with recalcitrant feedstocks [43]. Thermal, chemical, biological and mechanical pretreatments were reported to improve substrate accessibility, although their effectiveness depended on feedstock properties and operational conditions.

Reactor-level interventions also contributed to resilience. Improved mixing, thermal insulation and staged digestion configurations were associated with better control of environmental conditions and improved microbial stability [44]. These findings indicate that microbial resilience is partly dependent on the physical and operational environment in which microbial communities function.

4.7. Monitoring, Prediction and Adaptive Process Control

A growing proportion of the reviewed evidence examined the use of advanced monitoring and data-driven approaches to identify process instability. Sensor networks, machine learning, artificial intelligence and digital-twin approaches were investigated for monitoring variables associated with process failure, including pH, VFA concentration, methane production and organic loading.

These approaches provide an additional dimension of resilience by enabling disturbances to be detected before they result in severe process deterioration. Predictive models can potentially identify early warning signals and support timely adjustment of loading rates, temperature, pH or other operating parameters.

However, the evidence base remains heterogeneous. Differences in sensor configuration, data availability, modelling approaches and validation procedures limit direct comparison of reported predictive performance. Further standardized validation under full-scale operating conditions is therefore required before these approaches can be considered universally transferable.

4.8. Integrated Recovery of Energy, Water and Nutrients

The included studies indicate that resilience has implications beyond maintaining individual process-performance indicators. Stable biological conversion provides the foundation for recovering multiple resources from organic wastes and wastewater.

Anaerobic digestion enables organic matter to be converted into biogas, which can be used for electricity generation, heat production or upgrading to biomethane. At the same time, digestate contains recoverable nutrients, including nitrogen, phosphorus, potassium and organic carbon [45]. Digestate processing and nutrient recovery can therefore extend the value obtained from the same waste stream.

Wastewater treatment systems provided additional examples of integrated recovery. The reviewed studies described systems capable of combining biological treatment with

reclaimed-water production, phosphorus recovery, biogas generation and biomass production. Such integration reduces the extent to which waste streams are treated solely as disposal problems and instead positions them as sources of energy, water and nutrients.

The evidence suggests that process resilience is particularly important in integrated systems because instability in one biological conversion step can affect several downstream recovery pathways. Maintaining stable microbial activity can therefore protect not only methane production but also nutrient recovery, water reuse and the production of value-added bioproducts.

4.9. Implications for Circular Bioeconomy Applications

The synthesis indicates that resilient bioresource recovery systems can contribute to circular bioeconomy objectives through several interconnected pathways. These include renewable energy production, nutrient recycling, waste reduction, water reuse, production of bio-based products and reduction in greenhouse-gas emissions.

Anaerobic digestion represents a particularly important platform because it can simultaneously provide renewable energy and a nutrient-rich residual stream. Further processing of digestate can enable recovery of nitrogen and phosphorus through approaches such as nutrient precipitation, ammonia recovery and membrane-based separation.

The reviewed studies also identified emerging pathways involving volatile fatty acids, biohydrogen, carbon recovery, biochar and algal-bacterial systems. These approaches broaden the resource-recovery potential of biological treatment beyond conventional methane production.

Smart biorefineries represent a further development of this concept by integrating biological, chemical and thermochemical processes to maximize biomass utilization. The evidence suggests that the economic and environmental benefits of such systems depend strongly on stable process operation and the ability to maintain recovery performance under variable feedstock and environmental conditions.

Accordingly, resilience can be considered an important enabling characteristic of circular bioeconomy systems. Systems that frequently experience process failure may be unable to deliver consistent resource-recovery outputs, whereas systems capable of resisting and recovering from disturbance can support more reliable resource cycling.

4.10. Evidence Gaps and Future Research Priorities

The synthesis identified several areas in which the existing evidence remains limited or heterogeneous.

First, the mechanisms underlying microbial adaptation are not consistently investigated across studies. Many studies characterize changes in microbial community composition without simultaneously measuring functional activity or process recovery. Integrating metagenomics with transcriptomics, proteomics and metabolomics could therefore provide a more comprehensive understanding of the mechanisms linking community change to resilience.

Second, the long-term stability of engineered microbial communities remains insufficiently established. Although synthetic microbial consortia and bioaugmentation have demonstrated potential under controlled conditions, their persistence and performance under variable full-scale operating environments require further investigation.

