BILINGUAL PUBLISHING GROUP

Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

REVIEW

Enhancing Circular Bioeconomy through Aerobic Granular Sludge: Experimental Insights into Nutrient Recovery from Kitchen Waste Leachate

Xiaosu Wu

School of Water Conservancy and Civil Engineering, Beijing Vocational College of Agriculture, Beijing 102442, China

ABSTRACT

Kitchen waste leachate is a variable, nutrient-rich liquid stream generated during the collection, storage, and processing of food waste. While it significantly increases the organic load, ammonium, phosphate, suspended solids, oils, and fermentation products are very troublesome in the treatment process; it also provides for the recovery of carbon, nitrogen, and phosphorus. This review critically analyzes the use of aerobic granular sludge (AGS) as a biological platform to improve circular bioeconomy strategies for recovering nutrients from kitchen waste leachate. The review combines leachate characteristics, granulation mechanisms in AGS, microbial nutrient pathways, experimental evidence, and integration pathways with downstream technologies for leachate recovery. The difference between pollutant removal and resource recovery is discussed, as is the fact that conventional nitrogen and phosphorus removal may not yield reusable products. The advantages of AGS treatment include compact dimensions, superior settleability, high biomass retention, and the simultaneous occurrence of carbon degradation and nitrification, anoxic and anaerobic microenvironments, and phosphorus accumulation. But high organic loading, ammonia inhibition, fats, salinity, influent inconsistency, and granule instability remain significant challenges. For recovery-oriented AGS systems, it is therefore beneficial to combine pretreatment, fermentation, struvite precipitation, ammonium recovery, membrane separation, or biomass valorization. Nutrient mass balances, product safety, pilot-scale validation, assessment of greenhouse gas(es) (GHG), and techno-economic analysis should be given greater importance in future research. In general, AGS is a potential bridge between biological treatment and nutrient circularity in sustainable food waste management systems,

*CORRESPONDING AUTHOR:
Xiaosu Wu, School of Water Conservancy and Civil Engineering, Beijing Vocational College of Agriculture, Beijing 102442, China; Email: 72470@bvca.edu.cn

ARTICLE INFO
Received: 2 June 2026 | Revised: 1 July 2026 | Accepted: 7 July 2026 | Published Online: 12 August 2026
DOI: https://doi.org/10.30564/jees.v8i8.13585

CITATION
Wu, X., 2026. Enhancing Circular Bioeconomy through Aerobic Granular Sludge: Experimental Insights into Nutrient Recovery from Kitchen Waste Leachate. Journal of Environmental & Earth Sciences. 8(8): 450–476. DOI: https://doi.org/10.30564/jees.v8i8.13585

COPYRIGHT
Copyright © 2026 by the author(s). Published by Bilingual Publishing Group. This is an open access article under the Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0) License (https://creativecommons.org/licenses/by-nc/4.0/).

and between decentralized urban resource recovery and future cities.

Keywords: Aerobic Granular Sludge; Kitchen Waste Leachate; Nutrient Recovery; Circular Bioeconomy; Struvite Precipitation

1. Introduction

The emergence of food waste at an unprecedented rate has made it a problem in environmental, economic, and resource management. The Food Waste Index Report 2024 estimates that in 2022, about 1.05 billion t of food waste were generated worldwide, equivalent to nearly 20% of the food available for consumption in the household, food service, and retail sectors. Households had the highest share, with the food service and retail industries coming in next, which is where the need for integrated measures to minimize waste production and/or valorize unavoidable residues is most critical. In this context, the leachate from kitchen waste is a specific liquid fraction produced during the collection and storage of food waste, as well as during hydrolysis, mechanical pressing, composting, and anaerobic digestion. Kitchen waste leachate is typically considered as a high-strength wastewater because it needs to be stabilized before discharge, while solid food waste can be used to produce biogas, animal feed, and platform chemicals. It also contains high levels of biodegradable organic matter, ammonium nitrogen, phosphate, volatile fatty acids, suspended solids, fats, oils, grease, and soluble salts, which can also make it a valuable secondary resource [1].

