JURNAL TEKNIK LINGKUNGAN
E-ISSN: 27146715
Journal homepage: www.envengjournal.com

Evaluation of Food Waste Anaerobic Baffled Reactor Residues as Organic Fertilizer Source

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Abstract

Food waste is an abundant organic resource that can be valorized through anaerobic digestion, producing both energy and nutrient-rich residues. This study assessed the potential of residues from a 75 L Anaerobic Baffled Reactor (ABR) as an alternative source of organic fertilizer. The reactor, equipped with four partitions, was operated for 17 days under mesophilic conditions using an influent mixture of 75% food waste and 25% activated sludge. Process performance was evaluated through suspended solids and ammonia nitrogen monitoring, while the residue was analyzed for nutrient content and tested for agronomic potential using seed germination assays. The ABR achieved an 88% reduction in suspended solids, confirming effective solids stabilization. However, the low C/N ratio of the feedstock led to continuous ammonia accumulation and acidic conditions, restricting methanogenesis. The solid residue contained 0.44% nitrogen, 0.13% phosphorus, and 0.42% potassium. In the germination test, 5 out of 10 Ipomoea seeds grew successfully after two weeks of residue application, showing partial fertilization potential. The findings indicate that ABR residues are more suitable as soil conditioners or supplementary fertilizer components rather than stand-alone fertilizers. Process optimization and nutrient recovery strategies are recommended to enhance their agronomic value.

Keywords: *anaerobic baffled reactor; food waste; organic fertilizer; residue*

ARTICLE INFO

Citation: *Viareco, H., Ardiansyah, E., & Sufra, R. (2025). Evaluation of Food Waste Anaerobic Baffled Reactor Residues as Organic Fertilizer Source. Jurnal Teknik Lingkungan, 31(2), 1-15.*

Article History:
Received 30 Aug 2025
Revised 04 Oct 2025
Accepted 21 Oct 2025
Available online 30 Oct 2025

1. Introduction

Anaerobic treatment is a means of processing organic waste to help convert most of the decomposing organic carbon into biogas for use as energy, and reduces pathogens and minimizes odors while allowing most of the nutrients to remain in the digested material (Kaushal et al., 2022; Liu et al., 2022). Anaerobic treatment only affects the quality of the treated waste, does not change its quantity at all, and it depends on several factors such as the biodegradability of the waste, retention time, and treatment temperature (Qi et al., 2021; Rashid et al., 2021; Sodergren et al., 2022). If the waste is not easily decomposed and the treatment is not good, the process of decomposition of organic matter does not change much (Cheong et al., 2020; Chuka-Ogwude et al., 2020; Clack et al., 2019). For other contents such as phosphorus, potassium, and other macro elements, it seems to remain unchanged, anaerobic treatment and its concentration increase after sludge treatment is optimized (Majee et al., 2021; Okebalama et al., 2022). Wastewater treatment residue (sludge) is a nutrient-rich material that can be used as fertilizer.

Waste is not easily decomposed and if digestion is not good, the process of decomposition of organic matter does not change much. For other contents such as phosphorus, potassium, and other macro elements, it appears to remain unchanged, while anaerobic processing and its concentration increase after digestion when the change to sludge is digested (Ahamed et al., 2015). Sludge that has been digested has the potential to be used as fertilizer for agriculture (Song et al., 2022; Vasmara et al., 2021). The liquid residue produced will contain dissolved organic matter, micro-nutrients and microorganisms as well as macro-nutrients that can be converted into good soil resources and useful in agricultural production by combining with other wastes (Yahaya et al., 2022). Used as fertilizer, anaerobic digested material can also be used as animal feed (Samoraj et al., 2022). These findings indicate that both the solid and liquid fractions of anaerobic digestion have potential agronomic value, but their actual performance as fertilizer must be verified experimentally.

Previous research on anaerobic digestion has largely focused on biogas production, process efficiency, and organic matter reduction, while only a few studies have examined the agronomic potential of the solid residues produced (Cheong et al., 2020; Liu et al., 2022). In particular, studies on residues from the Anaerobic Baffled Reactor (ABR) system remain limited. The ABR configuration, with its compartmentalized flow and phase separation, can produce residues with nutrient compositions and stabilization levels distinct from those generated by conventional continuous reactors (Qi et al., 2021; Rashid et al., 2021). However, most ABR-related studies still focus on energy recovery and methane yield, not on nutrient recovery or residue utilization. This study differs from previous ABR research because it evaluates the solid residues rather than the biogas output, aiming to identify their potential use as an organic fertilizer source (Chen et al., 2021).

Evaluating the residue as a fertilizer is important because digestate still contains essential nutrients that remain after anaerobic degradation and can improve soil fertility and plant growth (Möller & Müller, 2012; Zirkler et al., 2014). Utilization of ABR residues supports sustainable waste management by reducing the need for synthetic fertilizers and minimizing waste disposal problems. Without proper evaluation, these residues are often underutilized and may cause environmental issues such as odor, leachate generation, and nutrient runoff (Abbas et al., 2023; Byun et al., 2017). Therefore, this study aims to characterize the nutrient composition and evaluate the seed germination performance of food-waste residues from an ABR system to determine their suitability as an organic fertilizer source and contribute to circular economy-based waste valorization (Westerman et al., 2012; Krishnasamy et al., 2014).

2. Methodology

2.1 Anaerobic processing

The anaerobic treatment used in this experiment is an Anaerobic Baffled Reactor (ABR) on a laboratory scale. ABR has 4 compartments inside each compartment has an output pipe with a valve. The reactor is made of clear acrylic plastic with a full reactor volume capacity of 75 liters. The dimensions of the ABR are 750 mm long, 420 mm wide, and 270 mm high. The ABR is equipped with influent and effluent containers with a volume of 50 liters of each full capacity. The influent and effluent containers are connected to the ABR by fixed pipes with the valves attached to each other. The container and reactor are sealed tightly to provide anaerobic conditions inside the reactor. The container and reactor are closed to prevent sunlight from entering the interior. The ABR scheme used is illustrated in Figure 1.

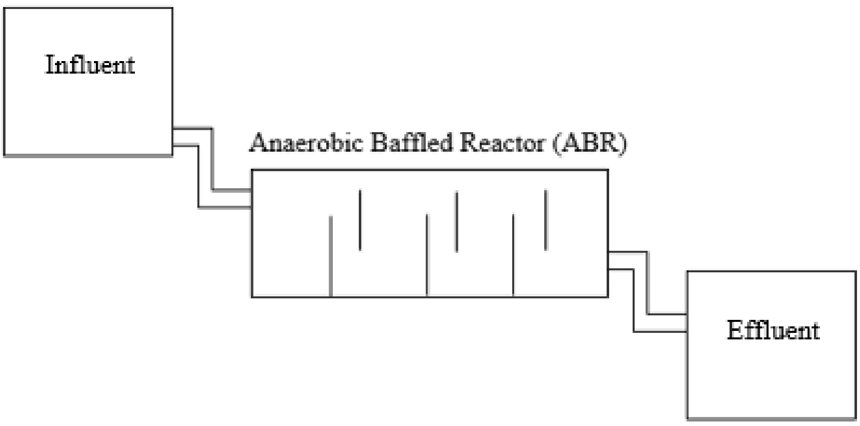

Figure 1. ABR reactor schematic diagram

2.2 Organic waste samples

The organic waste samples used are discarded food scraps from university canteens. Food scraps must go through selection before they can be used. Only food scraps with high biodegradability can be used, such as rice, and food waste with low biodegradability should be avoided, such as bones, that are not easily degraded through the processing process. After going through the selection process, food waste is collected, in this experiment as much as 1.25 kg of food waste is selected from the collected organic waste. Then the selected food residues are mashed with a blender. Moisture content and carbon-nitrogen (C/N) ratios were measured for food residue samples. After the leftovers are chopped, the leftovers are put in an influent container and mixed with water until they reach a volume of 50 liters.

