

Review

Advancements in Food Waste Recycling Technologies in South Africa: Novel Approaches for Biofertilizer and Bioenergy Production—A Review

Samukelo Zwelokuthula Mngadi, Emmanuel Kweinor Tetteh ^{*}, Siphesihle Mangena Khumalo and Sudesh Rathilal 

Green Engineering Research Group, Department of Chemical Engineering, Faculty of Engineering and the Built Environment, Durban University of Technology, Steve Biko Road, Durban 4001, South Africa

* Correspondence: emmanuelk@dut.ac.za

Abstract

Globally, tons of agricultural and food waste are inevitably produced daily due to increasing population demands. As fertilizer prices surge and environmental degradation worsens, sustainable farming practices are gaining attention, especially with circular economic principles. This study explores how food waste can be repurposed into biofertilizers and bioenergy using advanced technologies like anaerobic digestion, composting, pyrolysis, and heat treatment. These methods are evaluated for their effectiveness in recovering essential nutrients (nitrogen, phosphorus, and potassium) and generating energy, alongside their sustainability and cost-effectiveness. Data trends reveal a significant rise in studies focused on “circular economy” and “food waste valorization.” Early findings highlight anaerobic digestion and composting as the most practical approaches, offering efficient nutrient recovery and minimal greenhouse gas emissions. Overall, the integration of food waste recycling with sustainable agricultural practices presents a powerful path toward mitigating environmental impact, lowering fertilizer costs, and supporting global food security through circular economic solutions.



Academic Editor: Gianluca Cavalaglio

Received: 8 August 2025

Revised: 25 September 2025

Accepted: 3 October 2025

Published: 13 October 2025

Citation: Mngadi, S.Z.; Tetteh, E.K.; Khumalo, S.M.; Rathilal, S. Advancements in Food Waste Recycling Technologies in South Africa: Novel Approaches for Biofertilizer and Bioenergy Production—A Review. *Energies* **2025**, *18*, 5396. <https://doi.org/10.3390/en18205396>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: circular economy; food waste valorization; sustainable fertilizers; nutrient recovery; anaerobic digestion

1. Introduction

Globally, food waste (FW) is currently one of the most frequently generated types of biowaste. Food production, processing, distribution, and consumption are the primary drivers of global food waste generation [1]. Negative-emission technologies (NETs) have acquired substantial attention as a potential strategy for mitigating climate change. The target of the Paris Agreement confirmed this to limit the global temperature rise to less than 2 °C by utilizing these technologies [2]. In response to the increasing demands of a growing global population, substantial quantities of agricultural waste (AW) are generated daily. According to the Food and Agriculture Organization (FAO), approximately 1.3 billion tonnes of food are discarded each year [3]. Given the detrimental impacts of such waste on ecological systems, economic stability, and social well-being, a growing body of research has been dedicated to exploring effective strategies for its management [4]. Each year, the global production of fresh fruit amounts to millions of tons, resulting in substantial volumes of food waste. As a result, managing this waste has emerged as a worldwide concern, emphasized in

Sustainable Development Goal 12 (SDG 12), specifically under target 12.5 [5]. Inadequate waste management can result in an environment that is not conducive, such as one that allows flies, vermin, and rats to thrive, which could exacerbate poor health outcomes in communities [6]. In South Africa and most parts of the globe, local municipalities are responsible for the waste management function provided to communities, as well as to retail markets, which fall under their jurisdiction. The National Environmental Management Act: Waste Act (Act No. 59 of 2008), hereafter referred to as The Waste Act, delegates the responsibility of waste management to local government bodies [7]. In the South African context, landfills receive approximately 12.7 million tons of organic waste annually, with 90% of it untreated [8].

Globally, there is a growing research interest in converting food waste into biofertilizers, reflecting a shift toward sustainable resource recovery and agricultural innovation. [9]. Efforts to estimate the volume of food waste worldwide have spanned several decades, driven by the need to highlight its contribution to global malnutrition. These estimates are typically based on limited and fragmented data collected at various stages of the food supply chain and subsequently scaled up to reflect broader trends. When the FAO was established in 1945, one of its core objectives was to combat hunger on a global scale [10]. Food wastage occurs at various stages of the supply chain, with manufacturers contributing approximately 2%, farms accounting for 16%, restaurants and food services responsible for 40%, and households generating the largest share at 42% [11]. Within industrial settings, food waste, both solid and liquid, is typically confined to production facilities and tends to exhibit greater consistency in composition. Although the proportion from manufacturers appears relatively small, the absolute volume remains substantial. Consequently, developing valorization strategies for these waste streams holds potential for broader application across other waste categories. Inadequate systems for waste collection and disposal, combined with poorly sited treatment facilities, pose significant risks to public health and contribute substantially to environmental degradation. These shortcomings exacerbate climate change and lead to the contamination of air, land, and water resources. Globally, the volume of waste generated is on a steep upward trajectory, with projections indicating an increase from 3.5 million tonnes per day in 2010 to over 6 million tonnes by 2025 [12]. Tackling foundational limitations such as workforce efficiency, technical competencies, and capacity building can significantly reduce waste generation at its source. Subsequent phases involving technological advancement, infrastructural development, and facility optimization can then be strategically utilized to curtail waste output further [13]. Household waste typically falls into two broad categories. The first category comprises non-biodegradable materials, such as plastics, metals, and glass, as well as various domestic items that do not decompose naturally. The second category includes biodegradable substances, such as food scraps, vegetable and fruit peels, dried foliage, and garden refuse. Organic waste from plants and animals, including degradable carbon-based matter, also belongs to this group due to its capacity to break down through natural processes [14]. Effectively handling vast volumes of waste in an environmentally responsible manner remains a persistent and unresolved issue across global economies.

On the other hand, food waste degradation offers a sustainable solution to environmental challenges. By converting organic waste into energy and fertilizers, it contributes to the creation of a circular economy. Technologies that convert organic waste into a precious product include thermal, biological, and thermochemical methods [15]. Composting is also one of the widely used technologies, which is an aerobic process that transforms biological waste into humus for plant cultivation and sanitation. However, it has lost competition to anaerobic digestion (AD), which produces biogas for electricity generation [16]. Among the numerous valorization strategies, AD has emerged as the most promising technology for handling organic waste. Nonetheless, AD facilities face the critical challenge of sustainably maximizing nutrient recovery and recycling from the resulting digestate [17].

It is worth noting that among emerging technologies, hydrothermal liquefaction (HTL) has gained prominence as a thermochemical pathway for converting wet biomass into valuable products under subcritical water conditions (typically 200–374 °C and 5–25 MPa) without the need for prior drying [18]. While HTL is traditionally optimized for bio-crude production, recent studies [19–21] have highlighted its potential for generating nutrient-rich hydrochar and aqueous phases suitable for biofertilizer applications. HTL facilitates the breakdown of complex organic compounds in food waste, such as proteins, carbohydrates, and lipids, into smaller molecules. This process yields three primary fractions: bio-crude oil, aqueous phase, and solid residue (hydrochar) [18]. The aqueous phase and hydrochar are particularly relevant for biofertilizer development due to their enriched content in nitrogen (N), phosphorus (P), and humic substances. According to Wang et al. [18], the transformation of nitrogenous compounds during HTL leads to the formation of protein-derived nitrogen (PN) and inorganic nitrogen species, while phosphorus is released in both organic and inorganic forms. These nutrients, when stabilized in hydrochar or solubilised in the aqueous phase, can be harnessed as plant-available fertilizers. Moreover, the formation of humic acids and fulvic acids under alkaline HTL conditions enhances the agronomic value of the hydrochar, improving soil structure and nutrient retention. However, challenges remain in scaling the technology and ensuring the environmental safety of the products. The presence of potentially toxic compounds in the aqueous phase necessitates thorough characterization and treatment before land application [18,22].

This review provides a comprehensive synthesis of emerging food waste recycling technologies in South Africa, with a particular focus on their potential to generate biofertilizers and bioenergy within a circular economy framework. It critically evaluates thermochemical and biochemical pathways, including anaerobic digestion, pyrolysis, and composting, highlighting their applicability to local waste streams and socio-economic contexts. The study also discusses pre-treatment processes associated with biofertilizer production from food waste material. The review contributes insights by mapping the technological landscape of food waste valorization in South Africa, identifying region-specific challenges such as infrastructure gaps, policy limitations, and feedstock variability. The review also contributes to showcasing approaches for nutrient recovery and energy generation. By reclaiming nutrients from agricultural food waste and converting them into soil-applied fertilizers, the reliance on fossil-based inputs can be reduced, while simultaneously minimizing landfill disposal [16]. A growing body of literature advocates for the adoption of circular economy principles to address food waste challenges, as illustrated by publication trends in the South African context in Figures 1 and 2.

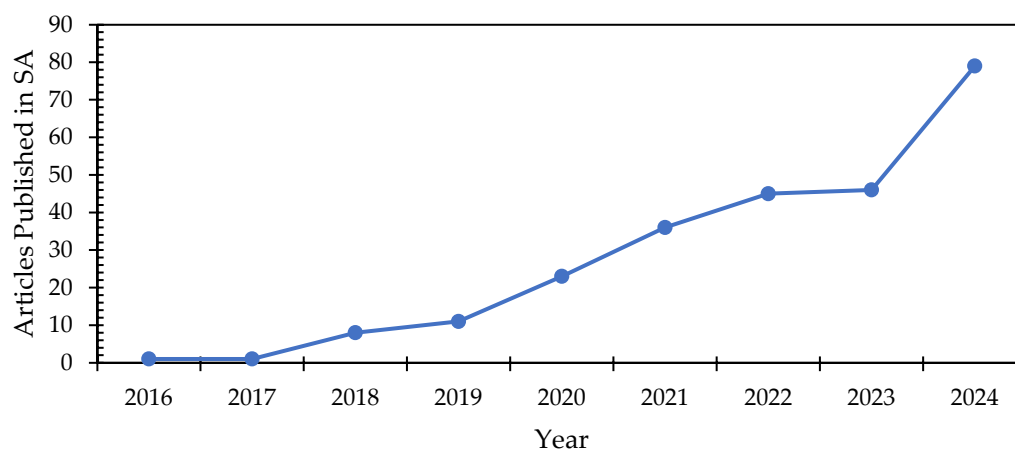


Figure 1. Number of publications for the circular economy in South Africa (SA) from 2014 to 2024, retrieved from Scopus.

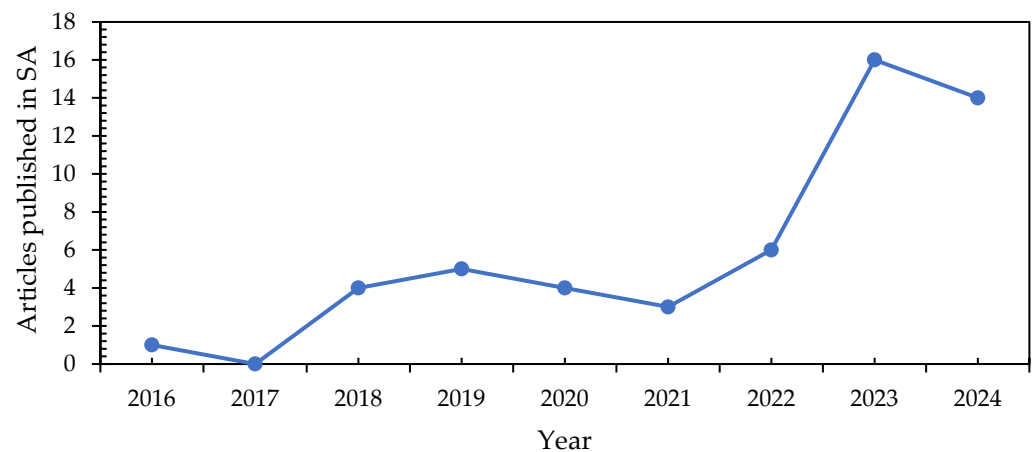


Figure 2. Number of publications for the food waste valorization in South Africa (SA) from 2016 to 2024, retrieved from Scopus.

2. Municipal Food Waste Management and Barriers

The circular economy seeks to establish a more balanced interaction between economic progress, environmental sustainability, and societal well-being. It promotes the efficient use of resources, aims to retain the intrinsic value of materials throughout the lifecycle, and encourages waste reduction through regenerative production and consumption systems embedded in modern economic development [12]. Figure 3 below shows the principles of the circular economy and the development of the waste management hierarchy.

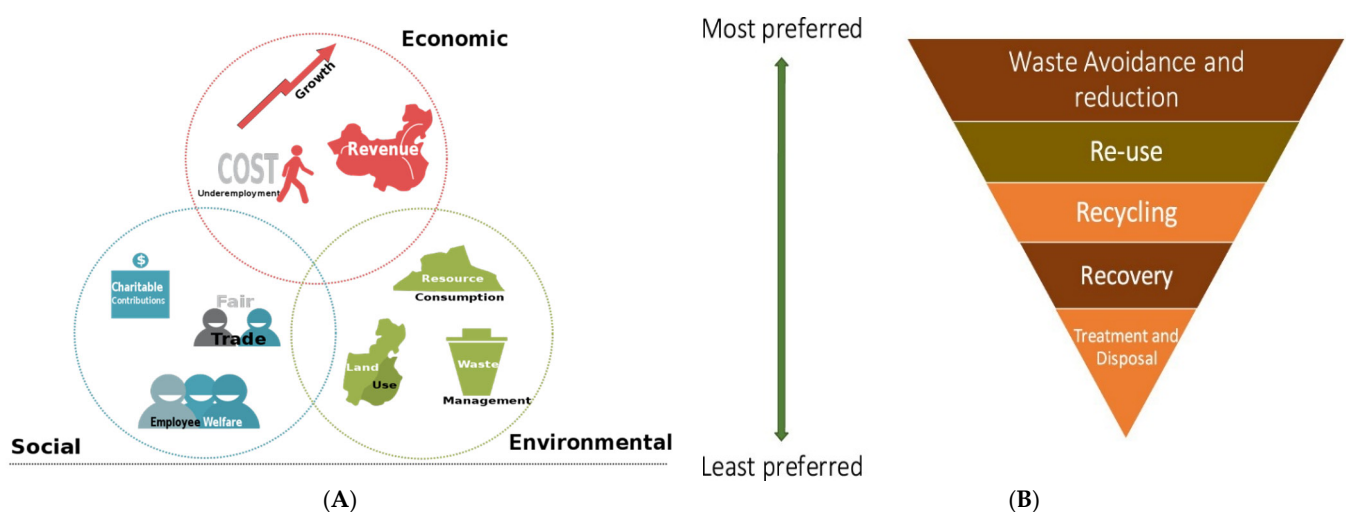


Figure 3. (A) Principles of circular economy in waste management, (B) Development of waste management hierarchy, adopted from [23].