Management of kitchen waste leachate is increasingly rethought from a circular bioeconomy perspective [2]. Traditional treatments have been geared towards pollution removal to minimize chemical oxygen demand, nitrogen, phosphorus, odors, and toxicity prior to environmental discharge. Such pollution-control measures are still needed, but they don't fully utilize the carbon and nutrient value in leachate. On the other hand, a circular bioeconomy approach considers leachate from kitchen waste as a recoverable stream for biofertilizers, nutrient salt recovery, bioenergy, and bioproducts. Food waste valorization has recently been put in the spotlight, with a push to transition from one-output systems to multi-output systems that recover multiple products whilst minimizing environmental impacts. This shift is especially important for urban food systems, which involve significant amounts of food waste produced at the point of nutrient demand, or potential treatment and reuse sites [3,4].

Nutrient recovery is key to this shift. Nitrogen and phosphorus are essential for crop yields, but their traditional production and utilization entail high energy use, limited availability of phosphate rock, losses, eutrophication, and GHG emissions [5]. Kitchen waste leachate can contain significant amounts of ammonium and phosphate, enabling biological assimilation, enhanced biological phosphorus accumulation, struvite precipitation, ion exchange, membrane separation, ammonia stripping, and liquid fertilizer production. Recovering nutrients as fertilizer products or concentrated nutrient solutions has been previously investigated in other high-strength leachates and wastewater streams, with ammonium and phosphorus being recovered. However, these technologies have yet to be applied directly to kitchen waste leachate because it is unstable, has a high organic load, oil/grease content, variable pH, salinity and inhibitory compounds. Hence, any kitchen waste leachate management platform should be able to: stabilize organic material, transform organic nutrients, withstand process failures, and integrate with post-process technologies for material recovery [6].

Aerobic granular sludge (AGS) has proven to be a promising biotechnology to meet several of these requirements. AGS are dense microbial aggregates that are self-immobilized under selective hydraulic, microbial, and operational conditions. Compared with the conventional activated sludge system, AGS is characterized by rapid settling, high biomass retention, compact reactor design, strong microbial stratification, and the ability to accommodate multiple redox processes within a single granule. Due to the multi-layered design of AGS, multiple micro-environments are created, enabling organic carbon oxidation, nitrification, denitrification, simultaneous nitrification/denitrification, and improved biological phosphorus removal (BPR) within a single system. AGS has been identified as an alternative to conventional activated sludge systems due to its reduced footprint, high solid–liquid separation, and potential energy and land savings, from recent reviews.

AGS's unique features make it particularly appealing for high-strength, variable wastewater streams such as kitchen waste leachate, where traditional flocculant sludge systems have encountered problems with poor settleability, biomass washout, filamentous bulking, and an inability to withstand shock loads [7–10].

In addition to the treatment performance, AGS is now known as a resource-recovery platform. It produces extracellular polymeric substances, microbial biomass, mineral precipitates, and phosphorus fractions, as well as intracellular storage products, all of which can be used in wastewater treatment for biorefineries. AGS has recently been reported to be a carrier of recoverable materials, such as alginate-like exopolymers, polyhydroxyalkanoates, phosphorus, and other value-added compounds. This resource-oriented perspective is particularly important for leachate from kitchen waste, as it contains significant amounts of biodegradable carbon and nutrients that can support microbial growth, nutrient accumulation, and the production of nutrient-rich biomass. Concurrently, AGS can also be used as a biological pre-treatment process prior to physicochemical recovery to convert organic nitrogen to ammonium, modify the nature of phosphorus species, remove organic interference, and generate effluents or side streams that are more amenable to struvite crystallization, membrane concentration, or ion exchange. So, the assessment of AGS must go beyond that of a wastewater treatment technology and should also be considered a biological interface between food waste management and nutrient circularity [11–14].

However, the use of AGS in kitchen waste leachate has not been well synthesized. Previous AGS studies have largely been conducted on municipal wastewater, industrial wastewater, granulation processes, microbial ecology, nutrient removal, or resource recovery in general. Likewise, waste and leachate treatments frequently focus on anaerobic digestion and/or composting, chemical precipitation, membrane processes, and/or advanced oxidation. The linkages among AGS technology, kitchen waste leachate treatment, and nutrient recovery remain poorly connected. Specifically, little attention has been paid in the literature to the impact of real or simulated kitchen waste leachate on granule formation, extracellular polymeric substances (EPS) production, microbial selection, nitrogen and phosphorus pathways, granule stability, and nutrient recovery in downstream fertilizer. This lack of knowledge prevents AGS-based systems from being developed as tools to promote the circular bioeconomy, rather than merely as pollutant removal systems [7,13].