2.3 Influent preparation

The influent was a mixture of organic waste and activated sludge with a ratio of 75% and 25%. Organic waste was collected from food waste and the activated sludge used comes from Communal Wastewater Treatment Plants. The concentration of activated sludge used was 40 g/l (Ahamed et al., 2015) To obtain the same concentration as recommended, as many as 20 liters with an activated sludge concentration of approximately 40 g/l were used in this experiment. Activated sludge was placed in the ABR reactor. For the mixing process, the influent pipe valve opens and let the liquid food waste mix with the activated sludge inside the ABR reactor.

2.4 Research procedure

The influent was placed in an influent container that has been connected to the ABR reactor. Influent was digested for 17 days of observation under naturally anaerobic conditions. For 17 days, several parameters such as TSS, VSS, and ammonia nitrogen were measured periodically, but for pH and temperature were measured daily to observe the digestive process. After 17 days, the effluent valve was opened and then separated by a layer of super natives, namely the sludge layer at the bottom of the reactor. The residue at the bottom of the reactor is collected and dried in an oven. The dry residue was ground to obtain a uniform shape and then its nutritional content is analyzed. The dry residue was dissolved into a liquid and then poured into 10 *Ipomoea* seeds. Seed growth was observed for a period of 2 weeks.

2.5. Analysis method

Analysis was carried out on samples of food waste, activated sludge, digested residue, and final liquid waste. The initial analysis of the food residue sample used consisted of the analysis of moisture content and C/N ratio. Digested residues are analyzed for TSS, volatile suspended solids (VSS), and Nitrogen-Phosphorus-Potassium (NPP). Temperature and pH data collection of samples in the ABR was carried out every day for 17 days of the digestive process. For the collection of TSS, VSS, and Ammonia Nitrogen samples in the reactor, it is carried out periodically, namely once every 2-3 days. The methods used for all parameters, namely pH, TSS, VSS, follow the methods issued by the American Public Health Association (APHA). The analytical parameters, methods, and instruments are summarized in Table 1.

Table 1. Analytical methods used in this study

Standard Methods	Parameter	Instrument
APHA 4500-H+B	pH	pH meter
APHA 2540 D (103–105 °C drying)	TSS	Glass-fiber filter, drying oven, analytical balance
APHA 2540 E (500 °C ignition)	VSS	Muffle furnace, analytical balance
APHA 4500-NH_3 B & C (2017)	Ammonia-Nitrogen (NH_3–N)	Kjeldahl distillation unit, burette & titration setup, boric acid receiver, sulfuric acid titrant
QuikChem FIA + Auto-analyzer	NPP	LACHAT ASX-500
CHNS Method	C/N Ratio	Thermo Finnigan EA 1112

3. Result and Discussion

The preliminary characterization revealed several important aspects regarding the suitability of materials for anaerobic digestion, as summarized in Table 2.

Table 2. Preliminary sample analysis results

Sample	Parameter	Result
Food scraps	Weight (kg)	1.25
	Moisture content (%)	47.63
	C/N ratio	3.69 / 1
Activated sludge	TSS (g/l)	40
Influent	TSS (g/l)	3.33
	C/N ratio	2.87 / 1

The food waste sample contained 47.63% moisture, a condition that facilitates microbial hydrolysis and solubilization of nutrients. This high-water fraction is typical of kitchen and canteen residues, which are often composed of vegetable scraps, cooked rice, and protein-rich leftovers. Moisture content in the range of 40% to 70% has been frequently reported for food waste, and it plays a dual role in anaerobic digestion. On the one hand, high water availability enhances microbial hydrolysis and solubilization of nutrients, allowing enzymes to access substrates and break them down into simpler compounds. The slurry-like nature created by high water content is advantageous in reactors such as ABRs, which rely on continuous flow through baffled compartments. Proper mixing and hydraulic movement are facilitated when the substrate is sufficiently wet, reducing the risk of clogging and dead zones. On the other hand, excessive water also leads to a dilution of organic matter. This reduces the organic loading rate and may result in lower biogas yields per unit volume of reactor, particularly when the system is operated at fixed hydraulic retention times. Furthermore, high-moisture waste, if not treated promptly, undergoes spontaneous putrefaction under aerobic conditions, releasing malodorous compounds and producing leachate that can become a secondary pollutant. Thus, while the water-rich characteristic of the food waste in this study is beneficial for microbial accessibility and flow behavior, it also highlights the necessity of timely treatment and careful control of organic load to prevent operational inefficiencies.

Of greater concern is the carbon-to-nitrogen ratio of the food waste, which was measured at only 3.69:1. This value is drastically below the optimal range of 20:1 to 30:1 recommended for anaerobic digestion. The C/N ratio functions as an indicator of nutrient balance and microbial suitability. When the ratio is low, nitrogen is present in excess relative to carbon. In food waste, this usually reflects a high content of proteins and amino acids, which upon degradation release ammonia. Ammonia exists in equilibrium between ammonium ion and free ammonia, the latter being toxic to methanogenic archaea. Free ammonia can permeate microbial membranes, disrupt intracellular pH homeostasis, and inhibit enzymatic activity, leading to suppression of methane formation. Numerous studies have demonstrated that free ammonia nitrogen concentrations above 1,500 to 3,000 mg/L result in significant reductions in methane production (Adriansyah et al., 2019; Qi et al., 2021). The very low C/N ratio of the food waste in this study therefore signaled at the outset that ammonia accumulation would likely become a major inhibitory factor during digestion.

The implication of such a nitrogen-rich substrate is that, although hydrolysis and acidogenesis may proceed rapidly due to abundant protein degradation, methanogenesis will be constrained unless corrective measures are taken. Previous researchers have attempted to overcome similar imbalances through co-digestion strategies. For instance, Cheong et al. (2020) and Liu et al. (2022) both reported improved process stability and methane yields when food waste was combined with carbon-rich co-substrates such as lignocellulosic biomass, sawdust, or crop residues. These materials not only increase the C/N ratio but also provide structural bulking agents that improve porosity and buffering capacity, thereby counteracting the inhibitory effects of ammonia. The absence of such corrective strategies in the present experiment meant that the low C/N ratio became a central driver of instability in the ABR.