The 3Rs rule (reduce, reuse, and recycle) is the most common way that the circular economy is discussed in the literature. Most governments throughout the world adopted the 3Rs approach and prioritized the “reduce” option as the primary principle for waste management planning. The World Framework Directive (WFD) established the fourth R “recover” as part of the 4R framework, which serves as the current European Union trash hierarchy. Disposal is the least desirable activity in the waste management hierarchy; therefore, it should always be avoided [24]. The disposal of organic waste, particularly through landfilling, results in the unnecessary loss of valuable resources and exacerbates environmental issues [14]. This section covers the potential barriers to organic waste management solutions. In both developed and developing countries,

waste management (WM) has become an issue, attributed to rapid population growth and industrialization [7,25].

In the United States of America (USA), the combined activities of food retailers, food service providers, and households generated approximately 66.2 million tonnes of food waste in 2019 [19,20]. Merely 5% of the discarded food was processed through composting. In the United States, food represents the most frequently landfilled material, accounting for 24.1% of the total municipal solid waste [26]. When combined with other organic components such as yard debris, wood, and paper-based products, these materials collectively make up 51.4% of the waste deposited in landfills [26]. India faces a significant challenge in managing large quantities of municipal solid waste (MSW) due to its high population density and insufficient infrastructure.

Furthermore, the waste management system in India is decentralized, with local municipal corporations tasked with the collection of waste from residences, streets, and other public areas. The majority of solid waste is generated by municipalities, producing thousands of tons per day, which includes hazardous, organic, and non-hazardous waste. A range of waste management strategies is currently in use, including incineration, pyrolysis, biorefining, biogas production, recycling, and composting. Among these, composting offers a sustainable and cost-effective solution for managing MSW, yet it accounts for only about 6–7% of MSW recycling. The broader scope of solid waste management involves activities such as waste generation, storage, collection, transport, treatment, and final disposal [27]. Effective management of solid waste is a significant challenge for cities with high population densities. However, there are significant improvements in social, economic, and environmental conditions in the context of India [27].

3. Generation and Composition of Food Waste

3.1. Global Perspective of Food Waste Generation and Composition

The emergence of supermarkets and fast food outlets in the 21st century has significantly transformed lifestyles in developed countries, setting them apart not only from earlier generations but also from populations in developing regions [28]. This growing concern is evident through a wide array of national and global campaigns, initiatives led by both corporate entities and non-profit organizations, increased media attention, and a surge in scholarly publications addressing the issue. The urgency of food waste reduction is further emphasized in the United Nations Sustainable Development Goals (SDGs), particularly Target 12.3, which advocates for having per capita food waste at consumer and retail levels and curbing losses throughout the production and distribution stages by 2030 [29]. Given the vast quantities of food discarded annually and the significant environmental and socio-economic consequences associated with it, policymakers are increasingly focused on implementing strategies to reduce food waste systematically. Accurate measurement and detailed characterization of food waste at each point in the supply chain are regarded as essential steps toward achieving meaningful reductions [30].

The composition of food waste varies significantly depending on its origin, geographic location, seasonal conditions, cultural practices, and the economic status of a given country. Its organic fraction generally consists of proteins, various polysaccharides, including starch, cellulose, hemicellulose, and lignin, along with oils, lipids, and organic acids [31]. Furthermore, food waste tends to be abundant in essential macronutrients such as nitrogen, phosphorus, and potassium, while exhibiting lower concentrations of micronutrients like iron, zinc, copper, and manganese [27]. It is also characterized by a relatively low carbon-to-nitrogen (C/N) ratio. Understanding both the generation and composition of household food waste is crucial for developing effective policies and interventions to reduce overall waste and improve sustainability.

3.2. South African Perspective of Food Waste Generation and Composition

Across numerous African nations, especially within Sub-Saharan Africa, there exists a persistent gap between energy supply and demand, leaving nearly 600 million individuals without reliable access to electricity and subjecting many regions to frequent power outages [32]. Projections indicate that electricity demand will increase by 2.4% by the year 2030 [28]. This growing need highlights the urgency for African countries to adopt sustainable, eco-conscious technologies and strategies that enhance energy production, particularly through the recovery and utilization of waste-based resources. In South Africa, households employ various food storage practices to mitigate the effects of load shedding. The prolonged and frequent load-shedding periods contribute to household food wastage as they reduce the refrigeration time of food. South Africa's pursuit of sustainable solid waste management has prompted the introduction of various laws and policy frameworks aimed at enhancing the effectiveness of waste handling practices. Nevertheless, despite notable advancements over time, South Africa continues to grapple with persistent obstacles and inefficiencies within the sector. Achieving long-term sustainability through a shift from the traditional linear economy to a circular model will require a comprehensive transformation of existing waste management systems [12]. Dlamini et al. [33] assessed how load-shedding affects the generation of household food waste in Merafong City Local Municipality, South Africa. It was reported that about 45% of municipal solid waste generated in South Africa is produced in the Gauteng province, with the highest population density. The relatively high food waste generation during power-cut hours is attributed to the mere fact that the majority of the population relies on fast food that comes in different packaging materials instead of home-cooked food.

3.3. Environmental and Social Impacts of Food Waste

Valorization of food waste into useful and high-value products plays a critical role in alleviating its environmental, economic, and societal impacts, while supporting the shift toward a circular economic model. The substantial volume of waste generated by the food sector, both in solid and liquid forms, has drawn increasing global attention. This concern stems not only from its ecological and socio-economic consequences but also from mounting pressures on food security, driven by rapid population growth, evolving demographic patterns, and the adverse effects of climate change on agricultural productivity [34]. The environmental consequences linked to food waste stemming from the resources consumed during its production span a wide array of concerns, including excessive use of water, land, fertilizers, and energy, alongside biodiversity loss and contributions to climate change [30]. More recently, public attention has turned to issues such as unpleasant odors, the presence of harmful substances in discarded food, and the release of gases and leachate from food waste digestate following its application to soil. In many regions, the absence of comprehensive policies and regulatory frameworks governing anaerobic digestion and digestate management poses significant barriers to the expansion of such technologies [31]. To address these challenges, countries around the world are formulating medium-term (by 2020) and long-term (by 2050) environmental strategies aimed at fostering a more innovative and resource-efficient economy, driven by the sustainable generation of bio-based products, including bioenergy and biomaterials from renewable biomass sources [17].

4. Valorization Technologies for Food Waste

Access to energy remains a pressing concern across Africa, with millions of individuals still lacking reliable electricity. Harnessing energy from municipal solid waste offers a dual advantage, it helps mitigate the environmental burden associated with waste accumulation

while simultaneously serving as a localized energy source to support regional energy needs [35]. Cudjoe et al. [36] investigated electricity production through the utilization of biogas derived from food waste in Ghana, where it was highlighted that the potential power generation of the project in Accra was 80.43–300.49 GWh/y, and 60.63–209.31 GWh/y in Kumasi. Consequently, the valorization of food waste is emerging as a progressive field focused on transforming waste into valuable resources. Zero-waste policy is still the most preferred strategy because prevention is better than cure; however, despite the implementation of zero-waste policies, a certain amount of food waste remains inevitable due to losses occurring during food processing, preparation, and transportation [1].

4.1. Anaerobic Digestion (AD)

Food waste is generated in both liquid and solid forms and is typically composed of complex organic compounds. Through anaerobic digestion (AD), this waste can be converted into biogas [36]. The technology behind anaerobic digestion has gained global recognition due to its cost-effectiveness and operational simplicity. Common feedstocks for digesters include fruit residues, meat scraps, vegetable waste, and animal-derived materials, which are rich in amino acids, vitamins, and essential nutrients [37]. AD is a biological process that occurs in oxygen-free conditions, facilitating the decomposition of biodegradable substances into valuable products such as biogas, bioethanol, compost, and other secondary metabolites [32]. This method is capable of processing a wide range of heterogeneous and non-sterile organic feedstock, utilizing diverse microbial communities to achieve the targeted result. Several factors, including the nature of the feedstock, operating temperature, microbial activity, and the design of the reactor system, influence the efficiency of biogas production. Biogas primarily consists of methane (CH_4), ranging from 40% to 75%, and carbon dioxide (CO_2), typically between 25% and 55%, with trace amounts of carbon monoxide (CO) and hydrogen sulfide (H_2S) also present [36,38]. AD systems are often favored for their compact infrastructure requirements, reduced sludge generation, lower operational temperatures, and suitability for intermittent use. The digestion process can function across a broad temperature spectrum from psychrophilic conditions (10–20 °C) and mesophilic ranges (20–45 °C) to thermophilic (45–65 °C) and even hyper-thermophilic environments (70 °C). This progression relies on the synergistic activity of anaerobic and facultative anaerobic microbes, which drive sequential biochemical stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis, ultimately leading to biogas formation [39]. The AD process is summarized in Figure 4.

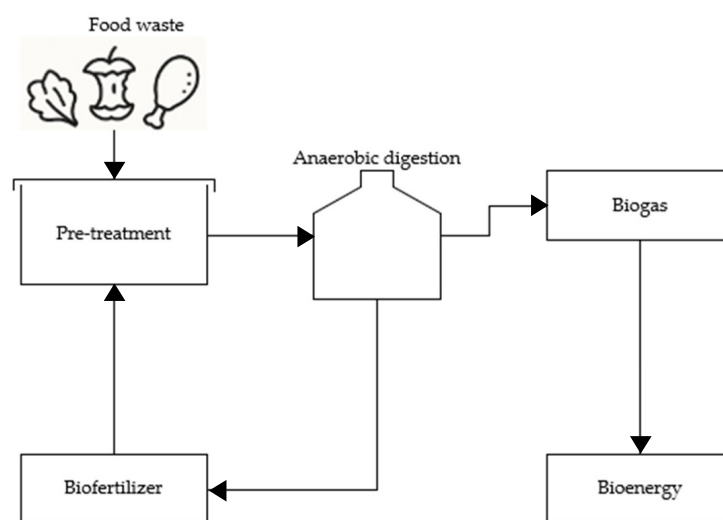


Figure 4. Anaerobic valorisation of food waste into biofertilizer and bioenergy.

Further research has been ongoing on AD. Studies have demonstrated that processing multiple feedstocks simultaneously, known as co-digestion, results in enhanced biogas output and elevated methane concentrations compared to the digestion of individual substrates [40]. This indicates a well-balanced nutrient profile across the substrates, which supports the development of an optimal microbial community and contributes to a more efficient AD process [41,42]. A study conducted by Awosusi et al. [43], where co-digestion of kitchen wastes and cow manure was explored in a configurable AD unit operating under conditions both with and without a low-density polyethylene (LDPE) cover, showed that the ideal feed ratio of three parts food waste to one part cow manure yielded the highest biogas output under a 30-day hydraulic retention time and an organic loading rate of 4.41 kgVS/L/day. Co-digestion trials revealed strong synergistic effects, whereas mono-digestion of kitchen waste was unsuccessful due to acidification [43]. Table 1 presents a summary of the four main phases that take place in a typical AD.

Table 1. Evaluation of the four different phases that take place in an anaerobic digester.

Phase	Description	Key Microorganisms	Primary Products	References
Hydrolysis	Rate-limiting step is materials rich in fiber	Clostridium Bacillus Vulgaris Vibrio Bacteroides Staphylococcus	Fatty acids Amino acids Sugars	[44,45]
Acidogenesis	During hydrolysis, soluble organic matter is transformed by acid-forming bacteria known as acidogens into organic acids such as acetate, butyrate, and propionate, along with alcohol, hydrogen, and carbon dioxide	Escherichia Bacillus Lactobacillus Staphylococcus Pseudomonas Veillonella Sarcina Desulfobacter	Soluble organic acids are formed	[46]
Acetogenesis	Acetates are formed as a series of organic acids	Clostridium Syntrophonas wolfeii Synrophomonas wolinii	Acetic acid, hydrogen, carbon dioxide	[46]
Methanogenesis	Metane and carbon dioxide are produced from acetic acid, hydrogen, and carbon dioxide	Acetogens or hydrogenotrophs	Methane	[46,47]

4.1.1. Life Cycle Assessment of Anaerobic Digestion of Food Waste for Biofertilizer and Biogas Production

To holistically evaluate the environmental performance of this process, life cycle assessment (LCA) provides a robust framework that quantifies emissions, resource use, and ecological impacts across the entire system boundary—from feedstock collection to end-product utilization. Studies on LCA indicate the environmental advantages of AD over conventional waste disposal methods such as landfilling or incineration. Nuanual et al. [48] conducted an LCA of semi-continuous AD of food waste co-digested with manure, revealing that the system produced 1.35 L of usable biogas per day, sufficient to replace liquefied petroleum gas for household cooking. This substitution reduced the global warming potential (GWP) by approximately 0.56 kg CO₂e/day. Moreover, the digestate generated from the biogas storage pond was shown to improve soil fertility and offset synthetic fertilizer use, further lowering GWP by 1.86 kg CO₂e/day. These findings highlight the dual environmental benefit of AD, viz., renewable energy generation and nutrient recycling.

