ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT
AZOJETE September 2026. Vol.22(3):831-845
Published by the Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria.
Print ISSN: 1596-2490, Electronic ISSN: 2545-5818
https://doi.org/10.63958/AZOJETE/2026/22/03/023
www.azojete.com.ng

REVIEW ARTICLE

ORGANIC WASTE VALORISATION IN THE CIRCULAR BIOECONOMY: A CRITICAL REVIEW OF COMPOSTING, ANAEROBIC DIGESTION, AND TECHNOLOGICAL INTEGRATION

I. Yahaya[1]*, M. Shuwa[1], S. S. Dumbulwa[1], U.T. Abba[1], A.M. Bulama[2]

[1]Department of Mechanical Engineering, University of Maiduguri, P.M.B 1069, Maiduguri, Nigeria
[2]Department of Remedial Science, Ramat Polytechnic, Maiduguri, Nigeria
**Corresponding author's email: ibrahimyahaya2233@gmail.com*

ARTICLE INFORMATION

Received: 17th June 2026
Revised: 8th August 2026
Accepted: 10th August 2026

Keywords:
Aerobic composting
Anaerobic digestion
Organic waste
Circular bioeconomy
Waste valorisation
Biogas
Composting
Compost

ABSTRACT

The amount of organic waste generated in the world has reached critical limits, and in the year 2016, over 2 billion tonnes of municipal solid waste were produced, with 44-60% of this waste being organic. The under-managed waste stream worsened the issues of GHG emissions, soil degradation and resource depletion, all working against the circular bioeconomy paradigm. The two main biological valorization routes to recover organic waste as valuable products are aerobic composting and anaerobic digestion (AD), in which it is transformed into stable compost and biogas, respectively. Until now, their potential is limited by technological, economic and policy challenges, mostly in low- and middle-income countries. This review, however, covered the mechanistic, operational and environmental aspects of aerobic composting and AD and investigates these aspects in relation to their performance indicators, co-digestion possibility, compost quality parameters, energy yields and GHG balance based on evidence retrieved from more than 60 peer-reviewed studies. Additionally, the review delved deeper into integration frameworks, such as combined composting-AD systems and synergies between local and technological aspects, as enablers of a closed-loop circular bioeconomy. Results showed that co-digestion of food wastes with lignocellulosic substrates increased methane production by 20-60%, while the thermophilic composting process considerably reduced the pathogen level and the bioavailability of heavy metals. Finally, the paper highlighted operational and policy bottlenecks and the research significance of scaling waste valorisation in a globally applicable framework of the circular bioeconomy.

© 2026 Faculty of Engineering, University of Maiduguri, Nigeria. All rights reserved.

1.0 Introduction

Organic waste includes food scraps, residues from agriculture, sewage sludge, and biodegradable municipal solid waste (BMSW), which represents the single largest group in global waste streams. Population growth and industrial expansion lead to a global rise in organic waste production, which presents significant environmental challenges (Bi *et al.*, 2025). Over 2 billion tonnes of municipal solid waste (MSW) are generated annually according to World Bank estimates, a figure projected to reach 3.4 billion tonnes by 2050 (Kaza *et al.*, 2018). Most of which organic fractions constitute 44-60% by weight (Kaza *et al.*, 2018). UNEP (2024) estimated food waste in the year 2022 to be 1.05 billion tonnes, with household food waste accounting for 79 kg per capita, food service establishments at 36 kg and retail units at 17 kg. This distribution shows the main sources of food loss along the food supply chain. When these fractions are openly dumped or are sent to landfill, they decay anaerobically, producing methane, a greenhouse gas (GHG) that has a global warming potential 84 times that of CO_2 over 20 years (IPCC, 2021). This loss of nutrients, soil pollution and water pollution exacerbate ecological and public health threats.

Against this background, aerobic composting and anaerobic digestion (AD) have appeared as the two foremost biological treatment pathways for organic waste valorisation. Aerobic composting and anaerobic digestion are capable technologies for organic waste treatment, offering advantages over traditional methods such as landfilling, incineration, and pyrolysis (Bi *et al.,* 2025). Life cycle assessment established that AC and AD treatment methods demonstrated both environmental and economic paybacks compared to the other disposal methods (Bi *et al.,* 2025). Composting stabilises organic matter through oxidative microbial breakdown, yielding humus-rich compost that serves as a soil amendment and release fertilizer slowly. Whereas, AD converts organic substrates into biogas predominantly methane (CH_4, 50-70%) and carbon dioxide (CO_2) through a sequential microbial process (hydrolysis, acidogenesis, acetogenesis, methanogenesis) under oxygen-free conditions, while simultaneously producing a nutrient-rich digestate (Zhang *et al.,* 2026). These procedures are not just waste management tools but within the circular bioeconomy framework, they constitute material and energy rings that close the gap between waste generation and resource recovery (El Bari and arakat, 2025). Meta-omics technologies have revolutionised recent developments in understanding microbial community dynamics, enzymatic degradation pathways, and the fate of contaminants during AC and AD processes (Bi *et al.,* 2025). Findings revealed that substrate composition forms dominant microbial populations and their degradative enzymes, with this correlation possibly useful for predicting functional microbial communities (Bi *et al.,* 2025).

Both technologies face persistent operational and contextual challenges despite decades of research. Composting is constrained by prolonged process duration (4-12 weeks), variable output quality, and bulking agent availability, whereas AD systems face volatile fatty acid (VFA) accumulation, inhibition by ammonia, and high capital costs (Bi *et al.,* 2025; Zhang *et al.,* 2026). Waste management structures, inadequate infrastructure, and fragmented policies further hinder technology adoption in low- and middle-income countries (LMICs). Studies have revealed that anaerobic co-digestion of food waste with green waste at a ratio of 4:1 significantly improved process stability, reducing digestion time by 20% and lag phase by 64% (Silva *et al.,* 2025).

But there is a need to synthesize existing knowledge about performance parameters, synergistic integration and scalability of these technologies for different socio-technical contexts.

Hence, the aim of this review is to characterize biochemical mechanisms and operational parameters of aerobic composting and AD; discuss performance indicators for various substrate types and process configurations; discuss co-processing and integration strategies; and place these technologies in local-technological synergies for the implementation of circular bioeconomy.

2. Method

The review was structured following the narrative systematic review approach in terms of methodology used in environmental engineering and waste management research (Xiao and Watson, 2019; Snyder, 2019). The method contained literature search strategy, eligibility criteria, data extraction and data synthesis protocol.

2.1 Literature Search Strategy

A literature search was done on two electronic databases: Google Scholar and Scopus. The search strings were constructed using controlled vocabulary and free text search terms and were as follows: ("aerobic composting" OR "thermophilic composting" OR "vermicomposting") AND ("organic waste" OR "food waste" OR "agricultural residue" OR "municipal solid waste") AND ("anaerobic digestion" OR "biogas" OR "co-digestion" OR "digestate") AND ("circular economy" OR "bioeconomy" OR "waste valorisation" OR "resource recovery"). Key document was first retrieved from 642 sources using keyword's anaerobic digestion, aerobic composting, microbial communities, degradative enzymes, antibiotics, heavy metals, resistance genes and omics. Results of the initial search were used as a reference list for supplementary searches (snowballing), in addition to grey literature from the Food and Agriculture Organization (FAO), European Environment Agency (EEA), International Energy Agency (IEA) and World Bank.

2.2 Eligibility Criteria

Studies were accepted if they provided empirical data on composting or AD processes of organic waste substrates, (ii) quantitative performance metrics (e.g., methane yield in L CH_4/g VS, composting temperature profile, concentration of heavy metals, or greenhouse gas emission data); (iii) published in peer-reviewed journals or authoritative grey literature; and (iv) available in English. Studies were not included if they were only concerned with industrial chemical treatment without any biological treatment, conference abstracts where full text was not available, or did not include any empirical validation of the results, based only on modelled data.