In contrast to food waste, activated sludge was characterized by a total suspended solids concentration of 40 g/L, which is typical of sludge withdrawn from municipal wastewater treatment processes. This high concentration of suspended matter reflects the abundance of microbial biomass, including hydrolytic, fermentative, and methanogenic microorganisms. Activated sludge therefore serves as an effective inoculum, seeding the digestion process with a diverse microbial community. The presence of extracellular polymeric substances (EPS) within the sludge further enhances microbial aggregation and floc formation, properties that are advantageous in compartmentalized reactors such as ABRs. By promoting microbial retention and stratification, activated sludge theoretically accelerates the establishment of anaerobic pathways and reduces the lag phase commonly observed when reactors are inoculated with non-acclimated biomass.

However, the role of activated sludge in this study was primarily as inoculum rather than as a balancing substrate. While it provided microbial richness, it did not resolve the nutrient imbalance inherent in the food waste. Indeed, when combined with food waste to form the influent, the mixture exhibited an even lower C/N ratio of 2.87:1. This further reduction suggests that the sludge contributed additional nitrogen, exacerbating the already unfavorable nutrient composition. The outcome was an influent with substantial microbial seeding potential but with a nutrient environment predisposed to ammonia accumulation and inhibition.

The influent also displayed lower total suspended solids compared to the pure sludge, which indicates a dilution effect when mixed with food waste. As a result, although microorganisms were present, their relative concentration in the feed entering the reactor was insufficient to counterbalance the rapid accumulation of inhibitory compounds. The microbial population was therefore subjected to an environment rich in degradable nitrogen but poor in carbon, creating dual stresses of nutrient imbalance and potential toxicity. This condition is consistent with observations by Rashid et al. (2021), who noted that nitrogen-rich feedstocks frequently overwhelm microbial communities, leading to inhibited methanogenesis even in systems inoculated with acclimated sludge.

The interplay between these characteristics sets the stage for the reactor performance observed later. The food waste provided abundant organic matter but in an imbalanced nutrient form. The activated sludge contributed valuable microorganisms but did not compensate for the excess nitrogen. The combined influent, therefore, carried the dual signature of microbial availability and metabolic stress. Such a profile is generally unfavorable for stable anaerobic digestion, as the microbial community is forced to adapt under conditions where ammonia accumulation, acidic pH shifts, and volatile fatty acid buildup are almost inevitable.

Table 3. Parameter changes during 17 days of digestive process

Day	TSS (g/l)	VSS (g/l)	NH_3-N (g/l)	pH	Temperature (°C)
1	-	-	-	4.97	31.7
2	6.23	9.50	0.050	4.97	31.7
3	-	-	-	4.92	30.8
4	-	-	-	4.96	30.3
5	6.40	5.80	0.112	4.94	30.8
6	-	-	-	4.92	30.3
7	-	-	-	4.89	32.1
8	4.60	6.40	0.112	4.9	32.9
9	-	-	-	4.89	32.1
10	-	-	-	4.92	30.5
11	-	-	-	4.96	32.7
12	78.60	81.40	0.117	5	32.2
13	-	-	-	5	32.2
14	-	-	-	5	31.8
15	28.60	67.00	0.140	4.96	30.3
16	-	-	-	5.12	32.1
17	-	-	-	5.12	29.6

The temporal dynamics of anaerobic digestion in the Anaerobic Baffled Reactor (ABR) were monitored over a 17-day period to evaluate the transformation of organic matter, nitrogen, and biomass within the system. The changes in pH, ammonia nitrogen, and suspended solids, summarized in Table 3 and illustrated in Figure 2, provide valuable insights into the sequence of biological processes that unfolded inside the reactor. These results reveal that while hydrolysis and acidogenesis proceeded rapidly, the digestion process did not achieve stable methanogenesis. Instead, the process remained dominated by hydrolysis and acidogenesis, with limited progression to the methanogenic phase. This finding aligns with previous studies that highlighted the inhibitory effect of low C/N ratios on methane production and long-term system stability (Qi et al., 2021; Rashid et al., 2021).

Recent advances have indicated that such inhibitory effects can be partially mitigated through targeted chemical or operational adjustments. For example, Hou et al. (2022) demonstrated that supplementation with alkaline agents such as KOH improved salt tolerance and sustained methanogenesis in a two-stage anaerobic digestion system treating food waste. Although the stressor in their study was salinity rather than nitrogen imbalance, the principle underscores that strategic supplementation can enhance system resilience against inhibitory conditions.

The ABR operated under mesophilic conditions, with temperatures ranging between 29 and 33 °C throughout the experiment. This thermal regime is generally considered optimal for anaerobic digestion, as it supports the enzymatic activity of hydrolytic and fermentative bacteria, while also sustaining methanogenic archaea under balanced nutrient conditions (Zhang et al., 2021). The steady mesophilic environment in this study indicates that temperature was not a limiting factor for microbial activity. However, the observed performance clearly demonstrates that thermal suitability alone is insufficient when other critical parameters—most notably substrate composition—are unfavorable.

The pH profile of the reactor reveals the dominance of acidogenesis during the digestion process. Throughout the 17-day operation, pH values remained within the acidic range of 4.89 to 5.12. Such conditions are characteristic of volatile fatty acid (VFA) accumulation, particularly acetic, propionic, and butyric acids, which are produced during the acidogenic phase of digestion. Acidification occurred rapidly, with a marked decline in pH observed by the third day of operation. This corresponds to the onset of acidogenesis, when fermentative microorganisms metabolize soluble sugars, proteins, and lipids into organic acids. Under ideal circumstances, methanogenic archaea would subsequently convert these acids into methane and carbon dioxide, thereby restoring pH to neutral or slightly alkaline conditions. However, in this experiment, the persistently low pH indicates that VFAs were not metabolized efficiently, reflecting the suppression of methanogenesis.

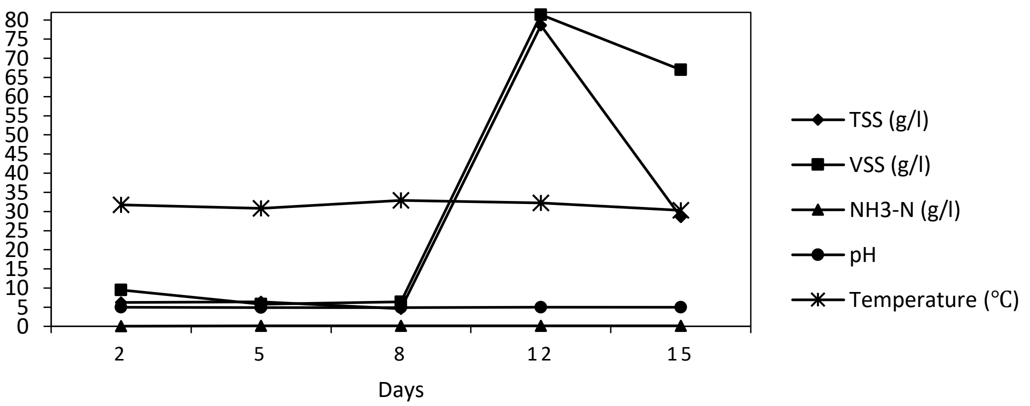

Figure 2. Changes in ABR sample parameters during digestion

The failure of the system to transition from acidogenesis to methanogenesis is strongly linked to ammonia accumulation. As shown in Figure 2, ammonia nitrogen levels increased significantly during the first week of digestion. A sharp rise occurred between the second and fifth day, reflecting the rapid breakdown of proteins and amino acids derived from the nitrogen-rich food waste. Concentrations continued to rise gradually until day twelve, before exhibiting another sharp increase on day fifteen. This two-phase pattern mirrors the availability of degradable nitrogenous compounds: the initial increase corresponds to early protein hydrolysis, while the later spike suggests continued deamination as microbial biomass proliferated and degraded more complex substrates.