The digestate, often overlooked in energy-centric evaluations, plays a pivotal role in circular agriculture. Martín-Sanz-Garrido et al. [49] reviewed the characteristics and environmental impacts of digestate from an LCA perspective, emphasizing its potential to replace synthetic N-P-K fertilizers while enhancing soil health. However, the environmental footprint of digestate depends heavily on feedstock composition, pretreatment strategies, and post-processing methods such as composting or solid–liquid separation. Their analysis [49] of 28 peer-reviewed LCA studies revealed that system boundaries and functional unit definitions significantly influence impact outcomes. It was reported that, when digestate is applied directly to fields without stabilization, risks of ammonia volatilization and nitrate leaching may offset its benefits. Conversely, composted or pelletized digestate shows improved nutrient retention and reduced emissions.

Zhao et al. [50] performed the Life Cycle Assessment (LCA) of the food waste energy and resource conversion scheme via a dual process of anaerobic digestion (AD) and hydrothermal carbonization (HTC). The results of the LCA proved a significantly lower environmental impact compared to the individual processes of AD and HTC. The dual process achieved a reduction in global warming (GW) potential, with a net carbon fixation of approximately $-141.16 \text{ kg CO}_2 \text{ eq.}$, which is substantially better than the other methods. The assessment also indicated that the energy generation from biogas contributes surplus electricity and heat, further reducing the environmental burden. Additionally, shortening transportation distance for food waste can further decrease environmental impacts by lowering emissions associated with logistics.

Effective LCA of AD systems requires careful consideration of system boundaries, i.e., whether the study includes upstream activities like feedstock transport or downstream impacts such as land application. Hanafiah et al. [51] emphasized that including pretreatment and digestate management stages can dramatically alter the environmental profile of AD systems. Additionally, co-digestion strategies (e.g., combining food waste with manure or agricultural residues) can improve biogas yield and nutrient balance, but may introduce complexity in LCA modeling due to variable feedstock ratios and microbial dynamics.

In the South African context, where food waste remains underutilized and energy access is uneven, AD offers a compelling solution. Integrating LCA into policy and project planning can guide technology selection, optimize resource recovery, and ensure environmental safeguards. Moreover, decentralized AD systems tailored to local waste streams and agricultural needs could enhance rural livelihoods while contributing to national sustainability goals.

4.1.2. Evaluation of Anaerobic Digestion of Food Waste for Biofertilizer and Biogas Generation

AD has emerged as a pivotal technology in the valorization of food waste, offering both environmental and economic benefits. Recent studies [49,52,53] have highlighted its multifaceted advantages, while also highlighting operational and regulatory challenges that must be addressed for broader adoption. As summarized in Table 2, the AD process effectively transforms organic waste into renewable biogas and nutrient-rich digestate, contributing to energy independence and circular economy models, as reported by Martín-Sanz-Garrido et al. [49]. The process significantly reduces greenhouse gas emissions compared to landfilling, thereby mitigating climate change impacts [52]. It is important to note that, when properly treated, the digestate enhances soil health and serves as a sustainable alternative to synthetic fertilizers [49]. However, despite its promise, AD systems are sensitive to feedstock variability and contamination, which can affect performance and biogas yield [49]. Skilled operation and continuous monitoring are essential to maintain process stability. Furthermore, untreated digestate may harbor pathogens or heavy metals,

posing risks to soil and crop safety [53]. Regulatory frameworks that classify digestate as livestock waste further complicate its agricultural application [53].

Table 2. Advantages, disadvantages, cost-effectiveness, and sustainability of the AD systems for biofertilizer generation.

Advantages	Disadvantages	Cost-Effectiveness	Sustainability	References
(1) Converts organic waste into renewable biogas and nutrient-rich digestate. (2) Reduces greenhouse gas emissions compared to landfilling. (3) Supports circular economy and energy independence. (4) Enhances soil health when digestate is properly treated.	(1) Performance varies with feedstock composition and contamination. (2) Requires skilled operation and monitoring. (3) Digestate may contain pathogens or heavy metals if not properly treated. (4) Regulatory classification as livestock waste can limit use.	(1) Capital costs are high for full-scale AD plants. (2) Operational costs can be offset by energy recovery and fertilizer sales. (3) More cost-effective when integrated with composting or nutrient recovery systems. (4) Economies of scale improve viability.	(1) Strong potential to reduce reliance on synthetic fertilizers. (2) Life cycle assessment shows a reduced environmental footprint when digestate is post-treated. (3) Promotes resilient agroecosystems.	[49,52,53]

High capital costs for full-scale installations influence the economic feasibility of AD. However, operational expenses can be offset through energy recovery and the sale of biofertilizers [52]. Integrating AD with composting or nutrient recovery systems enhances cost-effectiveness, especially when economies of scale are leveraged [53]. In the context of sustainability and policy alignment, AD aligns with several Sustainable Development Goals (SDGs), including zero hunger (SDG 2), clean water and sanitation (SDG 6), affordable and clean energy (SDG 7), responsible consumption and production (SDG 12), and climate action (SDG 13). It also supports the African Union’s Agenda 2063 by promoting resilient agroecosystems and reducing reliance on imported fertilizers [52].

4.2. Composting

The economic and environmental valuation of converting organic food waste into compost is assessed in alignment with circular economy metrics. However, the financial benefits derived from enriching soil with macronutrients such as carbon, nitrogen, phosphorus, and potassium through compost application, and its potential to substitute conventional mineral fertilizers, have yet to be documented within the framework of circular economy models [54]. Composting is widely recognized as an efficient method for managing food waste, converting it into a stable, nutrient-rich biofertilizer. However, due to food waste’s high moisture content, elevated acidity, low carbon-to-nitrogen ratio, and inadequate physical structure with limited porosity, effective composting requires the incorporation of bulking agents. Materials like sawdust, wood chips, straw, and rice husks are commonly incorporated into food waste to regulate moisture content, pH levels, and the carbon-to-nitrogen ratio, thereby optimizing conditions for composting [55]. Yaser et al. [56] examined the use of composting and anaerobic digestion for processing food waste and sewage sludge within campus sustainability frameworks. It was concluded that these biological treatment methods offer environmentally sound alternatives to conventional landfill disposal, particularly for biodegradable waste. Moreover, utilizing composting techniques to manage organic waste streams can lower operational costs, reduce environmental pollution, and yield beneficial end-products. Figure 5 illustrates a small-scale biofertilizer derived from

the composting process. Regardless of operational scale, the fundamental principles of composting remain consistent. Successful composting requires a balanced mix of carbon-dense inputs (e.g., dry leaves or wood chips) and nitrogen-rich materials (e.g., food residues or grass clippings). Ensuring appropriate moisture levels, aeration, particle size, and temperature is essential for microbial activity that facilitates the decomposition of organic matter into high-quality compost.



Figure 5. The matured biofertilizer after the composting process, adopted from [57].

Mataba et al. [57] performed an investigation on the production of biofertilizer from fruits and garden waste in Tanzania, with an average yearly consumption of 366,277 M tons. Composting was conducted within a 0.238 m³ unit, and it was determined that each kilogram of pineapple yields approximately 3 g of top waste. Based on a total consumption of 366,277 metric tonnes of pineapples, this translates to an estimated 109,883 metric tonnes of pineapple residues. These organic by-products present a viable feedstock for biofertilizer production. The biofertilizer was produced specifically using pineapple tops in the composting process. Table 3 presents the physicochemical properties of the produced biofertilizer.

Table 3. Physicochemical characteristics of biofertilizer [57].

Property	Property Value	Required Range
Moisture content (%)	36	30 to 60
pH	7.1	5.0–8.0
Temperature (°C)	35	30–40
Potassium (ppm)	5770	1000–35,000
Lead (ppm)	60	<300
Cadmium (ppm)	2	<15

4.2.1. Life Cycle Assessment of Composting Food Waste for Biofertilizer and Biogas Production

Composting has long been recognized as a practical and ecologically sound method for managing food waste, especially in regions like South Africa, where organic waste constitutes a significant portion of municipal solid waste. LCA studies consistently show that composting food waste reduces greenhouse gas emissions compared to landfilling,

primarily by avoiding methane generation and recovering nutrients. However, the environmental footprint of composting varies widely depending on system design, aeration method, energy inputs, and digestate handling.

Le Pera et al. [58] performed an LCA on the industrial-scale production of two compost variants derived from food waste, using operational data from a composting facility in Italy. Their findings confirmed that composting food waste yields significant environmental benefits, including a net climate change mitigation of approximately 434 kg CO₂-equivalent. Additional environmental savings were observed across multiple impact categories, such as ozone layer depletion, particulate matter formation, acidification, eutrophication, and photochemical oxidant formation. These benefits were largely attributed to the substitution of biomethane for conventional vehicle fuels and the use of compost as a replacement for synthetic fertilizers. Nonetheless, the study identified diesel consumption for food waste transportation as the primary contributor to residual environmental impacts.

In South Africa, where landfill space is limited and nutrient-depleted soils are common, composting offers a locally adaptable solution. Integrating LCA into municipal planning can help identify optimal composting sites, feedstock blends, and emission mitigation strategies. Moreover, community-based composting initiatives—especially those that recover both fertilizer and energy—can support food security, reduce urban pollution, and foster circular bioeconomy models.

4.2.2. Evaluation of Composting of Food Waste for Biofertilizer and Biogas Generation

Table 4 presents a multidimensional analysis of composting as a valorization strategy for food waste, emphasizing its role in producing biofertilizer and its limited potential for biogas generation. One of the advantages of composting as a food waste valorization strategy is its simplicity and adaptability across scales from household bins to municipal facilities. Its low-tech nature makes it accessible in both urban and rural contexts, especially where infrastructure is limited. The production of stable, nutrient-rich compost contributes to (1) soil health by enhancing microbial activity, structure, and water retention; (2) waste reduction by diverting organic waste from landfills, thereby mitigating methane emissions; and (3) circular economy by closing nutrient loops through the retention of organic matter in soil. These benefits align with the findings reported by Mahish et al. [53].

Table 4. Evaluation of composting as a valorization strategy for food waste.

Advantage	Disadvantage	Cost-Effectiveness	Sustainability	References
(1) Simple, low-tech process suitable for small and large scales. (2) Produces stable, nutrient-rich organic fertilizer. (3) Reduces landfill burden and methane emissions. (4) Enhances soil structure and microbial health.	(1) Limited biogas production compared to anaerobic digestion. (2) Requires careful control of moisture, aeration, and temperature. (3) May emit odors and attract pests if poorly managed. (4) Compost quality varies with feedstock.	(1) Low capital and operational costs, especially for decentralized systems. (2) Minimal energy input compared to other valorization methods. (3) Cost-effective for municipalities and rural communities. (4) Revenue potential from compost sales.	(1) Supports nutrient recycling and soil carbon sequestration. (2) Promotes agroecological resilience and food security.	[53,59,60]

Despite its strengths, composting has limitations that must be managed. Unlike anaerobic digestion, composting does not capture methane for energy, reducing its

potential as a renewable energy source. Effective composting requires careful control of moisture, aeration, and temperature. Poor management can lead to odor issues and pest attraction, making the process highly sensitive [59]. Moreover, the quality of compost depends heavily on the feedstock, which can affect nutrient content and contamination risks. These challenges are well documented by Sampaio et al. [59], highlighting the need for training and monitoring in composting operations. Economically, composting is highly favorable, particularly for decentralized systems. According to Mahish et al. [53], compared to anaerobic digestion or incineration, composting requires minimal infrastructure, suggesting that it requires relatively low capital and operational costs. This is attributed to the fact that the process relies on natural microbial activity, reducing energy requirements. Furthermore, composting contributes significantly to sustainability goals. It recovers nitrogen, phosphorus, and potassium from food waste, reducing reliance on synthetic fertilizers. Composting plays a pivotal role in carbon sequestration, enhancing soil organic carbon, aiding climate mitigation. By improving soil health and reducing input costs, composting strengthens food systems against climate and economic shocks. While composting may not match anaerobic digestion in energy recovery, its strengths in nutrient recycling, cost-effectiveness, and ecological resilience make it a compelling strategy for food waste valorization. For regions prioritizing soil health, low-cost solutions, and climate-smart agriculture, composting offers a scalable and sustainable pathway.

4.3. Pyrolysis

While composting offers a partial solution to some of the environmental risks associated with digestate, the growing volume of digestate, particularly in densely populated urban areas with limited land availability, necessitates alternative treatment strategies. There is an urgent need to develop scalable and cost-efficient technologies for managing solid digestate. One promising approach involves the integration of anaerobic digestion (AD) with pyrolysis (Py), enabling the conversion of biodegradable organic matter into biomethane, while transforming the remaining digestate into energy-rich products such as biochar, bio-oil, and pyrolysis gas. This combined method facilitates near-complete valorisation of biowaste and helps mitigate the challenges posed by digestate accumulation [61]. Pyrolysis involves the thermal breakdown of organic compounds in an oxygen-free environment, typically at temperatures ranging from 300 to 800 °C. Key operational parameters, including temperature, residence time, heating rate, type of inert gas, and flow rate, significantly influence the efficiency, yield, and characteristics of the resulting products. During pyrolysis, methane (CH_4) undergoes dehydrogenation and dissociation, forming reactive hydrogen and CH_x radicals that drive further pyrolytic reactions. The use of carbon dioxide (CO_2) as an oxidizing agent in fast pyrolysis at 1123 K has been shown to reduce char formation. CO_2 facilitates the breakdown of methylene and methyl groups as well as aromatic rings, while also diminishing the interaction between hydrogen radicals and solid char, ultimately enhancing both the yield and quality of the pyrolytic liquid [62]. Pyrolysis is widely regarded as an effective solution for reducing sludge volume, generating high-value products, and minimizing the release of harmful contaminants. Although extensive research has been conducted on pyrolysis using inert or single reactive agents, the use of mixed reductive and oxidative gases, such as biogas blends containing CH_4 and CO_2 , remains relatively underexplored [62]. Table 5 summarizes various pyrolysis studies reported in the literature for different biomass feedstocks.