This review is novel in that it takes a treatment-recovery approach. Firstly, it specifically identifies kitchen waste leachate as a valuable nutrient feedstock for the development of a circular bioeconomy, rather than as a problem wastewater per se. Second, it considers AGS as a multifunctional biological platform in which both the removal of organic matter and the transformation of nutrients can occur simultaneously, and recoverable nutrient streams can be prepared. Third, it links experimental results from AGS reactors to nutrient recovery pathways, including harvesting phosphorus-rich biomass, struvite precipitation, ammonia recovery, and biomass valorization. Fourth, it places a strong focus on case studies and experimental systems relevant to kitchen waste leachate and similar high-strength organic wastewater, making the laboratory work applicable to real-life applications. Lastly, the review pinpoints the operational, microbial, environmental, economic, and regulatory challenges that must be addressed to scale up AGS technology for decentralized or municipal food waste management. **Figure 1** presents the conceptual framework of this review, illustrating AGS as a biological interface connecting kitchen waste leachate treatment, organic matter stabilization, nutrient transformation, nutrient recovery pathways, and circular bioeconomy implementation [15–17].

Hence, the purpose of this review is to provide a comprehensive and critical evaluation of the application of aerobic granular sludge for improving nutrient recovery from kitchen waste leachate within the context of the circular bioeconomy. The article first covers the composition, variations, and resource potential of kitchen waste leachate. It then examines the mechanisms and pathways of AGS formation, and the mechanisms of nutrient transformation relevant to high-strength organic wastewaters. Special emphasis is placed on case studies and experimental evidence for AGS-based treatment, including reactor designs, operating conditions, granule stability, pollutant removal efficiencies, and recovery performance. The review also assesses the potential for synergies between AGS and downstream technologies for nutrient recovery and biomass valorization. In this article, these aspects are integrated to better understand the scientific rationale, technology, and future research directions for recovering kitchen waste leachate from waste to a valuable nutrient stream [13].

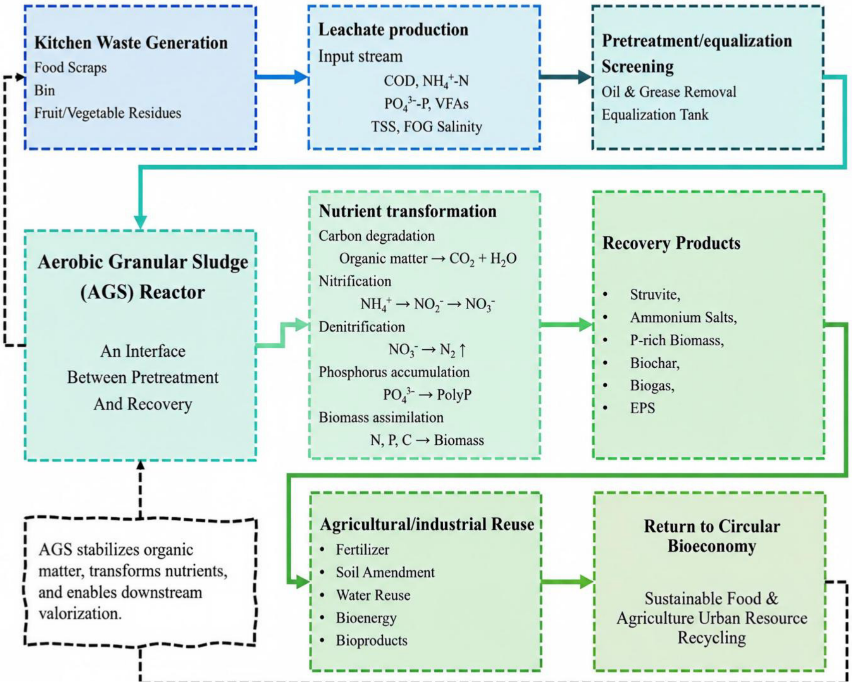

Figure 1. Conceptual framework of AGS-based kitchen waste leachate treatment and nutrient recovery within a circular bioeconomy system.