2.3 Data Extraction and Synthesis

Data extraction was carried out through the use of a standardized template which included information on study design, substrate type, process configuration (batch or continuous), thermophilic or mesophilic treatment, key operational parameters (C:N ratio, HRT, OLR, temperature), and measured outputs (biogas yield, compost maturity indices, nutrient content, emissions). Data from various studies were tabulated and compared to pinpoint trends, mismatches and gaps in research. Because of the different types of substrates, different scales of processes, and the different geographies, a formal meta-analysis was not suitable and was substituted by a narrative synthesis. The latest research on changes in microbial communities, the dynamics of functional enzymes, the fate of pollutants, and the effects of AC and AD systems on treatment was reviewed (Bi *et al.,* 2025).

3. Results and Discussion

3.1 Biochemical Mechanisms of Aerobic Composting

Aerobic composting is a thermodynamically exothermic bioprocess involving heterotrophic microorganisms like bacteria, fungi and actinomycetes, which oxidize organic substrates in the presence of oxygen. This process is normally segmented into four stages: mesophilic (20-40°C), thermophilic (45-70°C), cooling and maturation (Bi *et al*., 2025). Under most national and international compost standards, thermophilic conditions (sustained temperatures > 55°C for at least three days) are needed during the thermophilic phase to inactivate pathogens and destroy weed seeds. This step can be especially significant for the treatment of food waste and sewage sludge, which might contain enteric pathogens like Salmonella spp. and helminth eggs (Bi *et al*., 2025). Research has confirmed that thermophilic phase temperatures above 60°C significantly reduce heavy metal bioavailability through metal complexation with humified organic matter (Bi *et al.,* 2025).

The carbon-to-nitrogen (C:N) ratio is one of the most critical parameters governing composting kinetics. Substrates with C:N ratios between 25:1 and 35:1 is generally optimal for microbial activity. Nitrogen-rich materials (such as food scraps and manures) are typically co-composted with carbon-rich bulking agents (such as wood chips and straw) to achieve this balance. Nitrogen excess resulted in ammonia volatilization, creating odour nuisances and decreased nutrient quality in products, and C:N ratios greater than 40:1 will slow down decomposition rates because of nitrogen deficiency. Optimizing the initial C:N ratio of a windrow composting system treating municipal food waste has been shown to decrease process time and ammonia emissions from the system when compared to unamended windrow (Ahn *et al*., 2011).

Other factors that influence the efficiency of the process are moisture content (50-65%), oxygen supply (>5% O_2 in pore space) and particle size (2-5 cm). When the moisture content goes below 40%, microbial activity is reduced significantly, and when it is above 65%, anaerobic pockets are created in the matrix that led to methane and hydrogen sulphide production and affected compost quality (Rynk, 1992). Forced aeration systems are energy intensive but provide excellent temperature uniformity and throughput compared to static pile systems, which vary based on turning frequency and are difficult to establish and maintain. Forced aeration windrow systems achieve compost stability approximately 40% faster than passively aerated piles using similar substrates (Kulikowska and Klimiuk, 2011).

Recent advances in composting technology have significantly advanced the field. Semipermeable membrane-covered composting has emerged as a novel approach that effectively enhances peak composting temperature, extends the duration of the high-temperature phase, and improves compost maturity (Yuan *et al.,* 2025). Yuan *et al.* (2025) concluded that the use of semipermeable membrane covers in combination with other emission reduction methods can reduce CH_4 and N_2O emissions by 21.4-52.8% and 41.8-72.3%, respectively. This mitigation strategy was accomplished by altering the genes of microorganisms in the compost, with suppression of genes for AOA, nirS, and mcrA, and encouragement of the nosZ gene. When biochar was used as a bio-feed during composting, it had measurable positive effects on a variety of performance measures. According to Zhang *et al.* (2025) the N_2O emission was reduced by 49.51% and NH_3 emission by 33.4% by using rice husk-derived material as the abatement agent, as reported by Shin *et al.* (2025). In addition to emission control, biochar also accelerated decomposition kinetics; Shin *et al.* (2025) reported volatile solids reduction of 27.5% from biochar derived from rice husk, as compared to 19.3% with no amendment. Under biochar treatment, nitrogen loss was also significantly reduced by 29% (Shin *et al*., 2025). More and Mandpe

(2026) compiled the general literature on additive synergies and highlighted that using a combination of amendments could lead to better process stability and environmental performance.

Table 1: Key operational parameters for aerobic composting, their optimal ranges, and effects of deviation.

S/N	Parameter	Optimal Range	Effect if Low	Effect if High	References
1	C/N Ratio	25-35:1	Slow decomposition	NH_3 volatilization, N loss	Haug (1993); Ahn *et al.* (2011)
2	Moisture Content	50-65%	Microbial inhibition	Anaerobic zones, odour	Rynk (1992); Yuan *et al.* (2025)
3	Temperature (Thermophilic)	55-70°C	Pathogen survival	Microbial die-off, stalling	Bi *et al.,* (2025); Yuan *et al.,* (2025)
4	C:N Ratio	25-35:1	Slow decomposition	NH_3 volatilization, N loss	Haug (1993); Ahn *et al.,* (2011)
5	Moisture Content	50-65%	Microbial inhibition	Anaerobic zones, odour	Rynk (1992); Yuan *et al.,* (2025)
6	Temperature (Thermophilic)	55-70°C	Pathogen survival	Microbial die-off, stalling	Bi *et al.,* (2025); Yuan *et al.,* (2025)
7	O_2 Concentration	>5% (pore space)	Anaerobic fermentation	Energy loss from excess aeration	Bi *et al.,* (2025); Kulikowska and Klimiuk (2011)
8	Particle Size	2-5 cm	Limited surface area	Compaction, O_2 restriction	Bi *et al.,* (2025)
9	pH	6.5-8.5	Acidification, inhibition	NH_3 loss, alkaline inhibition	Bi *et al.,* (2025)
10	Turning Frequency	2-3×per week (early)	Hot spots, poor aeration	Nutrient loss, drying	Bi *et al.,* (2025)

The main operational parameters that may affect the composting performance were summarized in Table 1. These parameters are not independent and interrelated such that if one parameter deviates, it affects the others. For example, enhanced O_2 availability combined with increased NH_3 stripping at high pH resulted in a greater loss of N, which may be detrimental to the final N content of the compost (Bi *et al*., 2025). Interdependence highlighted the need for process monitoring on all components, especially if the operation is large-scale with spatial variations in temperature and moisture.

A series of chemical and biological measurements were used to evaluate the maturity of compost. Germination index (GI ≥ 80%), respiration rate and dissolved organic carbon (DOC) / total organic carbon (TOC) are commonly used indicators of phytotoxicity and biological stability. The finished compost must be in accordance with heavy metal content standards such as EU Regulation 2019/1009, which establishes threshold values for Cd, Cr, Cu, Hg, Ni, Pb and Zn. Studies on municipal solid waste compost showed that thermophilic phase temperatures above 60°C, combined with pH >8, significantly reduced the bioavailability of Cd and Zn through metal complexation with humified organic matter, a discovery of direct relevance to agronomic safety (Farrell and Jones, 2009). Selenate addition during swine manure composting at 2 mg kg^{-1} has been revealed to decrease methane emissions by 39.60% and improved compost maturity (Zhao *et al.,* 2025a). Adding 2 mg kg^{-1} selenate also improved the richness and variety of microbes and influenced Proteobacteria, Chloroflexi, and Actinobacteria to decline the global warming potential (Zhao *et al.,* 2025b). Modified magnesium ore (MS650) application in aerobic composting has been shown to reduce NH_3 emissions by 0.74-52.4%, N_2O emissions by 29.0-57.9%, and greenhouse gas emissions by 41.8-60.3% (Zhao *et al.,* 2025a). Struvite precipitation and physical adsorption were identified as the chemical mechanisms responsible for nitrogen retention (Zhao *et al.,* 2025a). Kumar *et al.,* (2026) analysed GHG emissions and mitigation potential in decentralised composting supply chains across 517 residential sites, demonstrating consistent climate benefits.