Table 5. Different types of biomasses and their optimum conditions with relevant results and observations.

Biomass	Conditions	Reactor	Yield	Relevant Result and Observation	References
Food waste	700–900 °C, 100–250 mL/min, N ₂ , H ₂	Fixed-bed reactor	68.77% (at max temp)	• An increase in temperature leads to a decline in the production of bio-oil and biochar, while simultaneously enhancing the yield of biogas and its lower heating value (LHV). • Increasing the flow rate of the carrier gas boosts biogas production; however, it results in a reduction in both the lower heating value (LHV) of the biogas and the yield of bio-oil. • An increase in H₂ concentration enhances biogas generation, but further elevation leads to a decline. In contrast, bio-oil production follows an inverse pattern, decreasing at first and then rising.	[63,64]
Food waste	800–1200 W, 2 h, CO ₂ /N ₂	Microwave reactor	67.90%	• Increasing microwave power stimulates biogas production. • Conducting pyrolysis in a CO₂ environment yields 44.13 wt% more biogas compared to operations carried out under a N₂ atmosphere. • Performing pyrolysis in a CO₂ environment enhances the biochar's specific surface area.	[64,65]
Food waste	320–480 °C, 30 min, N ₂	Microwave reactor	30.24%	• A bio-oil yield of 30.24 wt% was achieved when pyrolysis was conducted at 400 °C for 30 min under a N₂ flow rate of 50 mL/min. • The composition of bio-oil includes a variety of chemical groups such as alcohols, phenolic compounds, carboxylic acids, alkenes, aromatic hydrocarbons, aliphatic amines, and nitroalkanes.	[64,66]
Food waste	300–600 W, N ₂	Microwave reactor	-	• Increasing microwave power leads to a decline in biochar production, while simultaneously enhancing the yields of bio-oil and biogas. • Increasing microwave power boosts the energy yield of bio-oil while simultaneously lowering the energy output associated with biochar production.	[64]
Food waste feedstuff/Food waste compost	300–500 °C, 15–60 °C/min, N ₂	Fixed-bed reactor	32.80%	• Extended retention periods enhance the quality of the resulting biochar. • Higher temperatures lead to a decrease in the amount of biochar produced. • A temperature of 400 °C is ideal for achieving high-quality biochar.	[64,67]

Table 5. Cont.

Biomass	Conditions	Reactor	Yield	Relevant Result and Observation	References
Raw food waste/Food waste digestate	300–700 °C, 10 or 60 °C/min, N ₂	Fixed-bed reactor	52.2–60.3%	- As the temperature increases, the yield of biochar tends to decline. - Elevated temperatures markedly enhance the formation of large open pores in biochar derived from raw food waste pyrolysis. - Pyrolyzing raw food waste results in a greater production of bio-oil. - Bio-oil contains phenols, esters, hydrocarbons, and related compounds, and its composition is strongly influenced by the heating rate.	[64,68]

Zhao et al. [69] assessed the environmental impact of the integration of anaerobic digestion (AD) and co-pyrolysis (PY) to dispose of the food waste. Four cases were evaluated (namely, case 1: mono AD, case 2: mono PY, case 3: AD + PY, and case 4: AD + co-PY). The results depicted that integrated technology was more environmentally viable compared to other technologies assessed. Moreover, it was observed that the digestate in all cases contained a relatively high concentration of heavy metals, which is strongly linked to increased ecotoxicity. The results showed that a better environmental impact was observed in case 3 (17.2 kg CO₂ eq) and case 4 (23.86 kg CO₂ eq) compared to case 2 (46.23 kg CO₂ eq) and case 1 (64.84 kg CO₂ eq). These results proved that pyrolysis technology emits a substantial amount of emissions, which greatly impact global warming. However, when the pyrolysis technology is coupled with anaerobic digestion, the emissions are significantly lower.

4.3.1. Life Cycle Assessment of Pyrolysis of Food Waste for Biofertilizer and Biogas Production

While bio-oil and syngas offer energy recovery potential, biochar is increasingly recognized for its agronomic value as a biofertilizer and its role in carbon sequestration. An LCA provides a critical lens to evaluate the environmental performance of pyrolysis systems across their entire value chain, from feedstock collection to product utilization. Recent LCA studies suggest that pyrolysis of food waste can outperform traditional waste management strategies in terms of greenhouse gas (GHG) mitigation, nutrient recovery, and energy efficiency. For instance, Gahane et al. [70] conducted a cradle-to-grave LCA of biomass pyrolysis and found that the pyrolysis unit and bio-oil combustion stages contributed over 30% of total GHG emissions. However, when biochar was applied to soil, it acted as a negative emission technology, offsetting carbon and improving soil health. Similarly, Orlan-della and Fiore [71] reviewed 98 LCA studies on biofertilizer production from agricultural and food waste. They reported that thermochemical processes like pyrolysis exhibited the lowest average environmental impacts compared to anaerobic digestion and composting, especially when food waste was the primary feedstock. The study emphasized that biochar derived from pyrolysis not only reduces reliance on synthetic fertilizers but also enhances soil microbial activity and water retention.

Biochar, the solid residue from pyrolysis, is rich in stable carbon, essential nutrients (i.e., N, P, K), and porous structure, making it an ideal soil amendment. When applied to agricultural soils, biochar improves nutrient retention, reduces leaching, and enhances crop productivity. Moreover, its long-term stability in soil contributes to carbon sequestration, aligning with climate mitigation goals. In integrated systems, syngas and bio-oil can be combusted to generate heat or electricity, while biochar is valorized as a biofertilizer. This

dual output enhances the circularity of food waste valorization. Its ability to produce both energy and soil-enhancing biofertilizers aligns with national goals for renewable energy, sustainable agriculture, and circular economy development.

4.3.2. Evaluation of Pyrolysis of Food Waste for Biofertilizer and Biogas Generation

The pyrolysis evaluation table (Table 6) provides a structured overview of pyrolysis as a thermochemical strategy for converting food waste into valuable products, namely biochar, bio-oil, and syngas. Each aspect reflects a critical dimension of its feasibility, performance, and alignment with sustainability goals. Compared to other processes, pyrolysis offers a multifaceted valorization pathway. Pyrolysis offers product diversity such as biochar (solid), bio-oil (liquid), and syngas (gas), each with unique applications in agriculture, energy, and industry. Biochar enhances soil fertility, water retention, and carbon sequestration, contributing to long-term soil health and climate mitigation. Pyrolysis significantly reduces the volume and toxicity of food waste, contributing to waste reduction, making it a compelling alternative to landfilling or incineration. This process takes place under a controlled environment. Operating under oxygen-limited conditions minimizes combustion losses and allows for tailored product recovery. These advantages position pyrolysis as a high-value, circular economy solution for urban and industrial food waste streams.

Table 6. Evaluation for pyrolysis of food waste into biofertilizer and bioenergy.

Advantage	Disadvantage	Cost-Effectiveness	Sustainability	References
(1) Converts food waste into biochar, bio-oil, and syngas with high energy density. (2) Biochar improves soil fertility, water retention, and carbon sequestration. (3) Operates under oxygen-limited conditions, minimizing combustion losses.	(1) High capital and operational costs compared to biological. (2) Requires precise temperature control and feedstock pre-treatment. (3) Limited nutrient recovery unless biochar is enriched. (4) Potential release of toxic compounds if poorly managed.	(1) Economically viable when integrated with energy recovery systems. (2) Biochar has a growing market value in agriculture and carbon credit schemes. (3) Cost-intensive for small-scale applications without subsidies or co-products.	(1) Biochar application reduces greenhouse gas emissions and enhances soil carbon storage. (2) Syngas and bio-oil offer renewable energy alternatives. (3) Scalable for urban and industrial food waste streams.	[53,72]

Despite its promise, pyrolysis presents several operational and environmental challenges. The process is associated with cost barriers. High capital and operational costs can deter adoption, especially in low-resource settings or small-scale applications. Pyrolysis is characterized by technical sensitivity; it requires precise temperature control and feedstock pre-treatment to ensure consistent product quality and avoid toxic emissions. Nutrient limitation is also another drawback; biochar may lack essential nutrients unless enriched post-process, limiting its standalone use as a fertilizer. The pyrolysis process can pose environmental risks, as poorly managed systems can release polycyclic aromatic hydrocarbons, volatile organic compounds, and other harmful byproducts. These drawbacks suggest the need for robust reactor design, emission control technologies, and policy support to mitigate risks.

4.4. Heat Treatment Technologies

4.4.1. Hydrothermal Carbonization (HTC)

Recent years have seen a surge in experimental investigations into hydrothermal carbonization (HTC) of sewage sludge, focusing on how varying process parameters influence

the properties of hydrochar and the recovery of nutrients, carbon, and energy from the sludge material [73]. In agricultural biogas facilities, digestate is generated alongside biogas. Given its high moisture content and organic composition, digestate is well-suited for HTC treatment, offering an alternative to landfilling [74]. Hydrochar produced through HTC has found diverse applications, including use as a solid fuel, environmental adsorbent, feedstock for syngas via gasification, precursor for electrochemical energy storage, and soil conditioner [75]. The HTC process is primarily driven by hydrolysis, though it also involves reactions such as dehydration, decarboxylation, and condensation. During hydrolysis, structural components like hemicellulose, cellulose, and lignin are broken down into smaller molecules, enabling subsequent reactions to lower the hydrogen-to-carbon (H/C) and oxygen-to-carbon (O/C) ratios—key steps in forming a coal-like solid product [76]. The overarching goal is to convert cellulose into a carbon-rich fuel under elevated temperatures through hydrothermal treatment, thereby shedding light on the mechanisms underlying natural coal formation and transformation [77]. Figure 6 depicts a schematic for an HTC process.

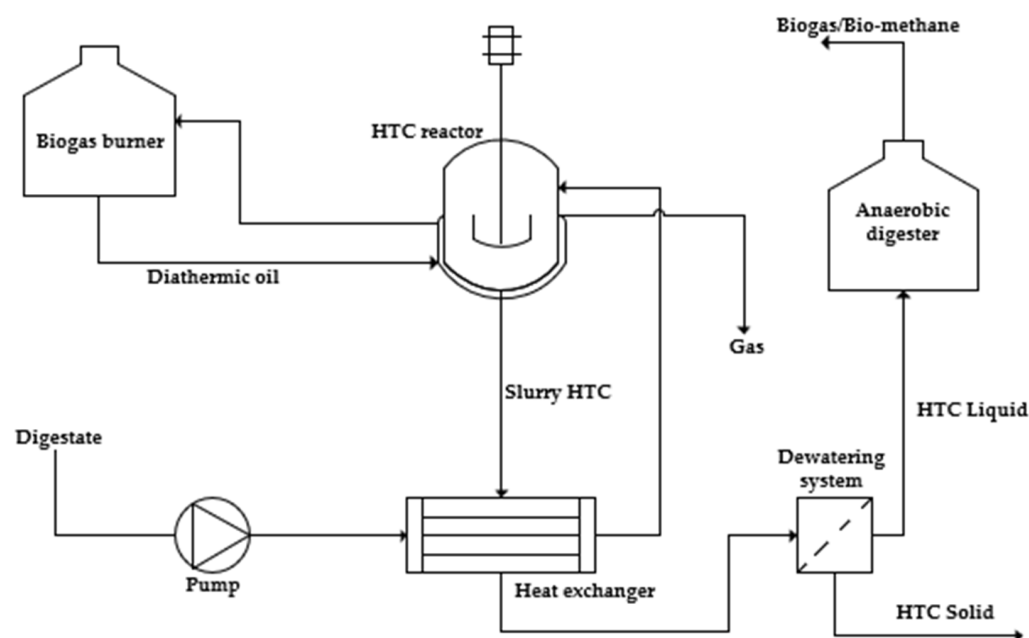


Figure 6. Schematic diagram of the hydrothermal carbonization plant, adopted from [78].

Given that the hydrothermal carbonization (HTC) process water is rich in water-soluble organic compounds, utilizing it through anaerobic digestion (AD) presents a promising valorization pathway. Although AD is a widely recognized and extensively applied technique for treating organic waste, its use for process water derived from food waste carbonization remains a relatively novel application [79]. McGaughy and Toufiq Reza [80] conducted hydrothermal carbonization of food waste using a batch reactor operated at 250 °C. Their findings revealed that the energy yield from HTC surpassed that obtained through conventional disposal or treatment methods, including disposal and treatment options like landfill use, organic composting, biogas production through anaerobic digestion, and thermal conversion via incineration. Additionally, the results demonstrated that the incorporation of HTC liquid and slurry into AD resulted in a 37% and 63% increase in biomethane production, respectively, compared to the organic fraction of municipal solid waste (OFMSW). Zhao et al. [50] studied and compared the LCA for the dual process of AD and HTC, the AD process, and the composting process. The dual process had the least environmental impact of the other processes. The hydrochar formed

from HTC made the dual process carbon fixation ($-141.46 \text{ kg CO}_2 \text{ eq}$) better than the AD process ($-38.87 \text{ kg CO}_2 \text{ eq}$) and composting ($607.68 \text{ kg CO}_2 \text{ eq}$). Furthermore, it is shown that reducing the transport distance for the raw material (food waste) and increasing biogas yield can produce better environmental benefits for the dual process.