The overall hypothesis of this review is that AGS can act as a link between biological wastewater treatment and resource recovery in food waste management. With proper design and integration, AGS-based systems may help reduce organic and nutrient pollution, recover nitrogen and phosphorus, produce value-added biomass, and close material loops in urban and agricultural systems. In regions where food waste streams are growing rapidly, and small, efficient, resource-oriented solutions are needed, AGS looks promising for next-generation circular bioeconomy infrastructure.

2. Kitchen Waste Leachate: Composition, Treatment Challenges, and Recovery Potential

2.1. Origin and Generation of Kitchen Waste Leachate

The water-based portion generated during the collection, storage, transportation, preconditioning, and biological treatment of food residues is known as Kitchen Waste Leachate (KWL). It is produced by mechanically compressing, hydrolyzing, degrading, and separating the moisture content in food waste in the presence of microorganisms. Kitchen wastewater leachate is usually highly saturated, intermittent, and variable in composition compared to municipal wastewater, which is usually diluted and continuous. It is highly dependent on the type of food waste, storage time, storage temperature, extent of decomposition, and processing method applied prior to final treatment. Leachate from fresh household food waste can include readily biodegradable carbohydrates, proteins, and lipids, whereas leachate from long-term storage or anaerobic hydrolysis can contain higher levels of volatile fatty acids, ammonium, soluble organic material, and odor-producing compounds.

The production of this leachate is not only a byproduct of the kitchen waste management system but also a key control point in the broader food waste management system. Controlled liquid can contribute to odor formation, attract vectors, cause corrosion of infrastructure and load downstream treatment facilities with pollution. The same liquid stream, however, also hosts high concentrations of carbon, nitrogen, and phosphorus that can be targeted for biological nutrient removal, fertilizer manufacturing, or microbial biomass production, depending on the resource-recovery project's goals. Kitchen waste leachate is a valuable substrate for circular bioeconomy applications due to its dual nature as both a pollutant and a resource [18,19].

2.2. Physicochemical Characteristics and Compositional Variability

The typical characteristics of the kitchen waste leachate are high levels of soluble and suspended organic material, ammonium nitrogen, organic nitrogen, phosphate, suspended solids, fats, oils, grease, salts, and a variety of fermentation intermediates. The organic fraction typically consists of easily biodegradable material such as sugars, amino acids and proteins, lipids, and volatile fatty acids. This type of composition results in high biochemical oxygen demand and leachate that are acceptable for biological conversion. Too much organic loading can, however, also lead to too fast a drop in oxygen levels, acidification, and sludge bulking as well as process instability if the leachate is directly added to aerobic treatment systems [20].

Organic nitrogen and ammonium often constitute the bulk of the nitrogen in kitchen waste leachate. Proteins and amino acids can be degraded during storage or hydrolysis, leading to ammonification and an increase in ammonium concentration. This is relevant because under certain conditions (high pH, high temperature), the ammonium can be converted into free ammonia that can be inhibitory to nitrifying microorganisms, depending on the pH. Phosphorus typically exists in soluble orthophosphate, organic phosphorus and particulate-bound phosphorus. While phosphorus may be less concentrated than carbon on a mass basis, it is significant for recovery because it is a finite mineral resource and a predominant factor in eutrophication when discharged untreated [21].

One characteristic of KW is its variability. It varies in composition depending on the diets used, seasonal food consumption, the efficiency of waste separation, storage time, and how the waste is processed prior to consumption. This variability hinders process design, since biological systems demand relatively stable substrate conditions for long-term performance. For AGS systems, influent variability may affect granule morphology, microbial community structure, extracellular polymeric substance production, and nutrient conversion pathways. Thus, the physicochemical profile of leachate is essential not only for treatment efficiency but also for predicting its suitability for direct biological treatment, dilution, fermentation, precipitation, and integrated recovery [4,11,22,23]. The key physicochemical properties of kitchen waste leachates and their relationship to AGS performance and nutrient recovery are summarised in **Table 1**.

Table 1. Major characteristics of kitchen waste leachate and their implications for AGS-based treatment and nutrient recovery.