Third, the application of artificial intelligence and digital twins to resilience management remains an emerging research area. Future studies should emphasize standardized datasets, independent validation and full-scale demonstrations to determine whether predictive models developed under laboratory conditions remain reliable under operational variability.

Fourth, the relationship between resilience and carbon-negative resource recovery requires further investigation. Integration of anaerobic digestion with carbon capture, biochar production, renewable energy and carbon-sequestration pathways may provide opportunities to improve the climate performance of resource recovery systems.

Fifth, nutrient recovery requires greater attention to process integration and economic feasibility. Although phosphorus and nitrogen recovery technologies are increasingly developed, their practical application depends on recovery efficiency, energy requirements, chemical consumption, product quality and market value.

Finally, climate change introduces additional uncertainty into the operation of biological treatment systems. Future research should therefore evaluate resilience under combinations of temperature variation, drought, hydraulic shocks, changing feedstock availability and contaminant exposure rather than examining individual stressors in isolation.

4.11. Overall Synthesis of the Results

The systematic synthesis demonstrates that microbial adaptation is a central determinant of resilience in anaerobic digestion and related bioresource recovery systems. Across the included evidence, four interconnected mechanisms—physiological adaptation, syntrophic cooperation, DIET and microbial community restructuring—were repeatedly associated with the maintenance or restoration of process function under environmental stress.

Environmental disturbances initially affected microbial activity and community structure, resulting in changes in methane production, VFA accumulation and substrate conversion [46]. However, adapted microbial communities were able to compensate for these disturbances through physiological responses, metabolic cooperation and selective enrichment of stress-tolerant populations. In some systems, conductive materials further strengthened electron transfer and supported recovery.

The evidence also demonstrates that resilience has consequences beyond the biological process itself. Stable microbial conversion supports reliable recovery of energy, nutrients, water and other valuable products and therefore strengthens the contribution of bioresource recovery systems to circular bioeconomy objectives.

Overall, the findings support a systems-level interpretation of resilience in which microbial adaptation, reactor operation, monitoring technologies and resource-recovery pathways are interconnected [47]. Rather than representing a single microbial trait or engineering intervention, resilience emerges from the interaction between microbial community structure, metabolic flexibility, operational management and the broader resource-recovery system.

5. Conceptual Framework for Process Resilience and Integrated Bioresource Recovery in Anaerobic Digestion

The novelty of the present review should be considered in relation to the substantial body of the previous review literature addressing anaerobic digestion (AD) process stability, microbial adaptation, process monitoring, intelligent control, and resource recovery. Previous reviews have made important contributions within these individual domains, but they differ in scope and emphasis from the integrated perspective developed in the present study. For example, Li et al. [22] reviewed process stability in food-waste AD, emphasizing process monitoring, control, and microbial management as complementary approaches for mitigating instability. Similarly, a systematic review by [47] examined microbial community composition and dynamics in relation to environmental and operational parameters, demonstrating how changes in microbial diversity and functional populations influence AD stability and performance [48–50]. These studies provide important foundations for understanding the biological basis of AD stability, but their primary emphasis is on micro-

bial responses and process stability rather than on the coordinated integration of biological, engineering, digital management, and resource-recovery dimensions.

Other reviews have focused specifically on resource recovery and circular bioeconomy applications. Tsapekos et al. [51,64] for example, reviewed the upcycling of AD streams and demonstrated pathways for converting methane, carbon dioxide, nutrients, and digestate into higher-value products and services within a circular bioeconomy. Other reviews have similarly examined digestate valorisation, nutrient recovery, biorefinery pathways, and integrated resource-recovery technologies. These contributions establish that AD can move beyond conventional biogas production towards the recovery of multiple products. However, resource-recovery reviews generally focus on downstream valorisation, product pathways, techno-economic considerations, or environmental performance rather than on how the capacity of the biological process to withstand and recover from disturbances affects the reliability of these resource-recovery outcomes.

A further body of research has addressed intelligent monitoring, prediction, optimisation, and control [52]. Recent reviews have examined artificial intelligence, machine learning, soft sensors, digital twins, and data-driven process optimisation for detecting disturbances and improving AD performance. These approaches provide important mechanisms for improving the anticipation and management of process disturbances. Nevertheless, they primarily address the computational and operational management of AD rather than treating intelligent process management as one component of a broader resilience system that also incorporates microbial adaptation, engineering interventions, and resource-valorisation outcomes.