4.4.2. Hydrothermal Liquefaction (HTL)

Hydrothermal Liquefaction (HTL) is a thermochemical valorization process that converts a variety of biomass into energy. It is the most widely used technology for the conversion of wet or high-moisture waste to a value-added product at high temperature and pressure [20,81,82]. HTC-char can be used as a fertilizer, absorbent, and in wastewater treatment [20]. This technology is a preferred pathway compared to pyrolysis because it does not require a drying stage that consumes a substantial amount of energy [83,84]. This process involves subjecting the material to a temperature and pressure range of $250\text{--}450^\circ\text{C}$ and $4\text{--}22 \text{ MPa}$, respectively. It utilizes a solvent to create a highly reactive environment [84]. Figure 7 presents a process flowchart of the HTL process.

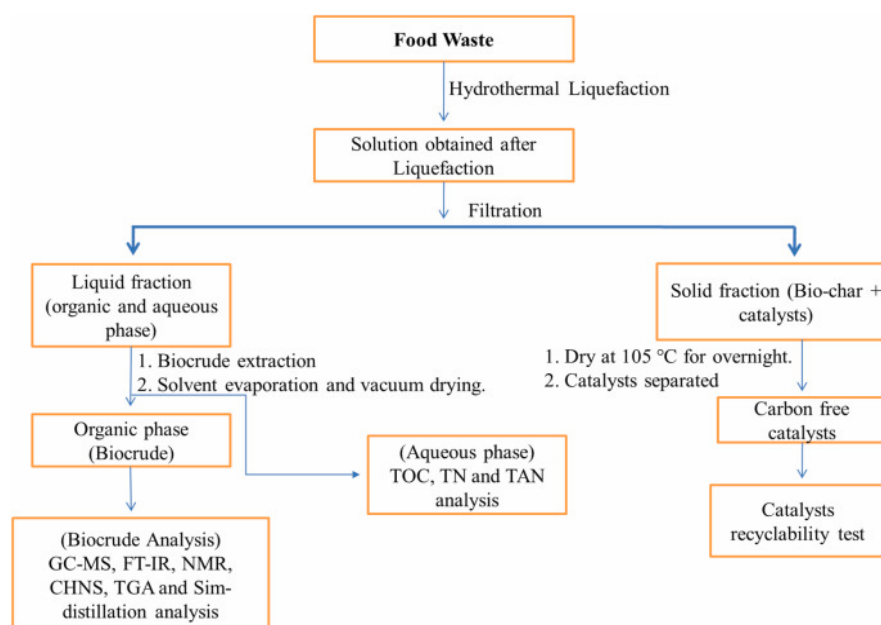


Figure 7. Flowchart for HTL of food waste.

Wang et al. [85] performed a comprehensive study on the environmental impact of three food waste hydrothermal liquefaction (HTL) scenarios (scenario 1: HTL and wastewater treatment, scenario 2: dark fermentation followed by HTL, and scenario 3: combined HTL with anaerobic). The results proved that scenario 2 produced the highest bio-oil yield and quality; however, it also resulted in the highest environmental impacts, mainly because of the increased carbon emissions. Scenario 3 demonstrated the most favorable environmental outcomes due to the production of biogas and the management of wastewater. Scenario 1 produced a lower environmental impact but resulted in lower-quality bio-oil.

4.5. Nutrient Recovery from Digestate

Roughly 80–90% of the material fed into anaerobic digestion (AD) is converted into digestate. As such, utilizing digestate as a secondary source of nutrients offers a valuable opportunity, delivering dual advantages: (a) enhancing circularity within the biogas AD system by identifying practical applications for the digestate, and (b) promoting nutrient recovery, which is critically needed in modern agriculture [86]. The choice of nutrient

recovery technology (NRT) is influenced by the nature of the incoming waste stream and significantly affects the chemical makeup and quality of both the final fertilizer product and any associated by-products. A thorough grasp of the underlying principles of these technologies is essential for the sustainable development of advanced, high-grade fertilizers [17]. Figure 8 presents a summary of the production of biogas and digestate from fermentation.

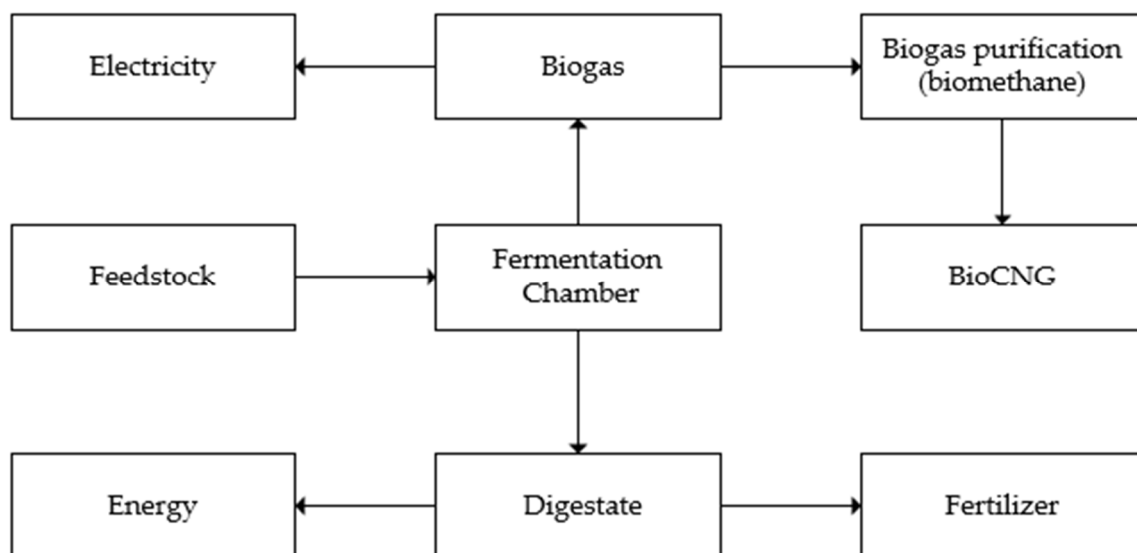


Figure 8. Scheme of Biogas and Digestate Production, adopted from [75].

4.6. Struvite Precipitation

Nutrient recovery from digestate offers a chance to recover nitrogen (N) and phosphorus (P) through a process called struvite precipitation. Anaerobic digestion technology yields a concentrated source of N and P. Multiple studies confirm that nutrients from the digestate can meet the global demand for fertilizers [87,88]. Struvite precipitation occurs through different mechanisms: nucleation and crystal growth. Nucleation is the first step, and it occurs when ions combine to form crystal embryos. The second crystal growth, which proceeds until equilibrium is reached. Nitrogen and phosphorus are typically found in both industrial and residential wastewater systems, including organic and industrial waste sources like piggery wastewater, landfill runoff, urine-derived effluents, dairy sludge, coke plant discharge, and beverage production residue. These nutrient-rich products cause eutrophication in water bodies and can be converted into struvite ($\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$) for the benefit of the environment [89]. According to Aldaach et al. [88], struvite is considered better than other technologies for P and N recovery because it can recover the nutrients simultaneously compared to ammonia stripping, which removes only ammonia from wastewater [90]. The following chemical reaction depicts the struvite formation [90].



The surface morphology of struvite crystals is an orthorhombic form. The morphology can be seen from the characterization of struvite crystals using the Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) characterization method. Sangeetha et al. [91] performed the SEM and EDS, and the qualitative elemental composition was found to be 9.6%, 0%, 0.08%, 0.21%, 0%, 0.38%, 1.12, 1.29%, and 18.47% for Mg, N, P, K, Ca, Na, S, Cl, and O, respectively.

4.7. Ammonia Stripping and Electrochemical Stripping

Conventional ammonia stripping techniques primarily utilize steam or air as the stripping medium, typically conducted within packed or plate towers to facilitate gas–liquid mass transfer (refer to Figure 9). Post-stripping, free ammonia (NH_3) is captured using acid, resulting in an ammonium-enriched solution suitable for use as a nitrogen fertilizer, thereby enabling nitrogen recovery [92]. In contrast, electrochemical stripping offers a more advanced alternative by elevating the pH internally without the need for external base addition and extracting ammonia from within the system rather than from the tower’s exterior. This method also enables the recovery of ammonia in the form of valuable compounds such as ammonium sulfate, a widely utilized fertilizer [93].

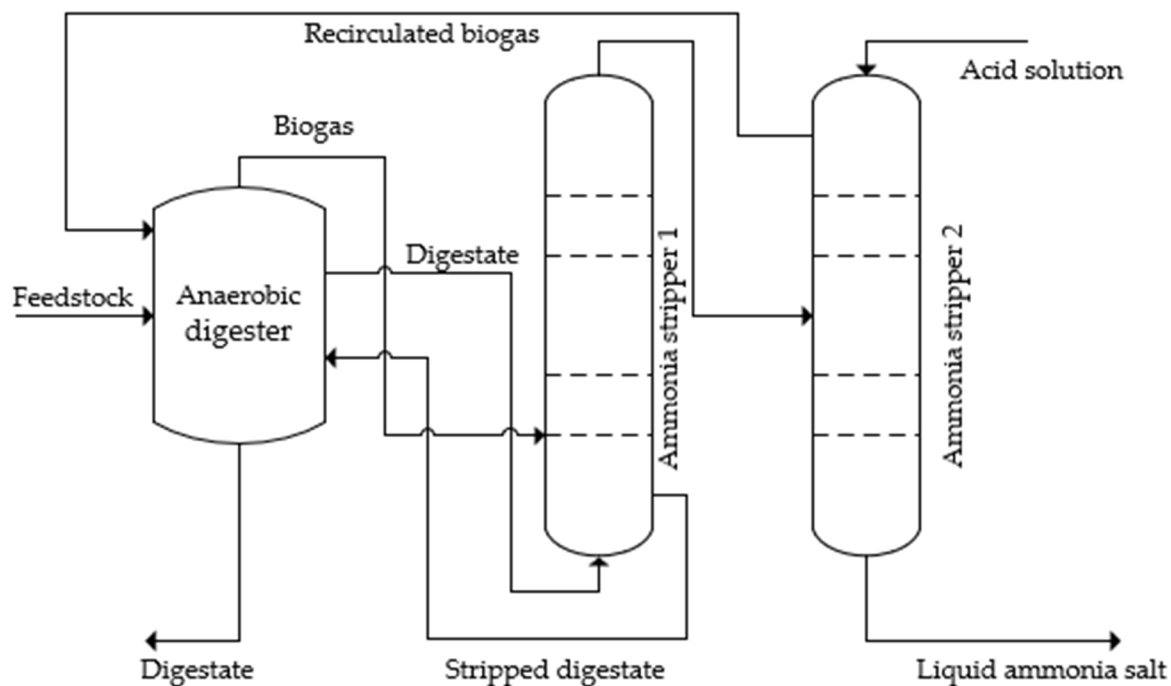


Figure 9. Ammonia recovery using stripping technology.

On the other hand, ammonia accumulation in anaerobic food waste digesters poses a significant challenge to process stability and biogas yield. High concentrations of free ammonia, particularly at elevated pH and temperature, inhibit methanogenic activity, leading to reduced biogas production and potential system failure [94].

Ammonia stripping involves the transfer of gaseous NH_4 from the liquid phase into a gas phase, facilitated by elevated temperature, increased pH, and enhanced mass transfer. Once stripped, ammonia gas can be captured using an acid solution, forming ammonium salts, which are valuable as fertilizers. Thus, the coupling of stripping and acid absorption enhances resource recovery and aligns with circular economy principles [95]. Several configurations exist for ammonia stripping: (1) *in situ* stripping—conducted within the digester, offering real-time ammonia control; (2) side-stream stripping—treats a portion of digestate externally, allowing flexible operation and minimal disruption to the main process [96]; (3) pre-digestion stripping—removes ammonia before digestion, reducing inhibition risks; and (4) post-digestion stripping—targets ammonia in the final digestate, optimizing fertilizer quality.

4.8. Membrane Separation

The membrane separation process of the liquid fraction aims to purify it by allowing the liquid fraction to move across the membrane with controlled extent and orientation

(see Figure 10). The size of the pores and the amount of pressure applied affect the degree and direction. Some particles are retained to create a concentrate, while the remainder passes through the membrane along with purified water [97].

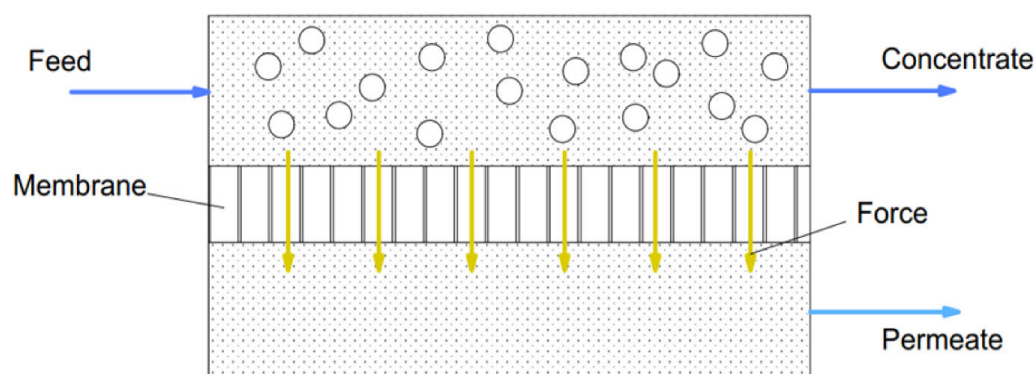


Figure 10. Schematic of the membrane separation process, adopted from [97].

Membrane technology enables the simultaneous treatment and nutrient recovery from the liquid portion of digestate. This advanced approach utilizes semi-permeable membranes to selectively isolate and extract nutrients and water, based on differences in molecular size or weight, making it a highly effective method for resource separation and reclamation.