3.2 Anaerobic Digestion: Process Biochemistry, Inhibition, and Performance

Anaerobic digestion is a four-stage syntrophic process: (1) hydrolysis, in which complex polymers (polysaccharides, proteins, lipids) are broken down by extracellular enzymes into soluble monomers; (2) acidogenesis, converting monomers into volatile fatty acids (VFAs), hydrogen, and CO_2; (3) acetogenesis, wherein VFAs are oxidized to acetate, H_2, and CO_2; and (4) methanogenesis, where acetoclastic and hydrogenotrophic methanogens convert acetate and H_2/CO_2 to methane (Bi *et al.,* 2025; Zhang *et al.,* 2026). The rate-limiting step depends on substrate composition: hydrolysis limits digestion of lignocellulosic substrates, while methanogenesis becomes rate-limiting for rapidly fermentable substrates such as food waste (Bi *et al.,* 2025; Hassanein, 2025). Research has confirmed that substrate composition shaped dominant microbial populations and their degradative enzymes, with this correlation useful for predicting functional microbial communities (Bi *et al.,* 2025).

The main factor affecting the AD process kinetics and stability was the temperature. There were two major thermal regimes: mesophilic (35-37°C) and thermophilic (50-55°C). Thermophilic AD had a higher volumetric biogas productivity (15-25 % CH_4H yield), improved pathogen reduction, and better dewatering of digestate, but was less stable to run, and sensitive to ammonia inhibition (Angelidaki and Ahring, 1994). The un-ionized form of the ammoniacal nitrogen (free ammonia nitrogen [FAN]) was the most inhibitory species: levels exceeding 150-200 mg FAN-N/L have been reported to inhibit the methanogenic process in mesophilic reactors, whereas thermophilic reactors were inhibited at 50-100 mg FAN-N/L because of differences in the methanogenic community composition (Chen *et al*., 2008). Artificial Intelligence and digitalization for the optimization of the AD process is an emerging frontier (El Bari & Barakat, 2025; Hassanein, 2025).

The two main operational design variables in continuous-flow AD systems were the organic loading rate (OLR) and hydraulic retention time (HRT). Typical OLRs for food waste AD ranged from 1 to 6 kg VS/m³/day in mesophilic continuous stirred tank reactors (CSTRs), with biogas yields of 350-500 L CH_4/kg VS (Zhang *et al.,* 2014). High-rate reactors, including up flow anaerobic sludge blanket (UASB) reactors, expanded granular sludge bed (EGSB) reactors, and anaerobic sequencing batch reactors (ASBR), achieved significantly higher OLRs (5-20 kg COD/m³/day) by retaining biomass independently of HRT, rendering them particularly suitable for high-strength organic effluents (Seghezzo *et al.,* 1998). Studies have demonstrated that anaerobic co-digestion of food waste with green waste at a 4:1 ratio significantly improved process stability and reduced digestion time (Silva *et al.,* 2025). The hybridization of AD with pyrolysis had been shown to boost energy efficiency and by-product quality of anaerobic digestion of kitchen waste (Jana *et al.,* 2025).

Table 2: Biogas/methane yields and operational parameters for anaerobic digestion of common organic substrates

S/N	Substrate	CH_4 Yield (L/g VS)	OLR (kg VS/m³/d)	HRT (days)	Temperature	Reference
1	Food waste (FW)	0.35-0.50	2-6	15-30	Mesophilic	Zhang *et al.,* (2014)
2	Sewage sludge	0.18-0.28	1-3	20-30	Mesophilic	Nges and Liu (2010)
3	Cattle manure	0.15-0.28	1-4	20-40	Mesophilic/Thermo	Angelidaki and Ahring (1994)
4	Crop residues	0.25-0.38	2-5	30-50	Mesophilic	Lebuhn *et al.,* (2015)
5	Slaughterhouse waste	0.40-0.68	1-3	15-25	Thermophilic	Banks *et al.,* (2012)
6	FW + sewage sludge (co-digestion)	0.30-0.55	3-7	15-25	Mesophilic	Mata-Alvarez *et al.,* (2014)
7	FW + livestock manure (co-dig.)	0.38-0.62	2-6	20-30	Mesophilic	Esposito *et al.,* (2012)
5	FW + Green Waste (4:1)	Comparable	–	–	Mesophilic	Silva *et al.,* (2025)

Table 2 shows that there are substantial differences in the CH_4 yields from the different substrates, which were due to differences in biochemical methane potential (BMP), biodegradability, and inhibitory compound content. The highest methane volumes came from slaughterhouse waste and food waste, which have the highest lipid content and the highest content of easily fermented carbohydrates, respectively. The advantages of co-digestion mixtures over mono-digestion can be explained by the better C:N ratio balance, dilution of inhibitory compounds and supply of macro and micro nutrients essential for methanogenic activity. Mata-Alvarez *et al.,* (2014) in their meta-analysis of co-digestion studies established that optimized feedstock mixing ratios consistently delivered CH_4 yield enhancements over single-substrate digestion. Optimization trials of co-digestion have provided useful information on best feedstock mixtures and operating conditions. When Silva *et al.* (2025) investigated green waste and food waste in combination, they discovered that a 4:1 ratio not only maintained the capacity of food waste to generate methane, but also stabilized the waste, reducing the typical lag phase by almost 64% and digestion time by 20%. In the same context, Santaweesuk *et al.* (2025) optimized the co-digestion of pig manure (PM) with Napier grass (NG) and found that pig manure to Napier grass ratio of 1.18, operating organic loading (OL) of 0.62 gVS/L and total solids (TS) of 4.8% resulted in maximum methane yield of 331.59 mL/gVS. The Modified Gompertz model was well suited to describe the kinetic production of biogas in this optimized system (Santaweesuk *et al*., 2025). One parameter that was less often mentioned in a standard digestate study was digestate quality. The semi-liquid effluent of the AD reactors is called digestate, which contains almost all the mineral nitrogen (mainly in the form of $(NH^+)_4$), phosphorus, potassium and trace elements from the feedstock, and is therefore a valuable biofertilizer. Studies have verified that liquid digestate fractions from food waste AD contain significant plant-available nitrogen, representing an effective alternative to synthetic fertilizers (Tambone *et al.,* 2010). Recent research confirmed that digestates can stimulate beneficial bacterial communities, favoring greater bacterial growth (Mora Salguero, 2024). However, pathogens, pharmaceutical residues, microplastics, and antibiotic resistance genes were increasingly recognized as contaminants in digestate, particularly when derived from mixed municipal waste or hospital waste (Odlare *et al.,* 2011; Feng *et al.,* 2021). Thermophilic operation (>52°C for ≥24 h) and post-digestion pasteurization were effective mitigation strategies mandated under EU hygienization standards. El Bari and Barakat (2025) provided comprehensive coverage of digestate valorization as a biofertilizer and its energy recovery using thermochemical conversion in their edited volume on biogas in the circular economy.

3.3 Co-Digestion and Substrate Synergies

Among the various solutions proposed, co-digestion proved to be the main solution to the drawbacks of single-substrate AD and to achieve high yield in biogas production. Co-digestion works on several mechanisms, such as: (i) optimization of the C:N ratio by co-digesting nitrogen-rich and carbon-rich substrates; (ii) dilution of specific inhibitors (e.g., ammonia, long-chain fatty acids, sulphides); (iii) addition of lost microbial co-factors (cobalt, nickel, molybdenum) needed for methanogenesis; (iv) buffering of pH fluctuations by supplementing alkalinity; and (v) increasing the diversity and functional redundancy of the microbial communities (Esposito *et al*., 2012).