The recent literature has also moved more explicitly towards resilience-oriented frameworks. A 2026 review proposed a stress–response–recovery framework for stressed AD systems, linking environmental stress to microbial ecological responses, microbial plasticity, alternative metabolic pathways, DIET, functional redundancy, microbial memory, and ecological hysteresis [53]. This work is particularly relevant to the present study because it demonstrates that resilience should not be understood simply as the maintenance of methane production, but also in terms of microbial reorganisation, adaptation, and recovery following disturbance. The present framework therefore does not claim to introduce the concept of resilience or the biological stress–response–recovery relationship for AD. Rather, it extends this line of thinking towards an implementation-oriented systems perspective by connecting biological resilience with engineering, intelligent process management, and integrated resource recovery.

The comparison demonstrates that the contribution of the present review lies not in introducing each individual component independently, but in connecting components that have predominantly been examined in separate strands of the literature [54–56]. Figure 2 therefore conceptualises resilience as a system-level property emerging from interactions among environmental conditions, microbial responses, engineering interventions, intelligent process management, and resource-recovery pathways. In this formulation, environmental and operational disturbances represent the initiating pressures; microbial adaptation provides an important biological capacity for resistance and recovery; engineering interventions modify the physical and chemical operating environment; intelligent monitoring and adaptive control improve disturbance detection and response; and resource-recovery pathways determine whether process stability is translated into sustained energy, nutrient, water, and other circular outputs.

This integration is necessary because the resilience of an AD system cannot be adequately assessed solely from methane yield or the persistence of individual microbial populations [57–60]. A digester may maintain short-term methane production while experiencing progressive accumulation of inhibitory compounds, loss of functional diversity,

declining nutrient-recovery efficiency, or increasing operational vulnerability. Conversely, a system may undergo substantial microbial restructuring without returning to its original community composition yet still recover functional performance [61–65]. Resilience therefore involves the capacity of the system to absorb disturbance, reorganise, recover functional performance, and continue delivering desired resource-recovery outcomes. This interpretation is consistent with emerging ecological perspectives on AD resilience, while extending the analysis towards engineering and implementation considerations.

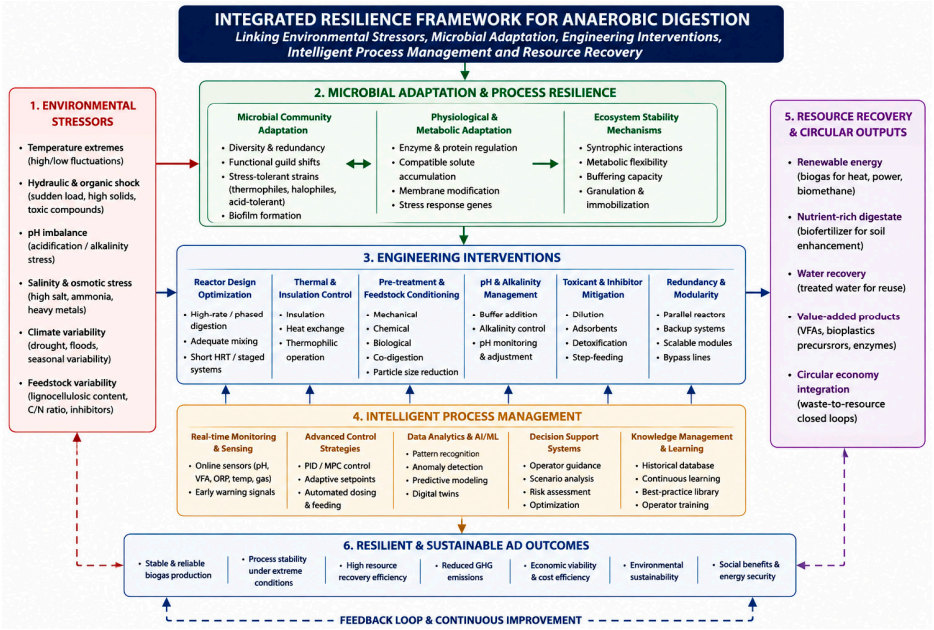


Figure 2. The Integrated Framework for Process Resilience and Integrated Bioresource Recovery in Anaerobic Digestion.

The Integrated Resilience Framework

Figure 2 presents the Integrated Framework for Process Resilience and Integrated Bioresource Recovery in Anaerobic Digestion. The framework synthesises the evidence identified across the reviewed literature into five interconnected dimensions: (i) environmental and operational stressors; (ii) microbial adaptation and process resilience; (iii) engineering interventions; (iv) intelligent process management; and (v) resource recovery and circular outputs.