By the end of the 17-day period, ammonia nitrogen in the effluent was 67.85% higher than the influent concentration. This substantial accumulation reflects the inherent nitrogen overload of the substrate mixture. Under mesophilic conditions, ammonium ions exist in equilibrium with free ammonia, with the latter being particularly inhibitory to methanogens. Rashid et al. (2021) and Adriansyah et al. (2019) reported that free ammonia concentrations exceeding 1,500 to 3,000 mg/L can inhibit methanogenic archaea, depending on acclimation and system design. In this experiment, the extremely low influent C/N ratio of 2.87:1 created conditions conducive to continuous ammonia release, with no sufficient carbon available to buffer or assimilate the excess nitrogen. The persistence of acidic conditions would normally favor the ammonium form over free ammonia, thereby reducing toxicity. However, the sheer magnitude of nitrogen release likely overwhelmed this equilibrium, leading to inhibitory effects even under acidic pH.

The interplay between pH and ammonia concentration is crucial in understanding the system's instability. On the one hand, the low pH reflects an accumulation of VFAs that methanogens failed to consume. On the other hand, high ammonia levels would have directly suppressed methanogenic activity, preventing the consumption of VFAs and perpetuating acidic conditions. This feedback loop effectively locked the system in a state dominated by hydrolytic and acidogenic activity, with little to no progression towards methanogenesis. Similar feedback loops have been described in other studies of protein-rich waste digestion. Qi et al. (2021) highlighted that in systems with low C/N ratios, ammonia accumulation and acidification reinforce each other, ultimately leading to process failure if corrective interventions are not applied.

Suspended solids (TSS) and volatile suspended solids (VSS) further illustrate the microbial dynamics within the ABR. Between the eighth and twelfth day of operation, both TSS and VSS sharp increased, suggesting microbial proliferation during this period. The increase in solids concentration reflects the growth of acidogenic and hydrolytic bacteria, which thrived under nitrogen-rich and acidic conditions. However, after the thirteenth day, TSS and VSS levels declined, indicating nutrient depletion and microbial decay. This decline corresponds to the point at which ammonia nitrogen reached inhibitory levels, suppressing further microbial activity and leading to biomass lysis. The rise and fall of TSS and VSS therefore depict a transient adaptation phase followed by inhibition, consistent with observations from Ahamed et al. (2015), who noted that ABR systems treating protein-rich waste often display initial microbial growth before succumbing to inhibition from accumulated by-products.

The compartmentalized design of the ABR is intended to separate microbial phases spatially, with early chambers dominated by hydrolysis and acidogenesis, and later chambers providing conditions for methanogenesis. However, in this study, the inhibitory conditions were not confined to the early chambers but extended throughout the system. The persistence of acidic pH and high ammonia nitrogen in all compartments suggests that the entire reactor environment was unfavorable for methanogens. This demonstrates that while ABR configurations can improve hydraulic retention and microbial stratification, they cannot overcome fundamental feedstock imbalances. The data therefore underscore the importance of substrate quality as a determinant of system performance, even in advanced reactor designs.

Comparisons with other ABR studies highlight the limitations observed here. Cheong et al. (2020) achieved stable methane production when food waste was co-digested with carbon-rich bulking agents, which raised the C/N ratio into the optimal range of 20–30:1. Liu et al. (2022) similarly demonstrated that co-digestion with agricultural residues improved both methane yield and microbial diversity, making systems more resilient to ammonia stress. In contrast, the present experiment, using food waste without carbon supplementation, illustrates the consequences of ignoring nutrient balance: ammonia inhibition dominated, VFAs accumulated, and the system failed to reach methanogenesis.

The trajectory of process dynamics observed here is not unique but reflects a common pattern in nitrogen-rich digestion. Early hydrolysis and acidogenesis release soluble compounds rapidly, resulting in acidification. Ammonia levels rise concurrently, exerting toxicity on methanogens and preventing further degradation. The microbial community responds with initial growth, but eventually succumbs to the dual stresses of low pH and high ammonia. The outcome is a reactor environment characterized by high ammonia nitrogen, acidic effluent, and limited gas production.

Table 4. Final sample analysis results

Sample	Parameter	Result
Effluent	TSS (g/l)	0.4
	VSS (g/l)	16.35
	NH_3-N (g/l)	0.1568
Reactor residue	TSS (g/l)	9.2
	VSS (g/l)	38.8

The evaluation of effluent quality after 17 days of operation provides an important indication of how effectively the Anaerobic Baffled Reactor (ABR) was able to stabilize the substrate and convert it into environmentally manageable by-products. Table 4 summarizes the performance of the system in terms of total suspended solids (TSS) removal and ammonia nitrogen dynamics. The results show a marked contrast between solid–liquid separation, which was highly efficient, and nitrogen stabilization, which was largely unsuccessful. This duality underscores the partial functionality of the ABR under conditions of nutrient imbalance, highlighting both its strengths and its inherent limitations when treating food waste characterized by a very low carbon-to-nitrogen (C/N) ratio.

The effluent demonstrated a substantial reduction in suspended solids, with removal efficiency reaching approximately 88%. This finding is consistent with the design intent of ABR systems, which employ sequential baffled chambers to promote the settling of particulate matter and enhance phase separation. The configuration allows heavier solids to remain within the earlier compartments, where they can undergo hydrolysis, while lighter soluble compounds move downstream for subsequent fermentation and methanogenesis. Even under inhibitory biochemical conditions, the hydraulic design of the ABR ensured effective retention of solids, thereby producing a clarified supernatant. Similar outcomes have been reported in previous studies. Clack et al. (2019) observed that ABR systems consistently achieve high suspended solids removal efficiencies, even when the feedstock is variable or inhibitory. This characteristic makes ABRs particularly suitable for waste streams with high particulate content, as physical separation is less dependent on metabolic performance and more on reactor hydrodynamics.

However, the apparent success in TSS reduction should be interpreted with caution. While the effluent was physically clarified, the suspended solids retained in the reactor compartments did not undergo complete stabilization. Instead, much of the organic matter remained in the form of residues rich in nitrogenous compounds, as revealed later by residue nutrient analysis. This suggests that the solids removal observed in the effluent is more a reflection of physical retention than of biological mineralization. From an operational perspective, this means that the ABR effectively prevented particulate pollution in the liquid effluent, but it did not eliminate the environmental burden of the retained residues, which continued to pose management challenges.