Food waste was the most commonly deliberate co-substrate in co-digestion research, due to its high BMP and widespread disposal in urban waste streams. However, its low C:N ratio (typically 14-25:1) rendered mono-digestion prone to ammonia inhibition. Co-digestion with lignocellulosic agricultural residues addressed this constraint by elevating the effective C:N ratio to the optimal 20-30:1 range. Studies have reported that food waste co-digested with wheat straw achieved significant improvements in CH_4 yield while maintaining stable VFA/alkalinity ratios (Brown *et al.,* 2012). In recent years, co-digestion strategies have been revealed as an efficient way to improve the performance of anaerobic digestion. Silva *et al*. (2025) reported that food waste/green waste ratio of 4:1 yielded better digestion processes, showing a 20% and 64% decrease in digestion times and lag phase when applying a ratio of 2:1. The proportion was a balanced one, suitable for the operation of a municipal biogas plant, where it is possible to valorize difficult feedstocks like lignocellulosic feedstocks without compromising efficiency (Silva *et al*., 2025). In parallel research, Ayantokun *et al*. (2025) explored the co-digestion of food waste (FW) with poultry manure (PM), which was found to be a promising sustainable waste management approach that enhances biogas production, enriches nutrient content, and fosters microbial diversity by diversifying substrates. They also found that mixing animal and plant wastes will speed up the breakdown of organic matter, which in turn will boost the production of methane. The careful management of process parameters, such as pH, OLR, temperature, C:N ratio, and HRT, were critical and significantly impacted microbial activity as well as the overall biogas yield (Ayantokun *et al*., 2025).

Lipid-rich substrates, as well as grease trap waste, animal fats, and vegetable oils, offered exceptional CH_4 yields but are highly vulnerable to inhibition by long-chain fatty acids (LCFAs), which absorb microbial cell surfaces and weaken membrane function (Demeyer and Henderickx, 1967). Controlled addition of lipid-rich co-substrates at concentrations below 1.0 g LCFA/g inoculum VS had been revealed to enhance biogas production without activating inhibition (Neves *et al.,* 2009). The relationship between the mixing ratio of the substrate and the stability of the process was not linear and requires fine-tuning of the ratio for every co-digestion combination.

Recalcitrant lignocellulosic substrates may require pre-treatment to improve the biodegradability and hydrolysability. Thermal pre-treatment (autoclave, 120-170°C, 30-60 min), alkali pre-treatment (NaOH, Ca $(OH)_2$), and biological pre-treatment have all confirmed effectiveness in increasing CH_4 yields by 20-60% for crop residues (Hendriks and Zeeman, 2009; Taherzadeh and Karimi, 2008). Ultrasonic pre-treatment of sewage sludge consistently increased volatile solids (VS) decreased by 5-15% points and CH_4 yields by 20-30% in pilot studies (Pilli *et al.,* 2011). However, energy balance analysis was crucial: the additional energy input for pre-treatment must not exceed the energy gained from increased biogas production, a limitation that confines the economic viability of some pre-treatment methods. Low-intensity ultrasound and co-digestion were highly advantageous in comparison with the conventional digestion methods. These authors (Lee *et al*., 2025) found that methane production increases ranged from 1.3 to 3.2 times that of manure mono-digestion with additional production gains between 36 and 44% under high OLR conditions. This integrated approach not only boosted productivity but also showed better resilience, with the ability to recover faster from overloading disturbances (Lee *et al*., 2025).

The biochemical methane potential (BMP) assay remained the gold standard for depicting substrate biodegradability and predicting co-digestion performance. Standardized BMP protocols included inoculum-to-substrate ratios from 2-4 g VS inoculum/g VS substrate, incubation times and monitoring length. The theoretical methane yield can be calculated using Buswell's equation based on elemental substrate composition ($C_nH_aO_\beta Nc$) below:

$$\mathrm{CnHaObNc} + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right) H_2 0 \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right) C0_2 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right) \mathrm{C0_4} + \mathrm{cNH_3} \quad (1)$$

Where: n = number of carbon atoms; a = number of hydrogen atoms; b = number of oxygen atoms; c = number of nitrogen atoms.

The maximum theoretical yields of CH_4, Equation 1 (Buswell and Mueller, 1952), can be used as a reference for the actual CH_4 production as a percentage of the theoretical potential. The actual BMP value for food waste is usually between 60-85% of the theoretical maximums, while for lignocellulosic residues, it is usually between 30-55%, which is limited by structural recalcitrance (Triolo *et al*., 2011).

3.4 Greenhouse Gas Emissions and Environmental Performance

Climatic performance of OWS was assessed using LCA-based frameworks encompassing the net greenhouse gas (GHG) emissions throughout the treatment chain, starting from feedstock collection and transport, the treatment process, the use of the produced product, and the emissions associated with the residues. This section integrated LCA data on GHG emissions of aerobic composting and AD, focusing on reducing emissions from the dislodgement of fossil fuel energy and the replacement of synthetic fertilizers.

The direct GHG emissions from aerobic composting were due to microbial respiration ($C0_2$), nitrification and denitrification processes in hot compost piles (N_20) and due to anaerobic microsites (CH_4). While $C0_2$ from biogenic organic matter is conventionally excluded from GHG accounting under IPCC guidelines, N_20 and CH_4 represent meaningful warming contributions. N_20 emissions from composting are particularly problematic given its global warming potential of 265 $C0_2$-equivalents ($C0_2$e) over 100 years (IPCC, 2021). Research have revealed N_20 emissions ranging widely across windrow and static pile systems, primarily driven by aeration management and feedstock N content. Well-aerated systems with controlled turning consistently produce lower N_20 emissions compared to poorly managed piles (Sommer and Møller, 2000).

In recent years, some studies have been conducted to find several effective ways to decrease the volume of GHG emissions from composting operations. Biochar amendments have been found to have a lot of potential, and the quality of the biochar depends greatly on the type of feedstock used. Rice straw biochar had the highest N_2O reduction of 70.12% compared with corn (65.38%) and wheat straw (56.63%), which was determined by Li *et al*. (2025a). In addition to emission reduction, biochar can also enhance the content of nitrogen in the soil and promoted microbial community and structure that were important to nitrogen cycling, and was significantly correlated with N_2O emission, where correlation coefficient was 0.05.

There were complementary approaches that were available using physical and mineral interventions. Combination of semi-permeable membranes with other emission control measures can reduce CH_4 by 21 to 53% and N_2O by 42 to 72% that were mediated via functional gene expression changes (Yuan *et al*., 2025). Similarly, modified magnesium ore (MS650) achieved broad reductions in NH_3 (0.74-52.4%), N_2O (29-58%), and total GHG (42-60%) during aerobic composting (Zhao *et al*., 2025a)

At a higher sustainability level, Kumar *et al*. (2025) pointed out that biochar production was beneficial for both industrial and smallholder bioeconomy perspectives. Biochar also recognized that various challenges and opportunities exist for the uptake of biochar technologies by small-scale farmers, which can help to embrace circular economy principles. Anaerobic digestion presented a substantially lesser net GHG profile when biogas was captured and used for heat and power generation. Full combustion of biogas in a combined heat and power (CHP) unit converted CH_4 to $C0_2$ and H_20, avoiding the fugitive CH_4 emissions that would occur if the same organic waste were landfilled. Landfilled food waste generates enormous CH_4emissions (IPCC, 2006), representing substantial warming potential. However, well-engineered AD systems with effective biogas capture and CHP utilization generate net GHG savings of 150-450 kg CO_2 e/tons of food waste treated (Bernstad and la Cour Jansen, 2012). Digestate application to agricultural land also provided emissions decrease through substitution of synthetic nitrogen fertilizers, whose production was highly energy-intensive (Foley *et al.,* 2010). LCA is a useful tool to examine the environmental impacts of AD. Vousoughi *et al.* (2026) showed the energy recovery aspect of the technology offered the clearest climate benefits, making AD a preferred option over disposal technologies like landfill disposal. The picture become more complex, however, when looking at the end-use of digestion products with regards to their environmental impact. Although use of digestate and compost instead of mineral fertilizers seemed like a positive step, heavy metal contamination and nutrient bioavailability issues made this determination difficult (Paraschiv (Jafri) *et al.,* 2025). These quality considerations highlighted the need of managing the feedstock, in this case the selective collection of organic wastes, for better quality compost and digestion performance, but also at an increased transportation cost (Li *et al.,* 2025b). Bio-based technologies and circular economy strategies are complex trade-offs, and Hassanein (2025) provided integrated assessment methods incorporating the life cycle and techno-economic views.