The first dimension comprises environmental and operational stressors, including temperature fluctuations, hydraulic and organic loading shocks, pH imbalance, salinity, toxic compounds, seasonal variability, and feedstock inconsistency. These disturbances can alter microbial activity, metabolic pathways, syntrophic relationships, and overall process stability. The reviewed evidence indicates that the effects of these disturbances are mediated not only by the magnitude of the disturbance but also by microbial community structure, acclimation history, functional redundancy, substrate characteristics, and operating conditions.

The second dimension concerns microbial adaptation and process resilience. Microbial diversity, functional redundancy, physiological acclimation, syntrophic interactions, alternative metabolic pathways, and microbial restructuring can contribute to AD communities' ability to maintain or recover functional performance following disturbance. This dimension is particularly important because microbial adaptation can occur through changes in community composition and metabolic function rather than through a simple return to the pre-disturbance state. Recent resilience research similarly highlights microbial plasticity,

alternative electron-transfer pathways, and reorganisation of microbial communities as important components of recovery.

The third dimension represents engineering interventions that modify the conditions under which biological adaptation occurs. These interventions include reactor configuration and design, thermal management, feedstock conditioning, co-digestion, pH and alkalinity management, inhibition mitigation, pretreatment, hydraulic and organic loading control, and system redundancy. Their role within the framework is not to replace microbial adaptation but to create operating conditions that facilitate microbial stability and recovery.

The fourth dimension is intelligent process management. Monitoring, sensor technologies, data analysis, predictive modelling, artificial intelligence, decision-support systems, and adaptive process control can improve the detection and management of disturbances. Existing reviews have demonstrated the potential of AI and machine learning for process prediction, anomaly detection, optimisation, and real-time control. Within the present framework, however, these technologies are positioned as part of a broader resilience architecture rather than as an independent technological solution.

The fifth dimension connects process resilience to resource recovery and circular outcomes. Stable and recoverable AD operation can support the production of biogas or biomethane, electricity and heat, nutrient-rich digestate, recovered nitrogen and phosphorus, water, and potentially higher-value bioproducts. Previous reviews have demonstrated the considerable potential for upcycling AD streams and developing digestate-based biorefineries. The contribution of the present framework is to make the relationship between process resilience and resource-recovery continuity explicit. In other words, resilience is not considered an end in itself; it is important because disturbances that compromise biological and operational stability can subsequently compromise the reliability, quality, and economic value of recovered resources.

The framework therefore represents a conceptual synthesis rather than a new technological configuration, predictive model, or validated operational control architecture. It should not be interpreted as suggesting that all five dimensions must be implemented simultaneously in every AD system. Instead, the framework provides a structured basis for identifying the relationships among disturbance pressures, biological responses, technological interventions, management strategies, and resource-recovery outcomes.

Its practical value is consequently expected to be context dependent. The selection and sequencing of interventions should consider feedstock characteristics, climatic conditions, agricultural practices, infrastructure, energy demand, technical capacity, institutional arrangements, financial resources, and the intended end uses of recovered products. For agricultural and community-scale applications, including integrated bioresource farming Systems (BIFSs), the framework can therefore guide the development of site-specific configurations in which biogas production, digestate utilisation, agricultural production, water management, and productive energy use are considered as interconnected components rather than isolated outputs.

The framework also provides a basis for future empirical testing. Future research should determine whether the proposed relationships can be operationalised through measurable resilience indicators, including resistance to disturbance, recovery time, recovery trajectory, functional redundancy, methane-production stability, nutrient-recovery efficiency, resource-recovery continuity, and economic performance. Such validation would enable the conceptual framework to evolve into a measurable resilience assessment and, ultimately, a decision-support tool for different AD scales and operating contexts.

6. Conceptual Application of the Integrated Resilience Framework to Biogas-Integrated Farming Systems in Limpopo Province, South Africa

The Integrated Resilience Framework provides a conceptual basis for evaluating and strengthening the resilience of Biogas-Integrated Farming Systems (BIFS) in Limpopo Province, South Africa. In this context, BIFS refers to an integrated agricultural approach that links livestock production, crop cultivation, anaerobic digestion, renewable energy generation, nutrient recovery, and, where feasible, water reuse and other circular-economy practices. Rather than representing a single technological model, BIFS can be adapted to the resources, production activities, infrastructure, energy requirements, and socio-economic conditions of individual farms and rural communities.