4.9. Production of Fertilizer From Biowaste Material

Over time, the extensive use of synthetic fertilizers rich in nitrogen, phosphorus, and potassium has significantly contributed to ecological deterioration in agricultural regions across the globe [92]. In response to this pressing issue, there is increasing emphasis on converting biomass residues, including animal manure, sewage sludge, and food waste, into sustainable organic fertilizers. To enhance their agricultural utility, these waste types undergo treatment processes aimed at maximizing nutrient availability and improving soil health, thereby supporting a more ecologically responsible and circular economy. Table 7 outlines the properties of different biowaste sources commonly used in fertilizer production, as discussed by Chew et al. [98] in their recent review. The available literature [98] suggest that employing appropriate processing technologies is crucial not only for transforming these materials into effective organic fertilizers but also for ensuring sustainable waste management practices. This contributes to improved soil quality, reduced environmental impact, and the development of a regenerative agricultural system.

Table 7. Characteristics of different types of biowaste materials used for fertilizer production. Adapted from Chew et al. [98].

Source of Biomass	Processing Treatment into Fertilizer	Parameters Monitored and Their Resulting Effects
Chicken manure, compost	<i>Azotobacter</i> -based microbial treatment	Biological yield: The highest biological yield is attained when livestock manure is utilized. Gain yield: Improved nutritional conditions from organic manure lead to greater biomass accumulation and enhanced plant height.

Table 7. Cont.

Source of Biomass	Processing Treatment into Fertilizer	Parameters Monitored and Their Resulting Effects
Solid dairy manure	Surface applied and incorporated using a cultivator implement	Bacterial diversity: Manure amendments promoted higher bacterial diversity and provided more sustained effects than granular urea nitrogen treatments.
Livestock: chicken, pig and pigeon	Supplemented with non-organic nutrient sources	Aggregate stability: Stability declined, while the concentration of biological binding agents rose.
Food waste and cattle manure	--	Soil properties: Leaching and soil erosion led to reductions in total nitrogen and organic carbon levels within the soil.
Olive mill waste	Subjected to manual or mechanical mixing and periodically irrigated to maintain optimal moisture levels.	Yield: A compost blend containing equal parts food waste and cattle manure resulted in increased maize yield.
Food waste: rice, cabbage, pork	High-temperature aerobic reactor with dynamic operational parameters.	Agronomic: Crop yields achieved with compost were on par with those obtained using chemical fertilizers.
Bakery industry sludge	Left for decomposition and vermicomposted for three months.	Humic content showed no notable variation between compost and chemical fertilizer treatments.
		Composting process: After 96 h of fermentation, the composting process reached stable pH and electrical conductivity levels, indicating the formation of mature organic fertilizer.
		The constant agitation and friction inside the bioreactor fostered optimal conditions for microbial proliferation.
		Vermicomposting demonstrates strong remediation potential, making it effective for stabilizing metal-rich soils and lowering contaminant levels. It serves as a valuable approach for managing ecotoxicity in soils polluted with heavy metals.

5. Challenges and Limitations

In many low-income nations, inadequate waste management systems have resulted in practices like open dumping, which severely contaminates soil and water resources. Rapid urban expansion often outpaces the development of sustainable waste disposal infrastructure, intensifying environmental degradation and health risks. The fertilizer sector has historically resisted transitioning to renewable feedstocks, largely due to the substantial financial outlay required and the unpredictability of waste-derived materials, which vary in composition and availability, which may introduce operational challenges [16]. Although membrane-based nutrient recovery offers promising advantages, its real-world deployment faces hurdles such as membrane clogging, ammonia loss through volatilization, and prohibitive costs [99]. Common issues linked to the disposal of untreated livestock waste include strong odors, emissions of methane and ammonia, and the dissemination of nutrients and pathogens, factors that pose health hazards and diminish environmental quality. Additionally, due to

spatial constraints and farm distribution, nearly one-third of manure produced lacks access to suitable agricultural land for application [100]. In many regions, food waste is not separated from general household or municipal refuse, complicating efforts to recycle or repurpose it and undermining the efficiency of waste management systems. Within the European Union, the Waste Framework Directive (2008/98/EC) requires member states to establish source-separated collection and recycling schemes for organic waste [100].

6. Research Gap and Future Perspectives

Despite growing international efforts to integrate manure-derived fertilizers into formal markets, regulatory frameworks, particularly in the European Union (EU), continue to impose restrictive nitrogen thresholds that exclude manure-based products from broader commercial use. The classification of processed manure as livestock waste under the Nitrates Directive further limits its agricultural application, indicating a persistent regulatory bottleneck. Although emerging safety criteria are beginning to facilitate policy exemptions and market access, these developments remain fragmented and region-specific, as summarized in Table 8.

Table 8. Summary of studies on regional-based frameworks on utilization of organic fertilizers.

Region	Description	Policy Framework Support	Circular Economic Impact	Sustainable Agricultural	Ref.
Sub-Saharan Africa	Manure management practices and policies in sub-Saharan Africa: implications on manure quality as a fertilizer	Limited policy coherence; weak enforcement. Supports AU Agenda 2063 goals for soil health.	Improved manure handling promotes nutrient recycling.	Enhances crop yields and soil fertility.	[101]
Asia, Africa and Latin America	Global assessment of manure policies; identifies barriers and opportunities.	Varies by country; need for integrated policies.	Promotes integrated manure management.	Improves food security and reduces methane emissions.	[102]
Europe	Recycled nutrient fertilizers face adoption barriers due to contamination concerns.	Supports EU Circular Economy Action Plan.	Encourages waste valorization and nutrient recovery.	Reduces reliance on synthetic fertilizers.	[103]
Global	Nutrient stewardship: Taking 4R further	Supports national climate strategies. Aligned with AU climate goals.	Promotes efficient nutrient use and carbon sequestration.	Improves resilience and reduces emissions.	[104]
China	Green manure and reduced fertilizer improve soil carbon and yield.	Supports China's sustainable agriculture goals.	Enhances organic matter recycling.	Boosts soil fertility and carbon sequestration.	[105]
Africa	Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: A meta-analysis	Supports national soil health strategies and AU Agenda 2063	Promotes local production and trade of organic fertilizers.	Reverses soil degradation and boosts productivity.	[106]

Table 8. *Cont.*

Region	Description	Policy Framework Support	Circular Economic Impact	Sustainable Agricultural	Ref.
Global	Nutrient cycling in warm-climate grasslands.	Supports national nutrient management policies. Indirect alignment with AU soil health goals.	Highlights nutrient recycling in grazing systems.	Supports ecosystem modeling and sustainability.	[107]
Europe/USA	Assessment of composted pelletized poultry litter as an alternative to chemical fertilizers based on the environmental impact of their production	Supports EU Green Deal.	Reduces pollution and supports waste valorization.	Improves soil health and reduces nitrate leaching.	[108]
Europe	Insect-based bioconversion: value from food waste	Supports waste management policies.	Creates circular bio-products.	Reduces pollution and enhances farm income.	[109]

In contrast, South Africa has adopted more inclusive national fertilizer policies that promote bio-based inputs, especially to support smallholder farmers and mitigate environmental degradation. Regionally, the African Union’s Fertiliser and Soil Health Action Plan 2062 offers a strategic vision for enhancing fertilizer efficiency, scaling organic alternatives, and fostering climate-resilient agroecosystems. These initiatives align with key UN Sustainable Development Goals (SDGs) and African Union Agenda 2063 targets, cementing the role of circular principles in sustainable agriculture.

However, a critical research gap exists in the operationalization of these policy frameworks within South Africa’s food waste recycling sector, particularly regarding the commercialization, safety validation, and scalability of biofertilizers derived from organic waste streams. There is limited empirical evidence on how regulatory standards, market incentives, and stakeholder engagement can be harmonized to accelerate adoption and ensure long-term viability.

Future studies should focus on:

- Developing standardized safety and quality benchmarks for manure- and food waste-derived biofertilizers to support regulatory approval and market entry.
- Evaluating the socio-economic and environmental impacts of biofertilizer use in small-scale and commercial farming systems.
- Designing implementation frameworks with clearly defined institutional roles, accountability mechanisms, and performance indicators.
- Investigating financial models and incentive structures that can mobilize public and private investment in food waste valorization technologies.
- Exploring behavioral and policy interventions that promote public awareness, recognition, and participation in food conservation and waste reduction initiatives.

By addressing these gaps, future research can help build a robust, inclusive, and climate-smart biofertilizer market in South Africa, anchored in circular economy principles and aligned with regional and global sustainability goals.

7. Conclusions

The valorization of food waste through technologies such as anaerobic digestion, composting, pyrolysis, hydrothermal carbonization, and hydrothermal liquefaction presents a promising pathway toward sustainable biofertilizer and bioenergy production. These approaches not only address pressing global waste management challenges but also contribute to climate mitigation, resource recovery, and agricultural resilience. Among them, anaerobic digestion and composting have emerged as the most feasible options for the South African context, owing to their capacity for nutrient recovery and reduced greenhouse gas emissions. Nonetheless, the widespread adoption of these technologies faces persistent challenges, including heterogeneous waste streams, relatively high operational costs, and insufficient regulatory infrastructure. Overcoming these barriers will require coordinated efforts to enhance technological integration, optimize process efficiencies, and establish enabling policy environments. Moreover, fostering public awareness and stakeholder engagement is essential to catalyze behavioral shifts and support the transition towards a circular bioeconomy. By transforming food waste into valuable products, South Africa can simultaneously reduce environmental burdens, strengthen food and energy security, and advance inclusive, low-carbon development. This review highlights the urgent need for interdisciplinary collaboration and systematic innovation to unlock the full potential of food waste recycling technologies in shaping a resilient and resource-efficient future.

Author Contributions: Conceptualization, S.Z.M. and E.K.T.; resources, E.K.T. and S.R.; writing—original draft preparation, S.Z.M., E.K.T. and S.M.K.; writing—review and editing, E.K.T., S.M.K. and S.R.; visualization, S.Z.M., E.K.T. and S.M.K.; supervision, E.K.T. and S.R.; funding acquisition, E.K.T. and S.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No data were generated for this study.

Acknowledgments: The authors declared that the use of Grammarly Pro version for Microsoft word 365 and Microsoft Copilot 365 were employed to improve the grammar of the write-up. After using these tools/services, the authors reviewed and edited the content as needed and took full responsibility.

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

References

1. Sarker, A.; Ahmmed, R.; Ahsan, S.; Rana, J.; Ghosh, M.K.; Nandi, R. A comprehensive review of food waste valorization for the sustainable management of global food waste. *Sustain. Food Technol.* **2024**, *2*, 48–69.
2. Jiang, H.; Deng, F.; Luo, Y.; Xie, Z.; Chen, Y.; Zhou, P.; Liu, X.; Li, D. Hydrothermal carbonization of corn straw in biogas slurry. *J. Clean. Prod.* **2022**, *353*, 131682. [[CrossRef](#)]
3. Rosenberg, M. Thoughts about food security, food loss and waste and what has to be done. *AIMS Agric. Food* **2021**, *6*, 797–798. [[CrossRef](#)]
4. Capanoglu, E.; Nemli, E.; Tomas-Barberan, F. Novel approaches in the valorization of agricultural wastes and their applications. *J. Agric. Food Chem.* **2022**, *70*, 6787–6804. [[CrossRef](#)]
5. Pérez, S.; Giraldo, S.; Forgionny, A.; Flórez, E.; Acelas, N. Eco-friendly reuse of agricultural wastes to produce biocomposites with high potential in water treatment and fertilizers. *Biomass Convers. Biorefinery* **2024**, *14*, 8537–8547. [[CrossRef](#)]
6. Mokotong, D.; Ribeiro, R.V. *Community Health Impact Assessment for the Proposed Multisand General Waste Management Facility Project*; Niara Environmental Consultants (Pty) Ltd.: Johannesburg, South Africa, 2023.
7. Sahathu, R. An Evaluation of the Waste Management Cycle Utilised by Fresh Produce Market Informal Traders in Durban, KwaZulu-Natal. Ph.D. Thesis, University of KwaZulu-Natal, KwaZulu-Natal, South Africa, 2021.
8. Ndobe, F.N. The Impacts of Landfill Management Site a on Grass, Soil, and Surface Water: A Preliminary Study in Kwazulu-Natal, South Africa. Master's Thesis, University of the Witwatersrand, Johannesburg, South Africa, 2023.