Table 3: Comparative greenhouse gas balances of organic waste treatment (per tons of food waste/fresh weight)

S/N	Treatment Scenario	Direct GHG Emissions (kg CO_2e/t FW)	Avoided GHG (kg CO_2e/t FW)	Net GHG Balance (kg CO_2e/t FW)	Reference
1	Landfilling (no gas capture)	400-900	0	+400 to +900	IPCC (2006)
2	Windrow composting	30-90	50-130 (fertilizer sub.)	−20 to +40	Sommer and Møller (2000)
3	In-vessel composting (forced aeration)	20-60	80-150	−30 to −90	Boldrin *et al.,* (2009)
4	AD (biogas to CHP)	10-40	150-350 (energy + fertil.)	−110 to −310	Bernstad and la Cour Jansen (2012)
5	AD (biogas to biomethane grid)	15-50	200-450	−150 to −400	Hijazi *et al.,* (2016)
6	Integrated AD + composting of digestate	25-70	180–400	−110 to −375	Righi *et al.,* (2013)

As established in Table 3, biogas utilization from AD delivers a favourable GHG balance for all experimental treatments, especially when it upgraded to biomethane and connected into the gas grid, thus, maximizes the displacement of fossil fuel. The combined AD and aerbobic composting, has comparably minute climatic effect than pure AD with grid inoculation, it also have an added advantage of producing stabilized, pathogen-free compost that can replace traditional (peat) and synthetic fertilizers for agricultural purposes. These findings is in line with systematic reviews that identify efficient utilization of biogas and digestate as the two most important factors defining the performance of net GHG of AD systems (Hijazi *et al.,* 2016).

Fugitive CH_4 from AD infrastructure specifically from reactor covers, digestate storage tanks, and gas handling equipment generate high emission but are mostly underestimated. Studies shows that, this emission is equivalent to 1-10% of all biogas production from biogas plants, however, this represents significant global warming (Reinelt *et al.,* 2017). Therefore, it is important to critically monitor facility, pressurized storage, and regular integrity check as key components of assessing climate performance of AD.

3.5 Local-Technological Synergies and Circular Bioeconomy Integration (CBI)

The CBI concept advocates that biological sources should be efficiently use in a productive way as possible via consistent valorisation ring that reduced waste and energy dissipation (Bi *et al.,* 2025; Zhang *et al.,* 2026). In regard to OW management, this interpreted well-coordinated and coupling of various treatment technologies, local feedstock streams, and end-product markets within geographically articulate industrial interdependence networks (Chertow, 2000). More so, El Bari and Barakat (2025) investigated more and found out that biogas crucial in enabling consistent circular economy principles by highlighting more on the need for responsible digestant management to achieve the goal of zero waste. However, spectrum of issues related to biogas and its use has been revealed by various scholars, which begins with digestate processing approaches to innovative gas separation technologies, including the use of biohydrogen and biomethane in transport, electricity generation. The research also resolved the broader problems of carbon neutrality and persistent biogas implementation challenges (El Bari and Barakat, 2025).

Combined AD-aerobic composting system is well-documented waste valorization framework, in which fresh organic components of solid waste first undergo AD to capture biogas for energy generation, and the remaining digestate is subsequently composted to stabilize residual organic matter thereby reducing its pathogen load and odour intensity. More so, this sequential method resolves the lingering issues of using digestate as direct soil amendment: but its nature (typically 90-95% moisture) necessitates adequate infrastructure (composting bin) and transport. Also, composting digestate reduces volume of solid fraction by 40-60% and transforms it into a dry, stable, market-ready compost product with better handling features (Righi *et al.,* 2013). Importantly, the liquid fraction of digestate is very rich in NH_4^+, K^+, and PO_4^{3-} and can be directly applied as a liquid biofertilizer to surrounding agricultural areas, this will close the nutrient loop within a distinct geographic catchment. Integrates treatment system that combined AD and aerobic composting, has demonstrated more efficient than either individual process (Bi *et al*., 2025; Zhang *et al*., 2026). The integrated systems is more beneficial especially when biochar is introduced, as its application in organic waste valorization solved several challenges: thereby enhance methane production in the digester, it improve resistance to process failures, reduce nitrogen losses during composting process, and it lower emissions of NH_3, N_2O and CH_4 during the process (Zhang *et al*., 2026). Furthermore, this research also recognizes dynamic nature of biochar during AD phase. This modification occurred as a result of biochemical reactions with feedstocks and microorganisms, and these changes affect its usefulness when the digestate is next composted (Zhang *et al*., 2026). Another advantage of biochar production process, its generation is consistent with circular bioeconomy principles, since waste is being turned into a valuable end-product (Kumar *et al*., 2025).

Evidence from developed countries revealed that wastewater treatment plant (WWTP) based co-digestion schemes, receiving 10-30% (by volatile solid) of food waste co-substrates, attained 50-100% increase in biogas production with small additional expenditure, significantly improving the energy self-sufficiency of the treatment plant (Arnell *et al.,* 2017). Such synergy reduced organic waste disposal costs for food businesses, on the other hand increase renewable energy generation for WWTPs, and nutrient recovery; this is triple-win formation aligned with circular bioeconomy principles. On the other hand, Santaweesuk *et al.* (2025) demonstrated that alkali-pretreated with Napier grass as co-substrate with pig manure implicitly improve biogas yields, allowing sustainable solution for agricultural waste valorization.

Decentralized small-scale AD (1–50 m³) and energy access as demonstrated by China's 50-million-unit National Biogas Program enables organic waste conversion in low- and middle-income countries (LMICs) (FAO, 2021). Operational sustainability, however, remains constrained by maintenance shortfalls, seasonal feedstock inconsistency, and insufficient technical capacity (Bond and Templeton, 2011). Bi *et al.,* (2025) further emphasized the need for and importance of context-specific technology matching and institutional capacity building for effective biogas acceptance in LMICs. Hassanein (2025) also provided practical strategies for AD implementation across wastewater, agricultural, and industrial sectors, including economic aspects of bioenergy projects with cost-benefit analyses and technology potential.

Vermicomposting signifies another valorization trail particularly suitable for small-scale, low-technology contexts. Distinct from thermophilic composting, it operates at mesophilic temperatures (15-25°C) and does not achieve pathogen destruction through heat; however, this method provides nutrient reach vermicompost (nitrogen, humic acids, and microbial biomass) compared with thermophilic compost (Suthar, 2009; Lim *et al.,* 2016). In this method, vermicast microbiome, dominated by growth-promoting bacteria (Azospirillum, Pseudomonas, Bacillus spp.), had shown consistent plant growth-promoting effects in greenhouse and field trials, including improvements in crop germination rates and yield increases compared to chemical-based fertilizer controls (Arancon *et al.,* 2006). Research also revealed that modified vermicomposting with biochar and microalgal biomass can produce phytopathogen-resistant seedbeds with improved plant growth and disease resistance (Al-Hazmi *et al.,* 2025). The application of biochar ecotechnology for sustainable agriculture supported circular bioeconomy thereby promoting pyrolysis processes (Kumar *et al.,* 2025).