The application of the framework is particularly relevant to Limpopo, where agriculture plays a significant role in rural livelihoods and where livestock production, crop cultivation, and agro-processing activities generate substantial quantities of organic residues suitable for anaerobic digestion [65–67]. By converting these residues into biogas and nutrient-rich digestate, BIFS can contribute to renewable energy production, waste management, agricultural productivity, and rural economic development. Such integration aligns with the growing need to address energy insecurity, resource constraints, climate variability, and sustainable agricultural development within the province [65–67].

Limpopo is characterised by high temperatures, variable rainfall patterns, and recurring drought events that influence agricultural productivity and feedstock availability [68–70]. These conditions may affect both the quantity and quality of substrates available for anaerobic digestion. Within a BIFS framework, locally available livestock manure, crop residues, fruit and vegetable wastes, and agro-processing by-products can provide opportunities for feedstock diversification and operational flexibility. However, the availability of such resources is often seasonal and location-specific; therefore, feedstock suitability and long-term supply must be evaluated prior to implementation.

The microbial adaptation component of the framework is particularly relevant because agricultural feedstocks differ considerably in terms of chemical composition, moisture content, carbon-to-nitrogen ratio, and biodegradability. Livestock manure, poultry litter, crop residues, and agro-processing wastes may therefore require feedstock management strategies such as pre-treatment or co-digestion to maintain stable digestion performance. Effective operation would depend on maintaining appropriate loading rates, pH, temperature, moisture content, and microbial community adaptation to changing feedstocks.

Evidence from the Vhembe District has demonstrated the substantial availability of livestock manure resources and their potential for biogas production [66]. These findings provide a foundation for considering anaerobic digestion within integrated agricultural systems in Limpopo. However, feedstock availability alone does not indicate the existence of operational BIFS systems but rather highlights the potential resource base upon which site-specific systems can be developed.

The engineering intervention dimension of the framework provides guidance on measures that can improve process performance and resilience. Potential interventions include thermal insulation, appropriate reactor sizing, feedstock pre-treatment, co-digestion, pH regulation, gas-cleaning technologies, and modular digester designs. Co-digestion may be particularly beneficial where livestock manure can be combined with crop residues or agro-processing wastes to optimise substrate balance and enhance biogas production. Recent studies have reported that co-digestion can improve methane yields, process stability, and resource recovery efficiency [67–71]. Nevertheless, the selection of engineering interventions should be based on site-specific technical requirements rather than assumed to be universally applicable.

The framework further highlights the importance of appropriately scaled and modular digester systems for smallholder and emerging farmers. System design should consider factors such as herd size, feedstock availability, water resources, energy demand, agricultural activities, available land, technical expertise, and financial capacity. Consequently, the framework should be viewed as a planning and decision-support tool for developing locally adapted BIFS configurations rather than a standardised model for direct replication.

Potential benefits of BIFS are multidimensional. Environmentally, such systems could improve organic waste management, reduce greenhouse gas emissions through methane capture, promote nutrient recycling, and decrease reliance on fossil fuels and synthetic fertilisers. Economically, BIFS may reduce energy and fertiliser costs while creating value from agricultural residues. Socially, the approach could contribute to improved energy access, employment creation, livelihood diversification, and rural development. However, the extent of these benefits will depend on system performance, economic viability, management capacity, and institutional support.

Importantly, the Integrated Resilience Framework presented in Figure 2 should not be interpreted as an already operational BIFS model in Limpopo Province. Rather, it represents a conceptual pathway for integrating microbial adaptation, engineering optimisation, intelligent process management, resource recovery, and continuous feedback mechanisms into future biogas-based agricultural systems. Existing biogas initiatives in the province provide evidence for several framework components, but the complete integration of these elements has yet to be demonstrated and validated within a single operational system.

Future implementation should therefore focus on developing site-specific BIFS models for selected farms or rural communities. Such models should incorporate locally available feedstocks, digester capacities, energy requirements, agricultural activities, infrastructure, technical skills, and market opportunities for biogas and digestate products. Comprehensive techno-economic assessments would then be required to evaluate system feasibility, implementation costs, expected energy outputs, nutrient recovery potential, environmental benefits, and financial viability.