In stark contrast to the success in solids removal, nitrogen stabilization in the effluent was ineffective. Ammonia nitrogen concentrations increased by approximately 67.85% compared to the influent, a result that highlights the central challenge of digesting protein-rich substrates. The increase in effluent nitrogen is a direct consequence of proteolysis and deamination processes, in which proteins and amino acids from food waste are broken down into ammonium ions. Under balanced C/N conditions, ammonium can be assimilated into microbial biomass or further transformed through microbial pathways. However, the very low influent C/N ratio of 2.87:1 created an environment in which nitrogen was released in excess and carbon was insufficient to support its assimilation.

The consequence of this imbalance was an effluent characterized by elevated ammonium and, likely, significant free ammonia. While the acidic conditions observed in the reactor would shift the ammonium–ammonia equilibrium towards the ionized form, the concentration of nitrogen was high enough to ensure that inhibitory free ammonia persisted. This explains why methanogenic activity was suppressed despite the pH being in a range that would normally mitigate free ammonia toxicity. The dual stress of elevated ammonium and low pH created an effluent that was both nutrient-rich and chemically unstable, posing risks for direct environmental discharge.

From a waste management perspective, the elevated nitrogen concentration in the effluent represents a significant limitation. If discharged untreated into aquatic systems, ammonium contributes to eutrophication, promoting algal blooms and depleting dissolved oxygen, which can cause fish kills and biodiversity loss. Moreover, high ammonium concentrations in effluent are regulated in most jurisdictions, meaning that additional treatment steps would be required before discharge. Researchers such as Ahamed et al. (2015) and Song et al. (2021) have emphasized that effluents from anaerobic digestion of food waste frequently require post-treatment specifically targeting nitrogen removal. Technologies such as nitrification–denitrification, partial nitritation–anammox, and struvite precipitation have been successfully applied to reduce ammonium concentrations in such effluents. The necessity of these additional processes reduces the standalone sustainability of ABRs when applied to nitrogen-rich wastes, as the system cannot achieve complete stabilization without supplementary steps.

The nitrogen dynamics observed in this study also highlight an important distinction between solid–liquid separation and nutrient stabilization. While the ABR proved effective in clarifying the effluent by retaining suspended solids, it did not transform the soluble nitrogen fraction into more stable forms. This distinction reflects the inherent limitations of anaerobic digestion when handling substrates with imbalanced nutrient profiles. Carbon-rich wastes, such as agricultural residues or energy crops, typically allow both solids and nitrogen to be stabilized through microbial uptake and methane generation. By contrast, nitrogen-rich wastes such as food residues with low C/N ratios release more ammonium than the microbial community can assimilate, overwhelming the system's capacity for stabilization.

Comparative literature further contextualizes the findings. Qi et al. (2021) and Rashid et al. (2021) documented similar increases in effluent ammonium when protein-rich feedstocks were digested without co-substrates. In both cases, the authors concluded that nutrient balancing through co-digestion is essential to avoid nitrogen overload. Adriansyah et al. (2019) similarly emphasized that unbalanced substrates generate inhibitory conditions that undermine both effluent quality and overall reactor stability. By contrast, studies that employed co-digestion with carbon-rich materials such as straw, manure, or crop residues consistently reported reduced ammonium concentrations in effluents (Cheong et al., 2020; Liu et al., 2022). These comparisons suggest that the elevated ammonium observed in this study was not an inherent limitation of the ABR design, but rather a consequence of the substrate composition.

Another aspect of effluent quality worth noting is the persistence of acidity. As indicated in Table 2, pH remained within the acidic range throughout the digestion period. This acidic effluent is problematic not only for biological treatment but also for agricultural application. If applied directly to soil, acidic effluents can disrupt soil pH, impair nutrient availability, and damage sensitive crops. Moreover, acidic conditions exacerbate the mobility of metals and other contaminants, potentially leading to groundwater pollution. The combination of high ammonium and low pH therefore renders the effluent unsuitable for direct discharge or reuse without conditioning.

It is also instructive to consider the implications of effluent quality in the broader context of circular economy goals. One of the motivations for anaerobic digestion is to convert waste into resources, producing renewable energy in the form of biogas and nutrient-rich effluents that can be reused as fertilizers. However, the results of this study demonstrate that when the substrate composition is not balanced, the effluent shifts from being a potential resource to being a pollutant. Instead of providing plant-available nutrients in a stable form, the effluent was dominated by ammonium and acids that are more likely to cause environmental harm than agricultural benefit. This represents a significant barrier to the integration of ABRs into sustainable food waste management strategies, unless nutrient balancing and effluent post-treatment are incorporated into system design.

The contrasting outcomes for TSS and nitrogen dynamics in the effluent illustrate a central theme in anaerobic digestion research: physical separation can be achieved through reactor design, but biochemical stabilization depends fundamentally on substrate composition. The ABR in this study fulfilled its hydraulic role by retaining solids, but it was unable to prevent nitrogen accumulation because the feedstock characteristics were beyond its biological capacity. This reinforces the argument made by Zhang et al. (2021) and others that substrate characterization should precede reactor operation, and where imbalances are identified, pre-treatment or co-digestion must be implemented to ensure effective nutrient stabilization.

Table 5. Comparison of NPP content analysis results

Sample	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Source
Reactor residue	0.44	0.13	0.42	This research
Anaerobically digested sewage sludge	3.7	3.1	-	Chojnacka et al., 2023
Mixed waste (food and wood ash)	5.4	1.4	3.2	Samoraj et al., 2022
Mixed mud (cow dung and fish waste)	19	1.7	20	Samoraj et al., 2022
Urea	45	-	-	Yahaya et al., 2022
Basic slag	-	14	-	Yahaya et al., 2022
Kainite	-	-	10	Yahaya et al., 2022

The residue that accumulated in the reactor after 17 days of digestion represents the solid fraction retained within the baffled compartments. Assessing its nutrient composition provides critical insights into its potential use as a soil amendment or organic fertilizer. Table 5 presents the nutrient analysis of the residue, with nitrogen, phosphorus, and potassium concentrations measured at 0.44%, 0.13%, and 0.42% respectively. These values are markedly lower than those typically found in conventional organic fertilizers or even in other types of anaerobic digestates reported in the literature. The low nutrient content of the residue, combined with its physicochemical characteristics, suggests that its potential as a direct fertilizer is limited, although it may still play a role as a soil conditioner or as a component in blended formulations.

The nitrogen concentration of 0.44% in the residue is notably low when compared to other organic waste-derived fertilizers. For instance, Chojnacka et al. (2023) reported nitrogen levels ranging between 2% and 4% in anaerobically digested sewage sludge, while Samoraj et al. (2022) observed comparable values when food waste was co-digested with biomass ash. Even mineral fertilizers such as urea, with nitrogen concentrations exceeding 40%, far surpass the levels found in the ABR residue (Yahaya et al., 2023). The relatively low nitrogen observed in this study is consistent with the high solubilization of nitrogen into the liquid phase, as reflected in the elevated ammonium concentrations in the effluent. Essentially, much of the nitrogen originally present in the food waste was not retained in the solid residue but was instead released into the supernatant, thereby depleting the residue’s fertilization potential.