Parameter	Typical Relevance in Kitchen Waste Leachate	Effect on AGS Performance	Implication for Nutrient Recovery
Chemical oxygen demand (COD)/Biochemical oxygen demand (BOD)	Indicates high organic strength and biodegradability	Supports heterotrophic growth but may cause oxygen limitation and granule instability at excessive loading	Provides carbon for denitrification and phosphorus-accumulating organisms
Volatile fatty acids	Generated during storage, hydrolysis, or fermentation	Can enhance feast, famine selection and support phosphorus-accumulating organism(s) (PAO) activity	Useful carbon source for biological phosphorus accumulation
Ammonium nitrogen	Produced from protein degradation and ammonification	High levels may inhibit nitrification through free ammonia formation	Can be recovered through stripping, ion exchange, membranes, or fertilizer production
Organic nitrogen	Present in proteins, amino acids, and particulate matter	Requires hydrolysis and ammonification before biological conversion	Contributes to recoverable nitrogen after mineralization
Orthophosphate	Soluble phosphorus fraction available for biological or chemical recovery	Supports enhanced biological phosphorus removal (EBPR) when PAOs are enriched	Can be recovered as struvite, calcium phosphate, or phosphorus-rich biomass

Table 1. *Cont.*

Parameter	Typical Relevance in Kitchen Waste Leachate	Effect on AGS Performance	Implication for Nutrient Recovery
Suspended solids	Derived from food particles and colloidal matter	May interfere with settling, mass transfer, and granule structure	May contribute nutrients but requires separation or hydrolysis
Fats, oils, and grease	Common in food-derived leachate	Can inhibit oxygen transfer, coat granules, and promote instability	Pretreatment may be needed before biological nutrient recovery
Salinity/conductivity	Influenced by food residues, seasoning, and cleaning water	May impose osmotic stress on microbial communities	Can affect fertilizer reuse quality and downstream recovery
pH and alkalinity	Govern ammonia speciation, microbial activity, and precipitation	Low pH may inhibit nitrification; high pH may increase free ammonia toxicity	Important for struvite precipitation and ammonium recovery
Pathogens and contaminants	May originate from food residues and handling systems	May affect biosafety of biomass-based products	Determines suitability of recovered products for agricultural use

2.3. Treatment Challenges Associated with Kitchen Waste Leachate

Kitchen waste leachate is hard to treat due to its high biodegradability and inhibitory properties. High COD levels can generate high microbial activity. If too much organic loading occurs, then the aerobic systems may become unstable due to oxygen limitation, excessive biomass growth, and poor settling. These conditions can result in filamentous growth, bulking sludge, and washout in conventional activated sludge systems. High organic shock loads in AGS reactors can disrupt this feast-feast regime, thereby maintaining a stable granulation, encouraging loose floccular growth, and reducing the structural strength of granules [24]. Another significant challenge is the ammonia inhibition. Ammonium is a useful nitrogen source, but high ammonia levels can inhibit nitrification, particularly under conditions that promote free ammonia formation (e.g., at high pH and temperature). Nitrifying bacteria tend to be slower growing than heterotrophic bacteria and will be more sensitive to abrupt changes in ammonium, which can result in incomplete nitrification, accumulation of nitrite or loss of total nitrogen removal. In granular systems, gradients of oxygen and substrate can partially mitigate these effects by providing microbial-protective microenvironments, but under extreme conditions, microbial activity can be inhibited and the balance of the microbial community can shift.

Fats, oils and greases are also troublesome elements. Lipid-rich fractions can be attached to biomass surfaces, limit oxygen transfer, slow down biodegradation and create hydrophobic interactions that can influence microbial aggregation. An increase in hydrophobicity will help with granule formation but too much lipid can affect mass transfer and cause granule instability. Similarly, the salinity and dissolved ions may impact microbial osmotic balance, extracellular polymeric substances, and settling behavior. Further factors to consider are suspended solids and colloids, which may increase turbidity, block systems, and disrupt downstream nutrient recovery processes.

These inhibitory characteristics should not be interpreted as minor operational disturbances. In real kitchen waste leachate treatment, excessive oil and grease may coat granule surfaces and reduce oxygen transfer; high salinity may impose osmotic stress and alter EPS composition; high ammonium may inhibit nitrifiers through free ammonia formation; and excessive organic loading may promote filamentous or loose floccular growth rather than compact granules. Under these conditions, AGS failure may occur through granule swelling, surface roughening, fragmentation, poor settling, biomass washout, and loss of nitrification or phosphorus-accumulating activity. Therefore, stable operation may require more than adjustment of aeration, settling time, or loading rate. In many practical cases, source equalization, dilution, oil and grease removal, pre-settling, staged feeding, or partial pretreatment are necessary before AGS can be operated reliably [25].