Implementation costs will inevitably vary according to system scale and technological complexity. While a basic 6 m^3 digester in the Limpopo context may cost approximately R30,000 [73–81], more advanced configurations incorporating gas cleaning, automated monitoring, water treatment, combined heat and power systems, and decision-support technologies would require substantially greater investment. Consequently, detailed techno-economic evaluation is required before site-specific deployment.

Overall, the Integrated Resilience Framework provides a structured approach for guiding the development of resilient and sustainable Biogas-Integrated Farming Systems in Limpopo Province. By integrating biological, technological, managerial, and resource-recovery dimensions, the framework offers a foundation for future pilot projects, field validation, techno-economic assessment, and the refinement of context-specific BIFS models suited to the environmental and socio-economic conditions of rural South Africa.

7. Operationalising the Integrated Resilience Framework for Biogas-Integrated Farming Systems in Limpopo Province, South Africa

The Integrated Resilience Framework provides a conceptual basis for applying the resilience principles identified in this review to Biogas-Integrated Farming Systems (BIFSs) in Limpopo Province, South Africa. BIFS can be understood as a circular agricultural configuration that links livestock production, crop cultivation, anaerobic digestion, renewable energy generation, nutrient recycling, water management, and productive use of recovered resources. Rather than treating anaerobic digestion as an isolated waste-treatment technology, the BIFS approach positions the digester within a wider agricultural system in which

waste streams become inputs for energy and nutrient production. This configuration is particularly relevant to Limpopo, where rural agricultural communities face interconnected challenges involving energy access, water scarcity, agricultural waste management, soil fertility, climate variability, and livelihood diversification [66–68].

7.1. Environmental and Operational Stressors in Limpopo BIFS

The first dimension of the Integrated Resilience Framework concerns environmental and operational stressors. Limpopo is characterised by relatively high temperatures, seasonal rainfall variability, recurrent drought conditions, and increasing climate variability. These conditions can affect agricultural production, livestock management, water availability, and the quantity and composition of organic materials available for anaerobic digestion [69]. Recurring droughts may reduce crop productivity and therefore the availability of crop residues, while water shortages can constrain feedstock preparation, digester operation, and agricultural reuse of digestate. At the same time, seasonal changes in temperature and feedstock availability may alter hydraulic loading, organic loading, substrate characteristics, and microbial activity within digesters [69–74].

The resilience perspective is therefore relevant because BIFS systems must be capable of responding to changes in both the agricultural resource base and the conditions under which anaerobic digestion operates. Feedstock inconsistency, seasonal availability, water constraints, temperature fluctuations, and changes in livestock numbers can collectively create disturbances that affect process stability. Consequently, resilience in a Limpopo BIFS should not be defined solely by the maintenance of methane production [75]. It should also include the capacity to maintain the availability and quality of feedstocks, adjust system operation to changing conditions, recover from disturbances, and continue providing useful energy, nutrients, water, and agricultural services.

7.2. Feedstock Diversity and Microbial Adaptation

The second dimension concerns microbial adaptation and process resilience. BIFS offers an opportunity to maintain a diverse and relatively flexible feedstock portfolio because livestock manure, crop residues, fruit and vegetable wastes, and agro-processing by-products can potentially be incorporated into anaerobic digestion [76]. Such feedstock diversification can reduce dependence on a single substrate and provide opportunities for co-digestion when the availability or composition of individual feedstocks changes.

This characteristic is particularly relevant to microbial resilience. Different substrates provide different carbon, nitrogen, moisture, and micronutrient profiles and can therefore influence microbial community structure and metabolic pathways. However, feedstock diversity should not automatically be equated with microbial resilience [77]. Poorly controlled changes in substrate composition or excessive organic loading may instead increase process instability. The resilience objective is therefore to manage feedstock diversity within an appropriate operating range, allowing microbial communities to acclimatise while avoiding excessive loading or inhibitory conditions.

Evidence from Vhembe District has demonstrated the substantial potential of locally available livestock manure as a feedstock for biogas production [67]. This indicates that Limpopo possesses an important biological resource base for decentralised bioenergy systems. Within BIFS, the strategic management of this resource base can support both energy production and nutrient recovery [78]. Co-digestion can further improve substrate balance where appropriate feedstocks are available. Recent South African research has reported improvements in biogas and methane production through co-digestion compared with selected mono-digestion configurations [79–84]. Nevertheless, the suitability of particular

feedstock combinations should be established through site-specific biochemical, operational, and economic assessment rather than assumed universally.