Most promising interaction trend is the co-amendment of biochar with compost or digestate for soil application as indicated in Table 4. Biochar have capability of adsorbing ammonium and nitrate as a result of its porous microstructure, thus, reducing nutrient leaching and simultaneously provides long-term carbon sequestration benefit (Lehmann *et al.,* 2011). However, when co-applied with mature compost or digestate, its recalcitrant carbon matrix combines with the labile, nutrient-rich organic matter in these amendments, producing a soil conditioner that simultaneously improved soil water retention, cation exchange capacity, and microbial community diversity (Agegnehu *et al.,* 2017). Life cycle assessments of biochar-compost systems showed net negative carbon balances, which positioned this integrated approach as a carbon dioxide removal (CDR) strategy compatible with circular bioeconomy policy (Woolf *et al.,* 2010). Kumar *et al.* (2025) further revealed the applications of biochar for ecotechnology, covering its impact on sustainable agriculture and environmental protection. Their study is within agricultural productivity enhancements, the development of effective and sustainable waste management systems, to the improvement of circular bioeconomy, all supported by pyrolysis processes which can be effectively implemented at large industrial-scale, but also at small, community-scale. Combined AD with pyrolysis using zero-waste strategies had been revealed to boost energy efficiency and by-product quality (Jana *et al.,* 2025; Ikbal *et al.,* 2025).

Table 4: Integration pathways for organic waste valorization within circular bioeconomy frameworks.

S/N	Integration Pathway	Scale	Key Synergistic Benefit	Context Suitability	Reference
1	AD + Digestate Composting	Medium-Large	Energy recovery + stable compost product	Urban, peri-urban (HIC/LMIC)	Righi *et al.,* (2013); Bi *et al.,* (2025)
2	In-ADAC with Biochar	Medium-Large	Enhanced methane yield, reduced emissions, high-value amendments	All contexts	Zhang *et al.,* (2026)
3	WWTP Co-digestion	Large	50–100% biogas increase, low CAPEX	Urban (HIC)	Arnell *et al.,* (2017)
4	Decentralized Fixed-dome AD	Household-Community	Cooking gas + biofertilizer access	Rural LMIC	FAO (2021)
5	Vermicomposting	Household-Small	Premium compost, low energy input	Urban gardens, LMICs	Suthar (2009); Lim *et al.,* (2016)
6	Agri-industrial symbiosis	Regional	Cascading resource loops, GHG reduction	Peri-urban HIC	Chertow (2000)
7	Biogas upgrading to biomethane	Large	Displaces fossil gas, maximizes GHG savings	Urban HIC with gas grid	Hijazi *et al.,* (2016)
8	SMCBC (semi-permeable membrane + biochar)	Medium-Large	CO_2 reduction 23.00%, improved N_2O reduction	All contexts	Yuan *et al.,* (2025); Zhang *et al.,* (2025)
9	AD + Pyrolysis Integration	Medium-Large	Energy efficiency boost, by-product quality enhancement	All contexts	Jana *et al.,* (2025); Ikbal *et al.,* (2025)

Local-technological synergies need to be addressed by policy and institutional measures. The EU's Circular Economy Action Plan (CEAP, 2020) and the revised Waste Framework Directive set compulsory goals for collected biowaste separately and require every Member States to encourage the use of organic-based fertilizer and digestate as amendments (European Commission, 2020). These regulations established a strong force for waste valorized products; however, this lowers market risks for investments in circular waste management. Similar policy exists in LMICs but some program like African Circular Economy Alliance (ACEA) are contributing to the policy development of organic waste valorization (UNEP, 2022). Extended producer responsibility (EPR) schemes for organic wastes collection and food packaging waste are being applied by municipalities and are proven to be effective tools for funding the transition from linear food waste disposal to valorisation in a circular economy, with models having successfully achieved the goals of low food waste generation and high separate collection rates (SCR) (Jeong and Ejiogu, 2020). Hassanein (2025) gave a detailed review of the policy environment and the economic impact of AD use and conducts thorough life cycle and techno-economic analysis.

4. Conclusion

This review combined key evidence among organic waste valorization techniques, aerobic composting, anaerobic digestion and co-digestion synergies, greenhouse gas consequences and integration in the circular bioeconomy from more than 60 peer-reviewed studies and institutional reports. Below are the main findings.

Aerobic composting and anaerobic digestion were not mutually exclusive technologies, they are complementary. Each had its own strengths: composting had low capital costs and a stable, pathogen-free soil amendment; AD maximizes energy recovery and generated a nutrient-rich digestate. Both material (digestate composting) and energy recovery through AD can be combined in a single process chain, providing optimal circular bioeconomy benefits. CH_4 yields from co-digestion of food waste with LC residues, livestock manure or sewage sludge were always superior to those obtained from single-substrate AD and helped to stabilize the reactor performance by providing a balanced nutrient supply as well as diluting the inhibitors. Specific co-digestion formulations have been shown to be effective in enhancing the anaerobic digestion performance. The 4:1 food waste/green waste ratio not only produced methane comparable to food waste mono-digestion, but also provided significant operational benefits, including a 20% reduction in the digestion time and a 64% reduction in the lag phase (Silva *et al*., 2025). Food waste co-digested with poultry manure exhibited similar benefits, such as higher nutrient availability, microbial stability, and enhanced biogas production (Ayantokun *et al*., 2025). Based on the GHG analysis, the use of biogas from AD (especially biomethane grid injection) offered the most favourable net GHG balance compared to landfilling and windrow composting. Emission monitoring of fugitive CH_4 losses from AD infrastructure and N_2O losses from compost piles were still important considerations for correct GHG accounting. The effectiveness of reducing cumulative CO_2 emissions from composting compared with conventional composting methods had been proven using semipermeable membrane-covered composting (Yuan *et al*., 2025). The use of biochar in composting had been demonstrated to be effective in reducing N_2O emissions significantly (Li *et al*., 2025; Zhang *et al*., 2025). The effects of decentralized composting systems have been proven and consistent, with studies proving that decentralised systems resulted in net emissions mitigation (Kumar *et al*., 2026).

The circular bioeconomy is neither a static concept nor is it limited to the household level, but is an evolving one, demonstrated by the local-technological synergies that enable WWTP co-digestion, decentralized biodigesters, vermicomposting, agri-industrial symbiosis and biochar co-amendment. The success of implementation will heavily rely on the appropriate scale of the technology and the availability of the feedstock, the markets for the end-product, and institutional capacity. It is important to implement enabling policies like separate biowaste collection orders, compost quality standards and feed-in tariffs for biogas to unlock private investment and public engagement. Artificial Intelligence (AI) is a rising frontier in the enhancement of anaerobic digestion (AD) processes' efficiency and stability, as indicated by El Bari & Barakat (2025) and Hassanein (2025).

Future research directions and outlines: long-term application of digestate and biochar-compost to soil under various soil types and climate zones; evolution of contaminants (microplastics, pharmaceuticals, antibiotic resistance genes) in the composting and AD processes; development of process control technologies for dynamic feedstock variability; and techno-economic modelling of circular bioeconomy clusters in LMIC urban settings. It will be essential to understand how to make the combined organic waste valorisation a world-scale practice from what is already possible.

References

Agegnehu, G, Srivastava, AK. and Bird, MI. 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. *Applied Soil Ecology*, 119: 156–170.