The problems highlighted show that the leachate from kitchen waste cannot be assessed using only conventional parameters like COD, ammonium or phosphates. More process-oriented characterization is needed, which includes biodegradability, volatile fatty acid(s) (VFA) profile, free ammonia potential, oil and grease, alkalinity, salinity, suspended solids, and nutrient ratios. All these pieces of information are crucial for deciding whether pretreatment, dilution, staged feeding, anaerobic fermentation or post-treatment recovery should be incorporated into the operation of AGS [25–29].

2.4. Resource Potential of Carbon, Nitrogen, and Phosphorus

Kitchen waste leachate is very resourceful, although it is difficult to treat. The organic carbon fraction may serve as an internal source of carbon for denitrification and improved biological phosphorus removal. In many wastewater treatment systems, N and P removal is limited by the availability of readily biodegradable carbon (RBC), and an external carbon source (ECS), such as acetate or methanol, is needed. Volatile fatty acids may be supplied to the denitrifying bacteria and to the phosphorus-accumulating organisms from kitchen waste leachates, particularly from partially fermented wastes. This is not only because it is a waste stream to be treated, but also because it is a useful substrate to enhance biological nutrient removal [30].

There are several ways to recover nitrogen from kitchen waste leachate, including biological assimilation in sludge biomass, ammonium concentration, ammonia stripping, acid absorption, ion exchange, and membrane separation. In AGS systems, N discharge can be minimized by initially reducing N by biological transformation via nitrification and denitrification. However, if all the NH_4 is converted to N gas, it is not a nutrient recovery; it is a nutrient removal. This distinction is relevant from a circular-bioeconomy perspective. Denitrification eliminates the risk of eutrophication but also removes reactive nitrogen from the resource cycle. Thus, the design of future processes should allow for consideration of the need to remove, recover or partially conserve nitrogen in the final product, depending on the production goal and environmental goal.

The importance of phosphorus recovery is highlighted, as AGS can improve biological phosphorus removal, enriching phosphorus within microbial biomass. Under appropriate anaerobic–aerobic cycling conditions, phosphorus-accumulating organisms bind and store phosphate intracellularly as polyphosphates. This provides the opportunity to collect granular sludge with a high phosphorus content or to allow the phosphorus to run off in a concentrated sidestream for the precipitation of struvite or calcium phosphate. Biological phosphorus accumulation can also reduce organic interference and enhance recovery selectivity at the downstream site compared with direct chemical precipitation from raw leachate. However, the effectiveness of this pathway relies on the stable activity of the PAO, a sufficient supply of volatile fatty acids, proper cycling conditions, and control of competing glycogen-accumulating organisms [31].

2.5. Implications for AGS-Based Circular Bioeconomy Systems

The features of kitchen waste leachate indicate that AGS technology can work in two ways—treatment and resource recovery. The dense structure and good settling properties allow it to be used for simultaneous organic carbon degradation, nitrogen transformation, and phosphorus accumulation; its microbial micro-environment is stratified, enabling the cultivation of a variety of microorganisms simultaneously. AGS has the added benefit of serving as a biological upgrading process to create more manageable leachate streams for nutrient recovery downstream. For example, AGS treatment can be used to lower excessive organic matter prior to struvite precipitation, to stabilize nitrogen species prior to the recovery of ammonia, and to concentrate nutrients inside biomass for later valorization [7].

However, care must be taken when designing the operational process if using AGS to treat kitchen waste leachate is to succeed. Feeding raw leachate to the bacteria can give organic shock, ammonia inhibition, and lead to the disintegration of granules. For this reason, strategies such as dilution, pre-settling, oil removal, anaerobic pre-fermentation, staged feeding, and dissolved oxygen (DO) control may be required. Treatment and recovery expectations should also be well established. An optimized system for pollutant removal does not necessarily optimize nutrient removal, whereas an optimized system for nutrient removal requires preserving nutrients in recoverable forms and complying with discharge or reuse requirements.