Phosphorus levels were also very low, measured at just 0.13%. Phosphorus is a key macronutrient for plant growth, contributing to root development, energy transfer, and crop productivity. Typical values for anaerobic digestates range between 0.5% and 1.5% phosphorus, depending on the substrate composition and process stability (Samoraj et al., 2022; Chojnacka et al., 2023). The low phosphorus in the residue suggests that the digestion process failed to mineralize sufficient amounts of organic phosphorus compounds, possibly due to the acidic conditions that limited microbial diversity. Acidic pH can also promote the dissolution of phosphorus into the liquid phase, particularly as phosphate ions, thereby reducing its concentration in the solid residue. This phenomenon explains why the effluent in similar studies often contains soluble phosphorus, while the solid digestate remains nutrient-poor (Yahaya et al., 2023).

Potassium, measured at 0.42%, followed a similar trend of underperformance relative to expectations. Potassium is often more soluble than nitrogen or phosphorus, and its presence in digestates depends largely on whether it remains bound in organic matter or dissolves into the supernatant. In many digestion systems, potassium concentrations in residues exceed 1%, with higher values found in manure-based or co-digested wastes (Chojnacka et al., 2023). The relatively low potassium content in this study again reflects the partitioning of nutrients into the liquid effluent, consistent with the ABR's tendency to clarify solids while transferring soluble compounds downstream.

Collectively, the NPP composition of the residue underscores its limited role as a fertilizer when considered in isolation. The values fall below the thresholds typically recommended for organic amendments intended to supply primary nutrients to crops. While the presence of measurable amounts of nitrogen, phosphorus, and potassium indicates that the residue is not entirely devoid of fertilization potential, the concentrations are too low to meet crop demands. If applied as a stand-alone fertilizer, the residue would require large application rates to deliver sufficient nutrients, raising concerns over logistics, soil loading, and potential accumulation of undesirable compounds.

Nevertheless, the residue may still serve as a valuable soil conditioner. The presence of organic matter, even if nutrient-poor, can improve soil structure, increase water retention, and enhance microbial activity. Many studies have highlighted the role of low-nutrient organic amendments in improving soil physical properties, particularly in sandy or degraded soils (Samoraj et al., 2022). By enhancing soil porosity and moisture-holding capacity, such residues can indirectly support crop growth, even if they do not provide substantial nutrients. Moreover, the acidic nature of the residue observed in this study may contribute to soil pH adjustment in alkaline soils, although this would need to be carefully managed to avoid excessive acidification.

Comparisons with other fertilizer sources further highlight the limitations of the ABR residue. Anaerobic digestion residues from balanced substrates typically show nutrient contents sufficient for direct agricultural application. For example, co-digestion of food waste with straw has been reported to produce residues with nitrogen contents above 1%, phosphorus around 0.5%, and potassium exceeding 1% (Cheong et al., 2020). Similarly, digestates derived from livestock manure often contain balanced NPP levels, making them suitable for direct use as fertilizers (Liu et al., 2022). In contrast, the residue from this study is clearly deficient in all three major nutrients, confirming that the digestion of nitrogen-rich food waste without supplementation not only compromises process stability but also undermines the agronomic value of the solid outputs.

It is important to consider the nutrient dynamics that led to these outcomes. The high protein content of the food waste ensured that nitrogen was rapidly solubilized into ammonium, leaving little nitrogen bound in the solid fraction. Phosphorus and potassium, while less prone to volatilization, were likely released into the liquid phase under acidic conditions, reducing their retention in the residue. The result is a solid fraction that has lost much of its nutrient value but retains organic matter that may still contribute to soil health. This redistribution of nutrients between the liquid and solid fractions is consistent with findings by Clack et al. (2019), who reported that ABR systems often produce nutrient-rich effluents and nutrient-poor residues when treating imbalanced substrates.

From a practical standpoint, the low nutrient content of the residue limits its value as a commercial fertilizer product. Farmers typically prefer organic fertilizers with higher NPP concentrations, as they reduce the quantity needed for application and provide more predictable nutrient release. The residue in this study would require substantial enrichment—either through blending with nutrient-rich materials or through post-treatment processes such as composting with carbon-rich additives—to achieve comparable nutrient levels. For instance, co-composting ABR residue with crop residues or animal manure could increase its C/N ratio, improve nutrient retention, and enhance its suitability as an organic fertilizer. Alternatively, integration with nutrient recovery technologies, such as struvite precipitation for phosphorus recovery or biochar blending for carbon enrichment, could improve its agronomic value while addressing the nitrogen imbalance.

Despite these limitations, the presence of measurable NPP values indicates that the residue should not be dismissed entirely. Even at low concentrations, the nutrients contained in the residue may complement other fertilizers when used in combination. For example, blending ABR residue with mineral fertilizers could reduce the reliance on synthetic inputs while contributing organic matter that enhances soil health. Similarly, applying the residue as part of an integrated soil fertility management strategy—rather than as a stand-alone input—may yield benefits greater than its nutrient content alone would suggest. This aligns with the growing recognition that waste-derived residues can play a supporting role in sustainable agriculture by improving soil organic matter, even if their nutrient concentrations are modest.

To further evaluate the agricultural potential of the ABR residues, a simple germination bioassay was conducted using Ipomoea seeds. The choice of a seed germination test is significant because it provides a rapid, biologically relevant measure of the phytotoxicity and nutrient value of organic residues. Chemical analyses of nutrient content, while informative, do not capture the complex interactions between residue-derived compounds and living plants. Bioassays bridge this gap by directly assessing how plants respond to residue exposure under controlled conditions. In this study, 10 Ipomoea seeds were watered with a residue solution prepared at a concentration of 0.952 g/L, with 20 mL applied to each seed. After two weeks of observation, only five seeds exhibited healthy growth, while the others either failed to germinate or displayed poor development.

This 50% germination rate highlights both the potential and limitations of the residue as a growth medium amendment. On the one hand, the successful germination of half the seeds demonstrates that the residue does contain biologically available nutrients capable of supporting early plant growth. This finding aligns with the nutrient analysis, which confirmed measurable though low levels of nitrogen, phosphorus, and potassium. Even at modest concentrations, these macronutrients can stimulate germination and initial seedling development. Moreover, residues of organic origin may also contain secondary metabolites such as amino acids, organic acids, or micronutrients that contribute to seed vigor. Partial seed success therefore suggests that the residue has agronomic value that extends beyond its measured NPP content.

On the other hand, the failure of half the seeds to germinate or thrive points to the presence of inhibitory factors in the residue. Several explanations are plausible. First, the low C/N ratio of the original substrate and the resulting high ammonium concentrations in the effluent suggest that the residue may also contain elevated levels of ammonia or ammonium salts. Free ammonia is well known to be phytotoxic, interfering with nutrient uptake and damaging plant roots. Even at relatively low concentrations, ammonia can inhibit seed germination, especially in sensitive species. The observed partial germination is consistent with ammonia-induced inhibition, where some seeds tolerate the conditions while others are unable to establish.