9. Skrzypczak, D.; Trzaska, K.; Mironiuk, M.; Mikula, K.; Izydorczyk, G.; Polomska, X.; Wiśniewski, J.; Mielko, K.; Moustakas, K.; Chojnacka, K. Recent innovations in fertilization with treated digestate from food waste to recover nutrients for arid agricultural fields. *Environ. Sci. Pollut. Res.* **2024**, *31*, 41563–41585. [\[CrossRef\]](#)
10. Parfitt, J.; Barthel, M.; Macnaughton, S. Food waste within food supply chains: Quantification and potential for change to 2050. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 3065–3081. [\[CrossRef\]](#)
11. Saba, B.; Bharathidasan, A.K.; Ezeji, T.C.; Cornish, K. Characterization and potential valorization of industrial food processing wastes. *Sci. Total Environ.* **2023**, *868*, 161550. [\[CrossRef\]](#)
12. Adeleke, O.; Akinlabi, S.; Jen, T.-C.; Dunmade, I. Towards sustainability in municipal solid waste management in South Africa: A survey of challenges and prospects. *Trans. R. Soc. S. Afr.* **2021**, *76*, 53–66. [\[CrossRef\]](#)
13. Kharola, S.; Ram, M.; Kumar Mangla, S.; Goyal, N.; Nautiyal, O.P.; Pant, D.; Kazancoglu, Y. Exploring the green waste management problem in food supply chains: A circular economy context. *J. Clean. Prod.* **2022**, *351*, 131355. [\[CrossRef\]](#)
14. Kharola, S.; Ram, M.; Goyal, N.; Mangla, S.K.; Nautiyal, O.P.; Rawat, A.; Kazancoglu, Y.; Pant, D. Barriers to organic waste management in a circular economy. *J. Clean. Prod.* **2022**, *362*, 132282. [\[CrossRef\]](#)
15. Kassim, F.O.; Thomas, C.L.P.; Afolabi, O.O.D. Integrated conversion technologies for sustainable agri-food waste valorization: A critical review. *Biomass Bioenergy* **2022**, *156*, 106314. [\[CrossRef\]](#)
16. Chojnacka, K.; Moustakas, K.; Mikulewicz, M. Valorisation of agri-food waste to fertilisers is a challenge in implementing the circular economy concept in practice. *Environ. Pollut.* **2022**, *312*, 119906. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Vaneeckhaute, C.; Lebuf, V.; Michels, E.; Belia, E.; Vanrolleghem, P.A.; Tack, F.M.; Meers, E. Nutrient recovery from digestate: Systematic technology review and product classification. *Waste Biomass Valorization* **2017**, *8*, 21–40. [\[CrossRef\]](#)
18. Wang, L.; Chi, Y.; Du, K.; Zhou, Z.; Wang, F.; Huang, Q. Hydrothermal treatment of food waste for bio-fertilizer production: Regulation of humus substances and nutrient (N and P) in hydrochar by feedwater pH. *Waste Biomass Valorization* **2023**, *14*, 2767–2781. [\[CrossRef\]](#)
19. Vaishnavi, M.; Kumar, K.S.; Gopinath, K.P. Comparative studies on catalytic hydrothermal liquefaction of mixed household waste into bio crude. *Biomass Convers. Biorefinery* **2023**, *13*, 14253–14265. [\[CrossRef\]](#)
20. Bayat, H.; Dehghanizadeh, M.; Jarvis, J.M.; Brewer, C.E.; Jena, U. Hydrothermal liquefaction of food waste: Effect of process parameters on product yields and chemistry. *Front. Sustain. Food Syst.* **2021**, *5*, 658592. [\[CrossRef\]](#)
21. Shah, A.A.; Sharma, K.; Haider, M.S.; Toor, S.S.; Rosendahl, L.A.; Pedersen, T.H.; Castello, D. The Role of Catalysts in Biomass Hydrothermal Liquefaction and Biocrude Upgrading. *Processes* **2022**, *10*, 207. [\[CrossRef\]](#)
22. Dhalsamant, K.; Dalai, A.K. Optimization and characterization of biocrude produced from hydrothermal liquefaction of food waste. *Sustain. Energy Fuels* **2025**, *9*, 2119–2136. [\[CrossRef\]](#)
23. Fleaca, C.; Severin, I. Comparative analysis of organizational performance using the EFQM Excellence Model: The sustainability perspective. *Cogn. Sustain.* **2024**, *3*, 34–49. [\[CrossRef\]](#)
24. Reike, D.; Vermeulen, W.J.; Witjes, S. Conceptualization of circular economy 3.0: Synthesizing the 10R hierarchy of value retention options. In *Towards a Circular Economy*; Springer: Cham, Switzerland, 2022; pp. 47–69. [\[CrossRef\]](#)
25. Debrah, J.K.; Teye, G.K.; Dinis, M.A.P. Barriers and challenges to waste management hindering the circular economy in Sub-Saharan Africa. *Urban Sci.* **2022**, *6*, 57. [\[CrossRef\]](#)
26. Davis, J. Food waste in the United States. *Ballard Brief* **2022**, *2022*, 7.
27. Meena, M.D.; Dotaniya, M.L.; Meena, B.L.; Rai, P.K.; Antil, R.S.; Meena, H.S.; Meena, L.K.; Dotaniya, C.K.; Meena, V.S.; Ghosh, A.; et al. Municipal solid waste: Opportunities, challenges and management policies in India: A review. *Waste Manag. Bull.* **2023**, *1*, 4–18. [\[CrossRef\]](#)
28. Melikoglu, M.; Lin, C.S.K.; Webb, C. Analysing global food waste problem: Pinpointing the facts and estimating the energy content. *Cent. Eur. J. Eng.* **2013**, *3*, 157–164. [\[CrossRef\]](#)
29. Dou, Z.; Toth, J.D. Global primary data on consumer food waste: Rate and characteristics—A review. *Resour. Conserv. Recycl.* **2021**, *168*, 105332. [\[CrossRef\]](#)
30. Withanage, S.V.; Dias, G.M.; Habib, K. Review of household food waste quantification methods: Focus on composition analysis. *J. Clean. Prod.* **2021**, *279*, 123722. [\[CrossRef\]](#)
31. Chhandama, M.V.L.; Chetia, A.C.; Satyan, K.B.; Supongsenla, A.; Ruatpuia, J.V.L.; Rokhum, S.L. Valorisation of food waste to sustainable energy and other value-added products: A review. *Bioresour. Technol. Rep.* **2022**, *17*, 100945. [\[CrossRef\]](#)
32. Mbazima, S.J.; Masekameni, M.D.; Mmereki, D. Waste-to-energy in a developing country: The state of landfill gas to energy in the Republic of South Africa. *Energy Explor. Exploit.* **2022**, *40*, 1287–1312. [\[CrossRef\]](#)
33. Dlamini, N.; Rampedi, I.; Kwenda, P. Assessing how load-shedding affects the generation of household food waste in Merafong City Local Municipality, South Africa. *Dev. South. Afr.* **2025**, *42*, 1–18. [\[CrossRef\]](#)
34. Roy, P.; Mohanty, A.K.; Dick, P.; Misra, M. A review on the challenges and choices for food waste valorization: Environmental and economic impacts. *ACS Environ. Au* **2023**, *3*, 58–75. [\[CrossRef\]](#)

35. Scarlat, N.; Motola, V.; Dallemand, J.F.; Monforti-Ferrario, F.; Mofor, L. Evaluation of energy potential of Municipal Solid Waste from African urban areas. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1269–1286. [\[CrossRef\]](#)
36. Cudjoe, D.; Nketiah, E.; Obuobi, B.; Adu-Gyamfi, G.; Adjei, M.; Zhu, B. Forecasting the potential and economic feasibility of power generation using biogas from food waste in Ghana: Evidence from Accra and Kumasi. *Energy* **2021**, *226*, 120342. [\[CrossRef\]](#)
37. Tayyab, A.; Ahmad, Z.; Mahmood, T.; Khalid, A.; Qadeer, S.; Mahmood, S.; Andleeb, S.; Anjum, M. Anaerobic co-digestion of catering food waste utilizing *Parthenium hysterophorus* as co-substrate for biogas production. *Biomass Bioenergy* **2019**, *124*, 74–82. [\[CrossRef\]](#)
38. Joshi, S.M.; Gogate, P.R. Intensifying the biogas production from food waste using ultrasound: Understanding into effect of operating parameters. *Ultrason. Sonochem.* **2019**, *59*, 104755. [\[CrossRef\]](#)
39. Yentekakis, I.V.; Goula, G. Biogas management: Advanced utilization for production of renewable energy and added-value chemicals. *Front. Environ. Sci.* **2017**, *5*, 7. [\[CrossRef\]](#)
40. Mkhize, N.; Mjoli, N.S.; Khumalo, S.M.; Tettte, E.K.; Mahlangu, T.P.; Rathilal, S. Enhanced Biogas Production through Anaerobic Co-Digestion of Agricultural Wastes and Wastewater: A Case Study in South Africa. *Int. J. Energy Prod. Manag.* **2023**, *8*, 123–131. [\[CrossRef\]](#)
41. Tshemese, Z.; Deenadayalu, N.; Linganis, L.Z.; Chetty, M. An overview of biogas production from anaerobic digestion and the possibility of using sugarcane wastewater and municipal solid waste in a South African context. *Appl. Syst. Innov.* **2023**, *6*, 13. [\[CrossRef\]](#)
42. Chow, W.L.; Chong, S.; Lim, J.W.; Chan, Y.J.; Chong, M.F.; Tiong, T.J.; Chin, J.K.; Pan, G.-T. Anaerobic co-digestion of wastewater sludge: A review of potential co-substrates and operating factors for improved methane yield. *Processes* **2020**, *8*, 39. [\[CrossRef\]](#)
43. Awosusi, A.; Sethunya, V.; Matambo, T. Synergistic effect of anaerobic co-digestion of South African food waste with cow manure: Role of low density-polyethylene in process modulation. *Mater. Today Proc.* **2021**, *38*, 793–803. [\[CrossRef\]](#)
44. Ravi, B. Investigating the Use of Anaerobic Fungi to Enhance the Hydrolysis of Lignocellulose in Lab Scale Biodigesters. Master's Thesis, University of Guelph, Guelph, ON, Canada, 2017.
45. Saady, N.M.C.; Massé, D.I. Impact of organic loading rate on psychrophilic anaerobic digestion of solid dairy manure. *Energies* **2015**, *8*, 1990–2007. [\[CrossRef\]](#)
46. Armah, E.K. Anaerobic Co-Digestion of Agricultural Biomass with Industrial Wastewater for Biogas Production. Ph.D. Thesis, Durban University of Technology, Durban, South Africa, 2021.
47. Prabhu, M.S.; Mutnuri, S. Anaerobic co-digestion of sewage sludge and food waste. *Waste Manag. Res.* **2016**, *34*, 307–315. [\[CrossRef\]](#)
48. Nuanual, S.; Thanarak, P.; Maneechot, P.; Artkla, R. Life Cycle Assessment of Anaerobic Digestion of Food Waste in the Presence of Manure Concerned Global Warming Potential. *GMSARN Int. J.* **2024**, *18*, 340–347.
49. Martín-Sanz-Garrido, C.; Revuelta-Aramburu, M.; Santos-Montes, A.M.; Morales-Polo, C. A Review on Anaerobic Digestate as a Biofertilizer: Characteristics, Production, and Environmental Impacts from a Life Cycle Assessment Perspective. *Appl. Sci.* **2025**, *15*, 8635. [\[CrossRef\]](#)
50. Zhao, Z.; Qi, S.; Wang, R.; Li, H.; Song, G.; Li, H.; Yin, Q. Life cycle assessment of food waste energy and resource conversion scheme via the integrated process of anaerobic digestion and hydrothermal carbonization. *Int. J. Hydrogen Energy* **2024**, *52*, 122–132. [\[CrossRef\]](#)
51. Hanafiah, M.M.; Ansari, I.; Chelvam, K. Life cycle assessment of anaerobic digestion systems: An approach towards sustainable waste management. In *Renewable Energy Technologies for Energy Efficient Sustainable Development*; Springer: Heidelberg, Germany, 2022; pp. 391–414.
52. Alengebawy, A.; Ran, Y.; Osman, A.I.; Jin, K.; Samer, M.; Ai, P. Anaerobic digestion of agricultural waste for biogas production and sustainable bioenergy recovery: A review. *Environ. Chem. Lett.* **2024**, *22*, 2641–2668. [\[CrossRef\]](#)
53. Mahish, P.K.; Verma, D.K.; Ghritlahare, A.; Arora, C.; Otero, P. Microbial bioconversion of food waste to bio-fertilizers. *Sustain. Food Technol.* **2024**, *2*, 689–708. [\[CrossRef\]](#)
54. Rashid, M.I.; Shahzad, K. Food waste recycling for compost production and its economic and environmental assessment as circular economy indicators of solid waste management. *J. Clean. Prod.* **2021**, *317*, 128467. [\[CrossRef\]](#)
55. Wang, Y.; Tang, Y.; Yuan, Z. Improving food waste composting efficiency with mature compost addition. *Bioresour. Technol.* **2022**, *349*, 126830. [\[CrossRef\]](#)
56. Yaser, A.Z.; Lamaming, J.; Suali, E.; Rajin, M.; Saalah, S.; Kamin, Z.; Safie, N.N.; Aji, N.A.S.; Wid, N. Composting and anaerobic digestion of food waste and sewage sludge for campus sustainability: A review. *Int. J. Chem. Eng.* **2022**, *2022*, 6455889. [\[CrossRef\]](#)
57. Mataba, A.L.; Msuya, N.; Katima, Z. Production of Biofertilizer from Fruit and Garden Waste. *Tanzan. J. Eng. Technol.* **2024**, *43*, 158–168. [\[CrossRef\]](#)
58. Le Pera, A.; Sellaro, M.; Bencivenni, E. Composting food waste or digestate? Characteristics, statistical and life cycle assessment study based on an Italian composting plant. *J. Clean. Prod.* **2022**, *350*, 131552. [\[CrossRef\]](#)
59. Sampaio, I.C.F.; da Silva Quinto, A.S.; de Moura, I.V.L.; Cezar, K.S.; Franco, M.; de Almeida, P.F. The role of composting in sustainable agriculture and waste management. In *Progress in Hydrogen Energy, Fuel Cells, Nano-Biotechnology and Advanced, Bioactive Compounds*; Springer: Heidelberg, Germany, 2024; pp. 417–432.