7.3. Engineering Interventions for Resilient BIFSs

The third dimension of the framework involves engineering interventions that create conditions conducive to stable biological performance. In Limpopo, such interventions may include appropriately designed and insulated digesters, suitable reactor configurations, controlled feeding regimes, feedstock conditioning, co-digestion, pH and alkalinity management, and mechanisms for managing inhibitory compounds [85]. The choice of intervention should correspond to the scale of the farm, the characteristics of the feedstock, climatic conditions, available technical capacity, and intended energy and agricultural applications.

Thermal management is particularly relevant where temperature fluctuations affect microbial activity. Similarly, appropriate feedstock preparation and mixing can help manage variations in substrate characteristics [86–90]. Where crop residues or other lignocellulosic materials constitute an important component of the available biomass, pretreatment may improve biodegradability, although the additional energy, capital, and operational requirements must be considered.

Modular and appropriately scaled digester configurations may also improve accessibility for smallholder and emerging farmers by allowing system capacity to correspond more closely with locally available feedstocks. However, technological appropriateness should extend beyond initial construction costs. Long-term resilience depends on maintenance requirements, availability of spare parts, operator competence, water requirements, financing mechanisms, and access to technical support. Consequently, engineering resilience in BIFS should be evaluated over the full operational life of the system, rather than only at the installation stage.

7.4. Intelligent Process Management and Local Capacity

The fourth dimension of the framework concerns intelligent process management. BIFS implementation in rural Limpopo should progressively incorporate appropriate monitoring of parameters such as temperature, pH, loading conditions, gas production, methane concentration, and digestate characteristics [80]. Even relatively simple monitoring systems can provide early indications of process deterioration and support timely operational adjustments.

More advanced applications could incorporate sensors, data logging, predictive analytics, and artificial intelligence to identify deviations from normal operating conditions and support adaptive process management. Such technologies could be particularly valuable where environmental conditions and feedstock availability vary seasonally. However, digital technologies should be considered resilience-enhancing tools rather than prerequisites for BIFS implementation [81]. Their suitability will depend on electricity availability, connectivity, affordability, digital literacy, technical support, and the capacity of local operators to interpret and act upon the information generated.

Local knowledge and technical capacity are therefore integral to this dimension. Training farmers and community operators in feedstock management, digester operation, troubleshooting, safety, maintenance, and resource utilisation can strengthen the human capacity required to translate monitoring information into effective action [82–85]. In this respect, technological resilience and institutional capacity should be considered complementary rather than separate components.

7.5. Integrated Resource Recovery and Circular Agricultural Outcomes

The fifth dimension links process resilience to resource recovery. Within a BIFS configuration, anaerobic digestion can generate several interconnected outputs, including biogas,

heat, electricity, digestate, recovered nutrients, and potentially treated water [86]. These outputs can be returned to agricultural activities, thereby establishing feedback loops between livestock production, energy generation, crop production, and waste management.

Biogas can provide energy for cooking, water pumping, refrigeration, lighting, agro-processing, and other productive activities. Digestate can provide organic nutrients for crop production, potentially reducing dependence on purchased fertilisers [88]. Water recovery and reuse can further support agricultural production where appropriate treatment and quality controls are available. These linkages transform anaerobic digestion from a waste-management intervention into a component of a broader circular agricultural system.

The resilience of this configuration therefore depends on the performance of the entire resource-recovery chain. For example, a technically stable digester may provide limited livelihood benefits if the biogas cannot be used productively, digestate cannot be safely and effectively utilised, or the recovered resources have no viable local market. Conversely, diversified uses of recovered resources may increase the value and adaptive capacity of the overall system by reducing dependence on a single output. BIFS should therefore be assessed using multidimensional indicators that include not only methane production but also energy reliability, nutrient-recovery efficiency, agricultural productivity, input-cost reduction, resource utilisation, and livelihood outcomes.

7.6. From Resilience Framework to Site-Specific BIFS Implementation

Application of the Integrated Resilience Framework to Limpopo demonstrates that BIFS should not be implemented as a standardised technological package [90–92]. Instead, the framework can be used as a diagnostic and design tool for identifying locally relevant disturbances, vulnerabilities, adaptation mechanisms, interventions, and desired outcomes.