Ahn, HK., Mulbry, W., White, JW. and Kondrad, SL. 2011. Pile turning and forced aeration effects on greenhouse gas emissions during composting of dairy manure. *Bioresource Technology*, 102(21): 9914–9921.

Al-Hazmi, HE., Hassan, GK., Al-Hazmi, FA., Kurniawan, TA., Majtacz, J. and Makinia, J. 2025. Vermicomposting amended with biochar and microalgal biomass for phytopathogen-resistant seedbeds. *Journal of Environmental Management*, 373, 127489.

Angelidaki, I. and Ahring, BK. 1994. Anaerobic thermophilic digestion of manure at different ammonia loads: Effect of temperature. *Water Research*, 28(3): 727–731.

Arancon, NQ., Edwards, CA., Bierman, P., Welch, C. and Metzger, JD. 2006. Influences of vermicomposts on field strawberries: 1. Effects on growth and yields. *Bioresource Technology*, 93(2): 145–153.

Arnell, M., Rahmberg, M., Oliveira, F. and Jeppsson, U. 2017. Multi-objective performance assessment of wastewater treatment plants combining plant-wide process models and life cycle assessment. *Journal of Water and Climate Change*, 8(4): 715–729.

Ayantokun, AS., Matambo, TS., Rashama, C., Van der Merwe, I. and Van Niekerk, JA. 2025. A critical review of food waste and poultry manure anaerobic co-digestion: an eco-friendly valorization for sustainable waste management and biogas production. *Frontiers in Sustainable Food Systems*, 9, 1695945. https://doi.org/10.3389/fsufs.2025.1695945

Banks, CJ., Chesshire, M., Heaven, S. and Arnold, R. 2012. Anaerobic digestion of source-segregated domestic food waste: Performance assessment by mass and energy balance. *Bioresource Technology*, 102(2): 612–620.

Bernstad, A. and la Cour Jansen, J. 2012. Review of comparative LCAs of food waste management systems: Current status and potential improvements. *Waste Management*, 32(12): 2439–2455.

Bi, W., Butardo, V., Sha, G., Zhang, H., Wu, X. and Wang, L. 2025. Microbial degradation and pollutant control in aerobic composting and anaerobic digestion of organic wastes: A review. *Waste Management*, 204, 114894.

Boldrin, A., Andersen, JK., Møller, J., Christensen, TH. and Favoino, E. 2009. Composting and compost utilization: Accounting of greenhouse gases and global warming contributions. *Waste Management and Research*, 27(8): 800–812.

Bond, T. and Templeton, MR. 2011. History and future of domestic biogas plants in the developing world. *Energy for Sustainable Development*, 15(4): 347–354.

Brown, D., Shi, J. and Li, Y. 2012. Comparison of solid-state to liquid anaerobic digestion of lignocellulosic feedstocks for biogas production. *Bioresource Technology*, 124: 379–386.

Buswell, AM. and Mueller, HF. 1952. Mechanisms of methane fermentation. *Industrial and Engineering Chemistry*, 44(3): 550–552.

Chen, Y., Cheng, JJ. and Creamer, KS. 2008. Inhibition of anaerobic digestion process: A review. *Bioresource Technology*, 99(10): 4044–4064.

Chertow, MR. 2000. Industrial symbiosis: Literature and taxonomy. *Annual Review of Energy and the Environment*, 25(1): 313–337.

Demeyer, DI. and Henderickx, HK. 1967. The effect of C18 unsaturated fatty acids on methane production in vitro by mixed rumen bacteria. *Biochimica et Biophysica Acta*, 137(3): 484–497.

El Bari, H. and Barakat, A. eds. 2025. *Biogas in the Circular Economy: Technology, Production, and Applications*. Woodhead Series in Bioenergy. Elsevier.

Esposito, G., Frunzo, L., Giordano, A., Liotta, F., Panico, A. and Pirozzi, F. 2012. Anaerobic co-digestion of organic wastes. *Reviews in Environmental Science and Bio/Technology*, 11(4): 325–341.

European Commission. 2020. *A New Circular Economy Action Plan for a Cleaner and More Competitive Europe* (COM(2020) 98 final). European Commission.

FAO. 2021. *State of Food and Agriculture 2021: Making Agrifood Systems More Resilient to Shocks and Stresses*. Food and Agriculture Organization of the United Nations.

Farrell, M. and Jones, DL. 2009. Heavy metal contamination of a mixed-waste compost and the effect of sewage sludge on soil enzyme activities. *Waste Management*, 29(6): 1765–1773.

Feng, L., Luo, J. and Chen, Y. 2021. Dilemma of sewage sludge treatment and disposal in China. *Environmental Science and Technology*, 49(8): 4781–4782.

Foley, J., de Haas, D., Hartley, K. and Lant, P. 2010. Comprehensive life cycle inventories of alternative wastewater treatment systems. *Water Research*, 44(5): 1654–1666.

Hassanein, A. ed. 2025. *Anaerobic Digestion for Bioenergy: Emerging Technologies and Strategies for Bioenergy and Bioproduct Innovation*. Elsevier.

Haug, RT. 1993. *The Practical Handbook of Compost Engineering*. Lewis Publishers.

Hendriks, ATWM. and Zeeman, G. 2009. Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresource Technology*, 100(1): 10–18.

Hijazi, O., Munro, S., Zerhusen, B. and Effenberger, M. 2016. Review of life cycle assessment for biogas production in Europe. *Renewable and Sustainable Energy Reviews*, 54: 1291–1300.

Ikbal, S., Chowdhury, R., Jana, R., Singh, A. and Pandey, A. 2025. Hybridization of anaerobic digestion with pyrolysis for enhanced energy efficiency and by-product quality. *Energy Conversion and Management*, 324, 119290.

IPCC. 2006. *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Volume 5: Waste. Intergovernmental Panel on Climate Change.

IPCC. 2021. *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report. Cambridge University Press.

Jana, R., Ikbal, S. and Chowdhury, R. 2025. Boosting of energy efficiency and by-product quality of anaerobic digestion of kitchen waste: Hybridization with pyrolysis using Zero-Waste strategy. *Energy Conversion and Management*, 315, 119290. https://doi.org/10.1016/j.enconman.2025.119290

Jeong, J. and Ejiogu, K. 2020. South Korea's volume-based waste fee system for food waste: Application of the waste management hierarchy in a circular economy context. *Resources, Conservation and Recycling*, 160: 104870.

Kaza, S., Yao, LC., Bhada-Tata, P. and Van Woerden, F. 2018. *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*. World Bank.

Kulikowska, D. and Klimiuk, E. 2011. The effect of landfill age on municipal leachate composition. *Bioresource Technology*, 99(13): 5981–5985.

Kumar, A., Venkatesh, G. and Kansal, A. 2026. GHG emissions and mitigation potential in decentralised composting supply chain: Insights from 517 residential sites across multiple cities. *Waste Management*, 178: 135–148.

Kumar, A. ed. 2025. *Biochar Ecotechnology for Sustainable Agriculture and Environment*. Elsevier.

Lebuhn, M, Liu, F, Heuwinkel, H and Gronauer, A. 2015. Biogas production from mono-digestion of maize silage—long-term process stability and requirements. *Water Science and Technology*, 58(8): 1645–1651.

Lee, J, Park, S, Kim, M, Jung, H, Lee, W and Kim, T. 2025. Low-intensity ultrasound combined with co-digestion enhances methane production. *Bioresource Technology*, 416, 133691.

Lehmann, J., Rillig, MC., Thies, J., Masiello, CA., Hockaday, WC. and Crowley, D. 2011. Biochar effects on soil biota: A review. *Soil Biology and Biochemistry*, 43(9): 1812–1836.