60. Sayara, T.; Basheer-Salimia, R.; Hawamde, F.; Sánchez, A. Recycling of organic wastes through composting: Process performance and compost application in agriculture. *Agronomy* **2020**, *10*, 1838. [\[CrossRef\]](#)
61. Yang, J.; Tang, S.; Song, B.; Jiang, Y.; Zhu, W.; Zhou, W.; Yang, G. Optimization of integrated anaerobic digestion and pyrolysis for biogas, biochar and bio-oil production from the perspective of energy flow. *Sci. Total Environ.* **2023**, *872*, 162154. [\[CrossRef\]](#) [\[PubMed\]](#)
62. Lee, S.; Tsang, Y.F.; Lin, K.-Y.A.; Kwon, E.E.; Lee, J. Employment of biogas as pyrolysis medium and chemical feedstock. *J. CO2 Util.* **2022**, *57*, 101877. [\[CrossRef\]](#)
63. Xu, F.; Ming, X.; Jia, R.; Zhao, M.; Wang, B.; Qiao, Y.; Tian, Y. Effects of operating parameters on products yield and volatiles composition during fast pyrolysis of food waste in the presence of hydrogen. *Fuel Process. Technol.* **2020**, *210*, 106558. [\[CrossRef\]](#)
64. Su, G.; Ong, H.C.; Fattah, I.M.R.; Ok, Y.S.; Jang, J.-H.; Wang, C.-T. State-of-the-art of the pyrolysis and co-pyrolysis of food waste: Progress and challenges. *Sci. Total Environ.* **2022**, *809*, 151170. [\[CrossRef\]](#)
65. Lin, J.; Ma, R.; Luo, J.; Sun, S.; Cui, C.; Fang, L.; Huang, H. Microwave pyrolysis of food waste for high-quality syngas production: Positive effects of a CO₂ reaction atmosphere and insights into the intrinsic reaction mechanisms. *Energy Convers. Manag.* **2020**, *206*, 112490. [\[CrossRef\]](#)
66. Kadlimatti, H.; Mohan, B.R.; Saidutta, M. Bio-oil from microwave assisted pyrolysis of food waste-optimization using response surface methodology. *Biomass Bioenergy* **2019**, *123*, 25–33. [\[CrossRef\]](#)
67. Lee, Y.-E.; Shin, D.-C.; Jeong, Y.; Kim, I.-T.; Yoo, Y.-S. Effects of pyrolysis temperature and retention time on fuel characteristics of food waste feedstuff and compost for co-firing in coal power plants. *Energies* **2019**, *12*, 4538. [\[CrossRef\]](#)
68. Opatokun, S.A.; Kan, T.; Al Shoaibi, A.; Srinivasakannan, C.; Strezov, V. Characterization of food waste and its digestate as feedstock for thermochemical processing. *Energy Fuels* **2016**, *30*, 1589–1597. [\[CrossRef\]](#)
69. Zhao, J.; Zhao, J.; Wang, Z.; Lin, S.; Yan, B.; Chen, G.; Zhou, W. Life cycle assessment of anaerobic digestion coupled co-pyrolysis for treatment of food waste. *Bioresour. Technol.* **2025**, *421*, 132145. [\[CrossRef\]](#)
70. Gahane, D.; Biswal, D.; Mandavgane, S.A. Life Cycle Assessment of Biomass Pyrolysis. *BioEnergy Res.* **2022**, *15*, 1387–1406. [\[CrossRef\]](#)
71. Orlandella, I.; Fiore, S. Life Cycle Assessment of the Production of Biofertilizers from Agricultural Waste. *Sustainability* **2025**, *17*, 421. [\[CrossRef\]](#)
72. Pradhan, S.; Parthasarathy, P.; Mackey, H.R.; Al-Ansari, T.; McKay, G. Food waste biochar: A sustainable solution for agriculture application and soil–water remediation. *Carbon Res.* **2024**, *3*, 41. [\[CrossRef\]](#)
73. Hämäläinen, A.; Kokko, M.; Tolvanen, H.; Kinnunen, V.; Rintala, J. Towards the implementation of hydrothermal carbonization for nutrients, carbon, and energy recovery in centralized biogas plant treating sewage sludge. *Waste Manag.* **2024**, *173*, 99–108. [\[CrossRef\]](#)
74. Mikusińska, J.; Kuźnia, M.; Czerwińska, K.; Wilk, M. Hydrothermal carbonization of digestate produced in the biogas production process. *Energies* **2023**, *16*, 5458. [\[CrossRef\]](#)
75. Cao, Z.; Hülsemann, B.; Wüst, D.; Oechsner, H.; Lautenbach, A.; Kruse, A. Effect of residence time during hydrothermal carbonization of biogas digestate on the combustion characteristics of hydrochar and the biogas production of process water. *Bioresour. Technol.* **2021**, *333*, 125110. [\[CrossRef\]](#)
76. González-Arias, J.; Sánchez, M.E.; Cara-Jiménez, J.; Baena-Moreno, F.M.; Zhang, Z. Hydrothermal carbonization of biomass and waste: A review. *Environ. Chem. Lett.* **2022**, *20*, 211–221. [\[CrossRef\]](#)
77. Wang, Q.; Wu, S.; Cui, D.; Zhou, H.; Wu, D.; Pan, S.; Xu, F.; Wang, Z. Co-hydrothermal carbonization of organic solid wastes to hydrochar as potential fuel: A review. *Sci. Total Environ.* **2022**, *850*, 158034. [\[CrossRef\]](#)
78. Ho, T.T.-T.; Nadeem, A.; Choe, K. A review of upscaling hydrothermal carbonization. *Energies* **2024**, *17*, 1918. [\[CrossRef\]](#)
79. Mannarino, G.; Sarrion, A.; Diaz, E.; Gori, R.; De la Rubia, M.A.; Mohedano, A.F. Improved energy recovery from food waste through hydrothermal carbonization and anaerobic digestion. *Waste Manag.* **2022**, *142*, 9–18. [\[CrossRef\]](#)
80. McGaughy, K.; Toufiq Reza, M. Hydrothermal carbonization of food waste: Simplified process simulation model based on experimental results. *Biomass Convers. Biorefinery* **2018**, *8*, 283–292. [\[CrossRef\]](#)
81. Saengsuriwong, R.; Onsee, T.; Phromphithak, S.; Tippayawong, N. Biocrude oil production via hydrothermal liquefaction of food waste in a simplified high-throughput reactor. *Bioresour. Technol.* **2021**, *341*, 125750. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Tito, E.; Marcolongo, C.A.; Pipitone, G.; Monteverde, A.H.A.; Bensaid, S.; Pirone, R. Understanding the effect of heating rate on hydrothermal liquefaction: A comprehensive investigation from model compounds to a real food waste. *Bioresour. Technol.* **2024**, *396*, 130446. [\[CrossRef\]](#)
83. Ahmed Ebrahim, S.; Robertson, G.; Jiang, X.; Baranova, E.A.; Singh, D. Catalytic hydrothermal liquefaction of food waste: Influence of catalysts on bio-crude yield, asphaltenes, and pentane soluble fractions. *Fuel* **2022**, *324*, 124452. [\[CrossRef\]](#)
84. Biswas, B.; Rahman, T.; Adhikari, S. Mono-and bi-metal catalytic hydrothermal liquefaction of food waste: Screening the process parameter on product yield and characterizations. *J. Clean. Prod.* **2024**, *471*, 143398. [\[CrossRef\]](#)
85. Wang, T.; Dai, Y.; Shang, H.; Si, B.; Sanginova, O.; Yu, Y. Life cycle assessment of integrated hydrothermal liquefaction of food waste with biological process toward bio-oil production. *Biomass Convers. Biorefinery* **2025**, *15*, 14075–14088. [\[CrossRef\]](#)

86. Barampouti, E.M.; Mai, S.; Malamis, D.; Moustakas, K.; Loizidou, M. Exploring technological alternatives of nutrient recovery from digestate as a secondary resource. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110379. [\[CrossRef\]](#)
87. Trotta, S.; Adani, F.; Fedele, M.; Salvatori, M. Nitrogen and phosphorus recovery from cow digestate by struvite precipitation: Process optimization to maximize phosphorus recovery. *Results Eng.* **2023**, *20*, 101478. [\[CrossRef\]](#)
88. Aldaach, H.; Zaki, M.T.; Orner, K.D. Improving Prediction of Nutrient Recovery via Struvite Precipitation from Organic Waste Digestate. *Environ. Eng. Sci.* **2025**, *42*, 53–67. [\[CrossRef\]](#)
89. Kumar, R.; and Pal, P. Assessing the feasibility of N and P recovery by struvite precipitation from nutrient-rich wastewater: A review. *Environ. Sci. Pollut. Res.* **2015**, *22*, 17453–17464. [\[CrossRef\]](#) [\[PubMed\]](#)
90. Corona, F.; Hidalgo, D.; Martín-Marroquín, J.M.; Antolín, G. Study of the influence of the reaction parameters on nutrients recovering from digestate by struvite crystallisation. *Environ. Sci. Pollut. Res.* **2021**, *28*, 24362–24374. [\[CrossRef\]](#) [\[PubMed\]](#)
91. Sangeetha, V.; Devasena, M.; Nambi, I.M.; Dwarakanathan, S. Crystallization of struvite family crystals from cow urine: Analysis, characterization, and effects of crystallization method, retention time, rate of mixing, and competing ions. *Biomass Convers. Biorefinery* **2024**, *14*, 2357–2368. [\[CrossRef\]](#)
92. Yang, D.; Chen, Q.; Liu, R.; Song, L.; Zhang, Y.; Dai, X. Ammonia recovery from anaerobic digestate: State of the art, challenges and prospects. *Bioresour. Technol.* **2022**, *363*, 127957. [\[CrossRef\]](#)
93. Aung, S.L.; Choi, J.; Cha, H.; Woo, G.; Song, K.G. Ammonia-selective recovery from anaerobic digestate using electrochemical ammonia stripping combined with electrodialysis. *Chem. Eng. J.* **2024**, *479*, 147949. [\[CrossRef\]](#)
94. Tao, W.; Ukwuani, A.T.; Agyeman, F. Recovery of ammonia in anaerobic digestate using vacuum thermal stripping–acid absorption process: Scale-up considerations. *Water Sci. Technol.* **2018**, *78*, 878–885. [\[CrossRef\]](#)
95. Ghyselbrecht, K.; Monballiu, A.; Somers, M.; Sigurnjak, I.; Meers, E.; Appels, L.; Meesschaert, B. Stripping and scrubbing of ammonium using common fractionating columns to prove ammonium inhibition during anaerobic digestion. *Int. J. Energy Environ. Eng.* **2018**, *9*, 447–455. [\[CrossRef\]](#)
96. Walker, M.; Iyer, K.; Heaven, S.; Banks, C. Ammonia removal in anaerobic digestion by biogas stripping: An evaluation of process alternatives using a first order rate model based on experimental findings. *Chem. Eng. J.* **2011**, *178*, 138–145. [\[CrossRef\]](#)
97. Nowak, M.; Czekala, W. Sustainable Use of Digestate from Biogas Plants: Separation of Raw Digestate and Liquid Fraction Processing. *Sustainability* **2024**, *16*, 5461. [\[CrossRef\]](#)
98. Chew, K.W.; Chia, S.R.; Yen, H.-W.; Nomanbhay, S.; Ho, Y.-C.; Show, P.L. Transformation of biomass waste into sustainable organic fertilizers. *Sustainability* **2019**, *11*, 2266. [\[CrossRef\]](#)
99. Zielińska, M.; Bułkowska, K. Use of Membrane Techniques for Removal and Recovery of Nutrients from Liquid Fraction of Anaerobic Digestate. *Membranes* **2025**, *15*, 45. [\[CrossRef\]](#) [\[PubMed\]](#)
100. Ivanović, N.; Vučinić, A.; Marinković, V.; Krajnović, D.; Čurčić, M. Towards Sustainable Food Waste Management in Serbia: A Review of Challenges, Gaps, and Future Perspectives. *Sustainability* **2025**, *17*, 2961. [\[CrossRef\]](#)
101. Ndambi, O.A.; Pelster, D.E.; Owino, J.O.; De Buisson, F.; Vellinga, T. Manure management practices and policies in sub-Saharan Africa: Implications on manure quality as a fertilizer. *Front. Sustain. Food Syst.* **2019**, *3*, 29. [\[CrossRef\]](#)
102. Teenstra, E.; Vellinga, T.V.; Aektaeng, N.; Amatayakul, W.; Ndambi, A.; Pelster, D.E.; Germer, L.; Jenet, A.; Opio, C.; Andeweg, K. Global Assessment of Manure Management Policies and Practices. Wageningen UR Livestock Research: Wageningen, The Netherlands, 2014.
103. Cordeiro, C.M.; Sindhøj, E. Situating the discourse of recycled nutrient fertilizers in circular economy principles for sustainable agriculture. *Front. Sustain.* **2024**, *5*, 1465752. [\[CrossRef\]](#)
104. Bruulsema, T. Nutrient stewardship: Taking 4R further. *Crops Soils* **2022**, *55*, 34–40. [\[CrossRef\]](#)
105. Zhang, J.; He, W.; Wei, Z.; Chen, Y.; Gao, W. Integrating green manure and fertilizer reduction strategies to enhance soil carbon sequestration and crop yield: Evidence from a two-season pot experiment. *Front. Sustain. Food Syst.* **2025**, *8*, 1514409. [\[CrossRef\]](#)
106. Gram, G.; Roobroeck, D.; Pypers, P.; Six, J.; Merckx, R.; Vanlauwe, B. Combining organic and mineral fertilizers as a climate-smart integrated soil fertility management practice in sub-Saharan Africa: A meta-analysis. *PLoS ONE* **2020**, *15*, e0239552. [\[CrossRef\]](#)
107. Dubeux Jr, J.; Sollenberger, L.; Mathews, B.; Scholberg, J.; Santos, H. Nutrient cycling in warm-climate grasslands. *Crop Sci.* **2007**, *47*, 915–928. [\[CrossRef\]](#)
108. Kiss, N.É.; Tamás, J.; Szöllősi, N.; Gorliczay, E.; Nagy, A. Assessment of composted pelletized poultry litter as an alternative to chemical fertilizers based on the environmental impact of their production. *Agriculture* **2021**, *11*, 1130. [\[CrossRef\]](#)
109. Fowles, T.M.; Nansen, C. Insect-based bioconversion: Value from food waste. In *Food Waste Management: Solving the Wicked Problem*; Springer: Heidelberg, Germany, 2019; pp. 321–346.

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