For example, a BIFS in a livestock-dominated farming area may prioritise manure management, biogas production, digestate utilisation, and water pumping, whereas a mixed farming system with substantial crop and agro-processing residues may place greater emphasis on co-digestion, feedstock storage, pretreatment, and productive-use applications. Similarly, systems operating under severe water constraints may require greater emphasis on water-efficient digester operation and appropriate water-reuse pathways. The appropriate configuration should therefore emerge from an assessment of local resource availability, agricultural practices, climate conditions, energy demand, technical capacity, financing, institutional arrangements, and market opportunities.

This site-specific orientation is important because resilience is not an intrinsic property of a particular digester design. Rather, it emerges from the interaction between technology, microbial communities, feedstocks, operators, institutions, environmental conditions, and resource-use pathways. The framework consequently provides a means of translating the broader systematic-review findings into context-specific implementation questions for BIFS.

7.7. Potential Contribution to Sustainable Rural Development in Limpopo

When appropriately designed and managed, BIFS has the potential to generate interconnected environmental, economic, and social benefits. Environmentally, the approach can support organic-waste management, methane capture, nutrient recycling, and reduced dependence on fossil-based energy and synthetic agricultural inputs. Economically, productive use of biogas and digestate may contribute to reduced energy and fertiliser expenditure, while additional opportunities may arise through agro-processing, energy services, fertiliser products, or other circular-economy enterprises [93]. Socially, decentralised energy and resource-recovery systems may contribute to improved energy access, agricultural productivity, employment, skills development, and livelihood diversification.

These potential benefits should, however, be distinguished from demonstrated outcomes. The framework identifies plausible pathways through which BIFS could strengthen resilience and support sustainable rural development, but the magnitude and persistence of these benefits require empirical validation under specific Limpopo conditions. Future research should therefore test BIFS configurations using integrated technical, environmental, economic, social, and resilience indicators.

Overall, the application of the Integrated Resilience Framework demonstrates how anaerobic digestion can be positioned within a broader rural production system rather than treated as an isolated biogas technology. For Limpopo Province, the framework links climate and operational stressors with microbial adaptation, engineering responses, intelligent management, and integrated resource recovery. Its principal value is therefore as a decision and design framework for developing site-specific BIFS configurations capable of adapting to changing conditions while maintaining productive energy, nutrient, water, and agricultural functions. Empirical studies are required to determine the effectiveness, affordability, scalability, and long-term resilience of such configurations across the diverse agroecological and socioeconomic contexts of Limpopo.

8. Conclusions

This systematic review synthesized evidence from 98 peer-reviewed studies published between 2022 and 2025 to examine the resilience of anaerobic digestion (AD) systems under environmental and operational stress conditions. The reviewed studies identified ammonia toxicity, temperature extremes, salinity, pH instability, organic overloading, volatile fatty acid accumulation, and emerging contaminants as the principal stressors affecting process performance and methane production.

The evidence consistently demonstrated that microbial adaptation plays a central role in maintaining AD functionality under stress. Physiological adaptation, syntrophic interactions, direct interspecies electron transfer (DIET), and microbial community restructuring were the most frequently reported mechanisms supporting process resilience. Studies further showed that engineering interventions, including co-digestion, bioaugmentation, feedstock pretreatment, reactor optimization, and intelligent monitoring technologies, can enhance process stability and accelerate recovery following disturbances.

Beyond methane production, the reviewed literature highlighted the contribution of resilient AD systems to biomethane generation, nutrient recovery, digestate valorization, volatile fatty acid production, biohydrogen generation, and other resource-recovery pathways that support circular bioeconomy objectives. However, substantial heterogeneity among studies in feedstocks, reactor configurations, operating conditions, and performance indicators limited direct quantitative comparisons and prevented a formal meta-analysis.

Based on the synthesis of evidence, this review proposes an Integrated Resilience Framework that links environmental stressors, microbial adaptation mechanisms, engineering interventions, intelligent process management, and resource-recovery pathways. While the individual framework components are derived from the reviewed literature, integrating them into a single resilience-oriented perspective constitutes the conceptual contribution of this review.

Overall, the findings suggest that enhancing AD resilience requires coordinated biological, engineering, and operational strategies rather than reliance on individual interventions. Future research should focus on validating integrated resilience approaches under pilot- and full-scale conditions, improving quantitative assessment of resilience indicators, and investigating how emerging digital technologies can support adaptive process management in increasingly variable operating environments.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
VFAs	Volatile Fatty Acids
BIFs	Biogas-Integrated Farming Systems
SAOB	Syntrophic Acetate-Oxidizing Bacteria

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