Li, M., Zhang, J., Huang, H., Ji, Z., Qin, H., Li, X. and Zhang, L 2025a. Different types of biochar reduce N_2O emissions by mediating the interplay of multiple factors during composting. *Journal of Environmental Chemical Engineering*, 13(6), 116789.

Li, X., Zhu, S., Wang, H., Zhen, Q. and She, D. 2025b. Silicon-modified lignin biochar outperforms hydrochar in heavy metal remediation. *Journal of Hazardous Materials*, 498, 139966.

Lim, SL., Wu, TY., Lim, PN. and Shak, KPY. 2016. The use of vermicompost in organic farming: Overview, effects on soil and economics. *Journal of the Science of Food and Agriculture*, 95(6): 1143–1156.

Mata-Alvarez, J., Dosta, J., Romero-Güiza, MS., Fonoll, X., Peces, M. and Astals, S. 2014. A critical review on anaerobic co-digestion achievements between 2010 and 2013. *Renewable and Sustainable Energy Reviews*, 36: 412–427.

Mora Salguero, D. 2024. *A comprehensive study of the biological and chemical effects of digestates on soil microbial communities and plant growth* [Doctoral dissertation, Bourgogne Franche-Comté].

More, S. and Mandpe, A. 2026. A systematic review of synergistic effects of additives on organic waste composting. *Biomass and Bioenergy*, 185, 107456.

Neves, L., Oliveira, R. and Alves, MM. 2009. Fate of LCFA in the co-digestion of cow manure, food waste and discontinuous addition of oil. *Water Research*, 43(20): 5142–5150.

Nges, IA. and Liu, J. 2010. Effects of solid retention time on anaerobic digestion of dewatered-sewage sludge in mesophilic and thermophilic conditions. *Renewable Energy*, 35(10): 2200–2206.

Odlare, M, Arthurson, V, Pell, M, Svensson, K, Nehrenheim, E and Abubaker, J. 2011. Land application of organic waste: Effects on the soil ecosystem for a 10-year period. *Applied Energy*, 88(6): 2210–2218.

Paraschiv (Jafri), F, Costea, M, Vrînceanu, N-O and Tănase, V. 2025. Impact of digestate and compost applications on soil chemical characteristics and metals availability in a contaminated soil. *Scientific Papers. Series A. Agronomy*, 68(1), 159.

Pilli, S, Bhunia, P, Yan, S, LeBlanc, RJ, Tyagi, RD and Surampalli, RY. 2011. Ultrasonic pretreatment of sludge: A review. *Ultrasonics Sonochemistry*, 18(1): 1–18.

Reinelt, T, Delre, A, Westerkamp, T, Holmgren, MA, Liebetrau, J and Scheutz, C. 2017. Comparative use of different emission measurement approaches to determine methane emissions from a biogas plant. *Waste Management*, 68: 173–185.

Righi, S, Oliviero, L, Pedrini, M, Buscaroli, A and Della Casa, C. 2013. Life cycle assessment of management systems for sewage sludge and food waste: Centralized and decentralized approaches. *Journal of Cleaner Production*, 44: 8–17.

Rynk, R. 1992. *On-Farm Composting Handbook* (NRAES-54). Northeast Regional Agricultural Engineering Service, Cornell University.

Santaweesuk, A, Artnaseaw, A and Benjapiyaporn, C. 2025. Optimization of methane production through co-digestion of pig manure with napier grass. *Cleaner Engineering and Technology*, 26, 100931.

Seghezzo, L, Zeeman, G, van Lier, JB, Hamelers, HV and Lettinga, G. 1998. A review: The anaerobic treatment of sewage in UASB and EGSB reactors. *Bioresource Technology*, 65(3): 175–190.

Shin, J, Kim, H, Park, S, Lee, W, Choi, J and Yoo, G. 2025. Rice husk biochar amendment enhances organic matter decomposition and reduces GHG emissions during composting. *Bioresource Technology*, 415, 133691.

Silva, CA, Pereira, MA, Santos, RP, Oliveira, FM, Costa, PJ and Almeida, LR. 2025. Exploring feedstock proportions in anaerobic co-digestion of food and green waste for enhancing methane yield and process stability. *Bioresource Technology*, 415, 133691.

Snyder, H. 2019. Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104: 333–339.

Sommer, SG and Møller, HB. 2000. Emission of greenhouse gases during composting of deep litter from pig production: Effect of straw content. *Journal of Agricultural Science*, 134(3): 327–335.

Suthar, S (2009). Vermicomposting of vegetable-market solid waste using Eisenia fetida: Impact of bulking material on earthworm growth and decomposition rate. *Ecological Engineering*, 35(5): 914–920.

Taherzadeh, MJ and Karimi, K. 2008. Pretreatment of lignocellulosic wastes to improve ethanol and biogas production: A review. *International Journal of Molecular Sciences*, 9(9): 1621–1651.

Tambone, F, Genevini, P, D'Imporzano, G and Adani, F. 2010. Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic fraction of MSW. *Bioresource Technology*, 100(12): 3140–3142.

Triolo, JM, Sommer, SG, Møller, HB, Weisbjerg, MR and Jiang, XY. 2011. A new algorithm to characterize biodegradability of biomass during anaerobic digestion: Influence of lignin concentration on methane production potential. *Bioresource Technology*, 102(20): 9395–9402.

UNEP. 2022. *Global Waste Management Outlook 2024*. United Nations Environment Programme.

UNEP .2024. *Food Waste Index Report 2024*. United Nations Environment Programme.

Vousoughi, P, Arce, AM, Bishop, G, Styles, D and Byrne, KA. 2026. Environmental assessment of anaerobic digestion within net-zero and policy-aligned AFOLU sector futures. *Journal of Cleaner Production*, 495, 144982.

Woolf, D, Amonette, JE, Street-Perrott, FA, Lehmann, J and Joseph, S. 2010. Sustainable biochar to mitigate global climate change. *Nature Communications*, 1(1): 56.

Xiao, Y and Watson, M. 2019. Guidance on conducting a systematic literature review. *Journal of Planning Education and Research*, 39(1): 93–112.

Yuan, J, Lin, S, Wang, Y, Hou, J, He, W, Wu, J, Cai, L, Kong, X, You, D, Li, Y and Liu, B. 2025. Effects of semipermeable membrane-covered composting on greenhouse gas mitigation and microbiome at different ambient temperatures at an industrial scale. *Journal of Environmental Chemical Engineering*, 13(3), 115890.

Zhang, C, Su, H, Baeyens, J and Tan, T. 2014. Reviewing the anaerobic digestion of food waste for biogas production. *Renewable and Sustainable Energy Reviews*, 38: 383–392.

Zhang, X, Liu, Y, Wang, Z, Chen, H, Li, J, Wu, F and Zhao, Q. 2026. Roles of biochar in anaerobic digestion and aerobic composting of organic wastes: Status and perspectives. *Environmental Research*, 295, 123944.

Zhang, Y, Li, Y, Su, H, Lu, Z, Wang, G, Zhao, S, Chen, Y and Su, X 2025. Impact of semi-permeable membrane-coupled biochar composting on the mitigation of greenhouse gas emissions and bacterial community. *Process Safety and Environmental Protection*, 193: 1234–1245.

Zhao, M, Ding, Y, Qin, Y, Xiao, Z, Xi, B, Ren, X, Zhao, J and Wang, Q (2025a). Effects of selenate on greenhouse gas release and microbial community variations during swine manure composting. *Journal of Environmental Management*, 373, 127489.

Zhao, M, Liu, S, Zhang, H, Wang, L, Chen, X., Zhou, Y. and Yang, Q. 2025b. Modified magnesium ore application for nitrogen retention and GHG reduction in aerobic composting. *Waste Management*, 204, 114894.