In general, kitchen waste leachate is a complex yet valuable input for developing a circular bioeconomy using AGS. It is rich in organic matter and nutrients, providing a biochemical basis for nutrient transformation and recovery, as well as variability and inhibitory properties that pose significant operational challenges. The challenge for science and engineering is therefore not only to eliminate pollutants from leachate, but to develop systems that minimize its compositional variability, direct microbial processes, and recover carbon, nitrogen, and phosphorus in beneficial forms. This is a way of looking at AGS that will serve as a basis for examining AGS as a resource-oriented technology in the rest of this review [32].

3. Aerobic Granular Sludge Technology for Nutrient Recovery

3.1. Fundamentals of Aerobic Granular Sludge Formation

Aerobic granular sludge (AGS) is a naturally self-immobilized microbial aggregate that is produced under certain hydraulic, biological, and operational selection pressures. AGS is formed into granules, which are compact, denser, and spherically shaped as compared to conventional activated sludge and have high settling capacity and biomass retention. This structural difference is very important for its technological usefulness, as it enables biological treatment systems to operate at high microbial concentrations in a smaller reactor volume and to achieve better separation of solids.

The general principles that promote granulation are feast-famine operation, short settling time, high hydrodynamic shear, adequate organic loading, and selective washout of poorly settling biomass. In the feast phase, the microorganisms rapidly consume available substrates, store them as intracellular polymers, or transform organic matter into biomass. The less competitive flocculent biomass is gradually outcompeted and removed during the famine phase, while the slower-growing, better-adapted organisms survive by utilizing stored compounds. This is a cyclic selection for dense microbial aggregates that produce large amounts of extracellular polymeric substances. Proteins, polysaccharides, humic-like substances, and extracellular DNA are the primary constituents of EPS, which functions as a structural matrix providing the bacterial community with protection against environmental stresses and cell-cell interactions [8,17].

The potential for the formation of stable AGS is both promising and challenging in kitchen waste leachate treatment. Microbial growth and aggregation can be stimulated by the high level of readily biodegradable organic matter (RBOM), but excessive or uneven loading may also lead to proliferation of loose biomass, filamentous growth, and unstable granules. Hence, the granulation based on kitchen waste leachate should be controlled carefully for the strength of influents, feeding pattern, intensity of aeration, and selection of settling. The key problem is to use the microbial and physical characteristics of the granules to make use of the substrate concentration in the leachate without destroying the granules [33].

3.2. Structural Characteristics and Internal Microenvironments

The most distinctive feature of AGS is its stratified internal structure. Because oxygen, substrates, and nutrients diffuse from the granule surface toward the core, concentration gradients develop across the granule radius. The outer layer is generally aerobic and supports organic carbon oxidation and nitrification. Deeper layers may become anoxic, enabling denitrification, while the inner core can become anaerobic under certain operating conditions. This spatial heterogeneity allows multiple biochemical reactions to occur simultaneously within a single particle [34,35]. The spatial organization of aerobic, anoxic, and anaerobic zones within AGS is schematically shown in **Figure 2**, highlighting the oxygen and substrate gradients that enable simultaneous carbon oxidation, nitrogen transformation, and phosphorus cycling within a single biological aggregate.

This internal structure is especially important in relation to leachates, which contain nutrients. In a traditional suspended-growth system, aerobic, anoxic, and anaerobic zones are typically necessary to remove nitrogen and phosphorus. These zones may coexist at the microscale in AGS, enabling a compact reactor design and the simultaneous transformation of nutrients. The benefit of this, however, is linked to the appropriate granule size and density. Very small granules might not generate sufficient internal gradients, and very large granules might be unable to achieve proper diffusion of the substrate, and might have inactive cores, decaying cells, and structural forces. Therefore, granule size distribution should be considered an operational variable rather than a passive product.