Second, the acidic conditions that persisted throughout the digestion process likely carried over into the residue, which may have lowered the pH of the solution applied to the seeds. Acidic environments can impair germination by disrupting enzyme activity in the seed and limiting nutrient availability. For example, phosphorus becomes less available under acidic conditions, which could have restricted early seedling growth even though total phosphorus was present in the residue. Similarly, acidic residues may mobilize metal ions such as aluminum or manganese, which at elevated levels are toxic to seedlings. Thus, the pH factor provides another explanation for the incomplete germination observed.

Third, the residue may have contained residual volatile fatty acids (VFAs), such as acetic or butyric acid, which are known byproducts of acidogenesis. These compounds can persist in residues when methanogenesis is suppressed, as was the case in this study due to ammonia inhibition. VFAs are phytotoxic at relatively low concentrations and are frequently cited as causes of poor seed germination in digestates derived from unstable anaerobic processes (Ahamed et al., 2015). The presence of such compounds would explain why some seeds initially germinated but showed stunted growth, reflecting metabolic stress caused by toxic organics.

The observed 50% germination rate should therefore be interpreted as evidence of both the promise and the challenges of applying ABR residues in agriculture. The positive outcome is that the residue is not wholly toxic and does support plant growth under certain conditions. This suggests that, with appropriate post-treatment or blending, the residue could be converted into a viable soil amendment. For example, composting the residue with carbon-rich materials could reduce ammonia concentrations, neutralize acidity, and degrade VFAs, thereby mitigating phytotoxic effects. Numerous studies have shown that co-composting digestates significantly improves seed germination rates and enhances the stability of the final product (Cheong et al., 2020; Liu et al., 2022).

The negative outcome, however, is that direct use of the residue as a fertilizer or growth medium is not feasible. With only half the seeds germinating successfully, the residue cannot be recommended as a stand-alone input for agricultural production. Farmers require consistent and reliable nutrient inputs, and variability in germination outcomes represents a significant barrier to adoption. Moreover, the residue's low nutrient concentrations mean that even if all seeds had germinated, the growth benefits would be modest compared to those achieved with standard fertilizers.

Nevertheless, the bioassay result provides an important validation of the chemical analysis. Both sets of evidence converge on the conclusion that the residue has limited fertilization potential but retains some agronomic value. In particular, the fact that some seeds grew successfully suggests that the residue could function effectively as a soil conditioner, improving soil organic matter and supporting microbial activity, which in turn benefits plant growth indirectly. The partial success also indicates that the residue is not universally inhibitory, making it a candidate for further development through optimization strategies.

Comparisons with previous studies reinforce this interpretation. Yahaya et al. (2023) observed that digestate residues with low NPP content supported only partial seed germination, similar to the results of this study. They emphasized that such residues are better applied as supplements to other fertilizers rather than as primary nutrient sources. Similarly, Ahamed et al. (2015) reported poor germination rates in residues from protein-rich substrates, attributing the outcomes to ammonia inhibition and VFA accumulation. By contrast, studies of residues derived from balanced or co-digested substrates often report much higher germination success rates, reflecting the importance of nutrient balance in determining residue quality (Samoraj et al., 2022).

Taken together, the comparisons with previous studies indicate that the findings of this research are not isolated anomalies but rather reflect broader trends consistently reported in anaerobic digestion science. The results also highlight the role of simple bioassays as complementary diagnostic tools in residue evaluation. While advanced nutrient and microbial analyses provide detailed insights into chemical and biological composition, germination tests offer an integrative measure of residue quality from the perspective of plant response. The observed 50% germination rate of Ipomoea seeds serves as a straightforward indicator that the residue requires further stabilization before agricultural application. For both researchers and practitioners, this finding underscores the importance of incorporating bioassays into routine evaluations of digestate, as they capture functional outcomes that laboratory assays alone may overlook. Importantly, these results should not be interpreted as grounds to dismiss the residue as waste. Rather, they suggest that with proper enrichment or post-treatment, such as co-composting or nutrient recovery processes, the material can be upgraded into a viable soil amendment. This perspective aligns with the principle of resource recovery, which emphasizes cascading use of materials and iterative improvement of waste-derived products. Although the residues in their current state demonstrated only partial potential as soil conditioners, targeted optimization and integration into broader waste management and agricultural systems could enhance their agronomic value.

4. Conclusion

This study aimed to evaluate the potential of anaerobic digestion residues as a source of organic fertilizer using an Anaerobic Baffled Reactor (ABR). Suspended solids and ammonia nitrogen were used as key indicators to assess the digestion process. The ABR achieved an 88% reduction in suspended solids, demonstrating effective solids stabilization. However, ammonia nitrogen increased by 67.85%, indicating that the process did not adequately stabilize nitrogen. The residue collected after digestion contained nitrogen, phosphorus, and potassium with concentrations of 0.44%, 0.13%, and 0.42%, respectively. Although these values are lower than those found in typical organic fertilizers, the seed germination test provided evidence of partial agronomic potential. In the test, 5 out of 10 Ipomoea seeds irrigated with residue solution grew successfully over a two-week observation period, suggesting that the residue still retains some beneficial nutrient properties.

Overall, anaerobic digestion of food waste in ABR systems can reduce suspended solids and produce residues with measurable nutrient content, but the process is constrained by an imbalanced substrate composition and a very low C/N ratio. These conditions promoted ammonia accumulation and limited the progression to stable methanogenesis. In practical application, the residue is more suitable as a soil conditioner or as a component of mixed fertilizer formulations rather than as a stand-alone fertilizer. To increase its value, future studies should explore strategies such as co-digestion with carbon-rich substrates, optimization of retention time, and integration with nutrient recovery technologies. These approaches may improve nutrient balance, reduce ammonia inhibition, and enhance the agricultural utility of ABR residues.

Acknowledgement

The authors would like to express their sincere gratitude to the Faculty of Engineering, Universiti Kebangsaan Malaysia, for providing the facilities and technical support necessary to carry out this research as part of collaboration research. Special appreciation is also extended to the laboratory staff and fellow researcher who contributed to sample collection, preparation, and monitoring during the experimental period.

The authors deeply appreciate the support and collaboration of colleagues, staff, and lecturers from Universitas Jambi, Universitas Batanghari, Institut Teknologi Sumatera, and Universiti Kebangsaan Malaysia for their generous sharing of knowledge, constructive discussions, and valuable insights. Their contributions played an essential role in shaping the analysis and strengthening the conclusions of this study.

Reference

Abbas, A. M., Abdelazeem, M., & Novak, S. J. (2023). Anaerobic Digestion Reduces Seed Germination and Viability of Six Plant Species from the Upper Nile Valley, Egypt. Agronomy, vol. 13, February 2023:396.

Adriansyah, E., Agustina, T.E., Arita, S. (2019). Leachate Treatment of TPA Talang Gulo, Jambi City by Fenton method and adsorption. Indonesia Journal Fundamental and Applied Chemistry, vol.4, no. 1, February 2019:20–24.

Ahamed, A., Chen, C.L., Rajagopal, R., Wu, D., Mao, Y., Ho, I.J.R., Lim, J.W., Wang, J.Y. (2015). Multi-phased anaerobic baffled reactor treating food waste. Bioresource Technology, vol. 182, april 2015:239–244.

Byun, J. E., Choi, M. S., Seo, U. K., & Ryoo, J. W. (2017). Effect of anaerobic digestate on seed germination of perennial ryegrass seeds. In Proceedings of the Korean Society of Crop Science Conference (pp. 211-211). The Korean Society of Crop Science.

Cheong, J.C., Lee, J.T. E., Lim, J.W., Song, S., Tan, J.K.N., Chiam, Z.Y., Yap, K.Y., Lim, E.Y., Zhang, J., Tan, H.T.W., Tong, Y.W. (2020). Closing the food waste loop: Food waste anaerobic digestate as fertilizer for the cultivation of the leafy vegetable, xiao bai cai (Brassica rapa). Science of The Total Environment, vol. 715, May 2020:136789.

Chen, T., Qiu, X., Feng, H., Yin, J., & Shen, D. (2021). Solid digestate disposal strategies to reduce the environmental impact and energy consumption of food waste-based biogas systems. Bioresource Technology, vol 325, april 2021:124706.

Chojnacka, K., Skrzypczak, D., Szopa, D., Izydorczyk, G., Moustakas, K., Witek-Krowiak, A. (2023). Management of biological sewage sludge: Fertilizer nitrogen recovery as the solution to fertilizer crisis. Journal of Environmental Management, vol. 326(PA), January 2023: 116602.

Chuka-ogwude, D., Ogbonna, J., Moheimani, N.R. (2020). A review on microalgal culture to treat anaerobic digestate food waste effluent. Algal Research, vol. 47, May 2020:101841.

Clack, K., Pietruschka, B., Amoah, I.D., Muchaonyerwa, P., Odindo, O.A., Palomo, M., Buckley, C., Ngwane, Z., Mladenov, N. (2019). Transfer of coliform bacteria to duckweed harvested from anaerobic baffled reactor effluent. Bioresource Technology Reports, vol. 8, Desember 2019:100314.

Hou, T., Zhao, J., Lei, Z., Shimizu, K., Zhang, Z. (2022). Supplementation of KOH to improve salt tolerance of methanogenesis in the two-stage anaerobic digestion of food waste using pre-acclimated anaerobically digested sludge by air-nanobubble water. Bioresource Technology, vol. 346, February 2022:126360.

Kaushal, R., Sandhu, S., Kumar Soni, M. (2022). Anaerobic co-digestion of food waste, algae, and cow dung for biogas yield enhancement as a prospective approach for environmental sustainability. Sustainable Energy Technologies and Assessments, vol. 52(PC), August 2022:102236.

Krishnasamy, K., Nair, J., & Bell, R. (2014). Evaluation of anaerobic digestate as a substrate for vermicomposting. International Journal of Environment and Waste Management, vol. 14, January 2014: 149-164.

Liu, Y., Wang, T., Xing, Z., Ma, Y., Nan, F., Pan, L., Chen, J. (2022). Anaerobic co-digestion of Chinese cabbage waste and cow manure at mesophilic and thermophilic temperatures: Digestion performance, microbial community, and biogas slurry fertility. Bioresource Technology, vol. 363, November 2022:127976.

Majee, S., Halder, G., Mandal, D.D., Tiwari, O.N., Mandal, T. (2021). Transforming wet blue leather and potato peel into an eco-friendly bio-organic NPK fertilizer for intensifying crop productivity and retrieving value-added recyclable chromium salts. J. Hazard. Mat., vol. 411, June 2021:125046.

Möller, K., & Müller, T. (2012). Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review. Engineering in life sciences, vol. 12, June 2012:242-257.

Okebalama, C.B., & Marschner, B. (2023). Reapplication of Biochar, Sewage Waste Water, and Npk Fertilizers Affects Soil Fertility, Aggregate Stability, and Carbon and Nitrogen in Dry-Stable Aggregates of Semi-Arid Soil. Science of The Total Environment, vol. 866, March 2023:161203.

Qi, W. K., Liu, L.F., Shi, Q., Wang, C., Li, Y.Y., & Peng, Y. (2021). Detailed composition evolution of food waste in an intermittent self-agitation anaerobic digestion baffled reactor. Bioresource Technology, vol. 320(PA), January 2021:124342.

Rashid, M.I., Shahzad, K. (2021). Food waste recycling for compost production and its economic and environmental assessment as circular economy indicators of solid waste management. Journal of Cleaner Production, vol. 317, Oktober 2021:128467.

Samoraj, M., Mironiuk, M., Izydorczyk, G., Witek-Krowiak, A., Szopa, D., Moustakas, K., Chojnacka, K. (2022). The challenges and perspectives for anaerobic digestion of animal waste and fertilizer application of the digestate. Chemosphere, vol. 295, May 2022:133799.

Sodergren, J., Larsson, C.U., Wadso, L., Bergstrand, K.J., Asp, H., Hultberg, M., Schelin, J. (2022). Food waste to new food: Risk assessment and microbial community analysis of anaerobic digestate as a nutrient source in hydroponic production of vegetables. Journal of Cleaner Production, vol. 333, January 2022:130239.

Song, S., Lim, J.W., Lee, J.T.E., Cheong, J.C., Hoy, S.H., Hu, Q., Tan, J.K.N., Chiam, Z., Arora, S., Lum, T.Q.H., Lim, E.Y., Wang, C.H., Tan, H. T.W., Tong, Y.W. (2021). Food-waste anaerobic digestate as a fertilizer: The agronomic properties of untreated digestate and biochar-filtered digestate residue. Waste Management, vol. 136, December 2021:143–152.

Vasmara, C., Marchetti, R., Carminati, D. (2021). Wastewater from the production of lactic acid bacteria as feedstock in anaerobic digestion. Energy, vol. 229, August 2021:120740.

Westerman, P. R., Heiermann, M., Pottberg, U., Rodemann, B., & Gerowitt, B. (2012). Weed seed survival during mesophilic anaerobic digestion in biogas plants. Weed research, vol. 52, June 2012:307-316.

Yahaya, S.M., Mahmud, A.A., Abdullahi, M., Haruna, A. (2023). Recent advances in the chemistry of N, P, K as fertilizer in soil – A review. Pedosphere, vol. 33, No. 3, June 2023:385-406.

Zhang, X., Lopes, I.M., Ni, J.Q., Yuan, Y., Huang, C.H., Smith, D.R., Chaubey, I., Wu, S. (2021). Long-term performance of three mesophilic anaerobic digesters to convert animal and agro-industrial wastes into organic fertilizer. Journal of Cleaner Production, vol. 307, July 2021:127271.

Zirkler, D., Peters, A., & Kaupenjohann, M. (2014). Elemental composition of biogas residues: Variability and alteration during anaerobic digestion. Biomass and bioenergy, vol. 67, august 2014:89-98.