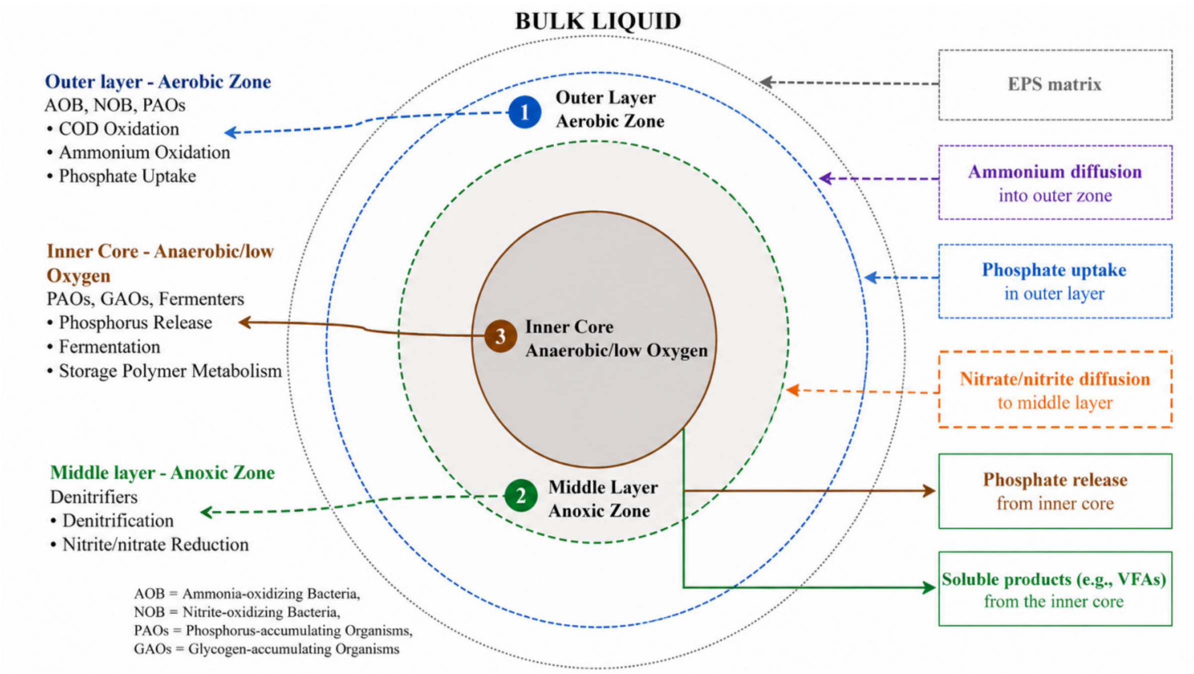

Figure 2. Schematic representation of aerobic granular sludge microstructure and internal aerobic, anoxic, and anaerobic zones.

The mass transfer is complicated by leachate from kitchen waste. If the concentration of organic matter is high, oxygen is consumed rapidly near the surface of the granule, creating an anoxic or even anoxic zone and potentially reducing nitrification capacity. Coatings of lipids and suspended solids on granule surfaces can also inhibit oxygen transfer. Such gradients can promote denitrification, but can also lead to an imbalance if nitrification is inhibited. Thus, the same structural trait that makes AGS attractive for simultaneous nutrient removal can be a restriction in the absence of a balanced substrate loading and oxygen transfer [36,37].

3.3. Microbial Communities and Functional Populations

A diversity of microbial groups is required for the coexistence and competition that is necessary for AGS performance. The degradation of organic matter is typically dominated by heterotrophic bacteria, which tend to respond most rapidly to high-carbon influents. Nitrification consists of the transformations that occur under aerobic conditions between ammonium and nitrite, and between nitrite and nitrate, and is carried out by ammonia-oxidizing bacteria and nitrite-oxidizing bacteria. Under anaerobic conditions, denitrifying bacteria convert nitrate or nitrite to gaseous N with organic carbon or stored polymers as electron donors. Under aerobic conditions, phosphorus-accumulating organisms take up phosphorus and release it under anaerobic conditions, thus improving biological phosphorus removal. Glycogen-accumulating organisms (GAOs) are also present in systems to remove PAOs, but are not a desired organism because they consume volatile fatty acids (VFAs) and do not play a significant role in the removal of phosphorus [34].

The microbial ecology of AGS treating kitchen waste leachate is hypothesized to be different from that of municipal wastewater due to the presence of relatively higher concentrations of proteins, lipids, volatile fatty acids, ammonium, and suspended organic particles in the leachate. Hydrolytic and fermentative bacteria may be more important, as they convert complex organic compounds in food into simpler ones. This can be useful when fermentation products (acetates and propionates) facilitate denitrification and P accumulation. However, if fast-growing heterotrophs are too prevalent, granules may be destabilized, and slow-growing nitrifiers may be suppressed. A critical question is then not just whether the removal of pollutants is possible, but whether the operating conditions can ensure the preservation of a balanced microbial community that treats and recovers simultaneously.

This competition is particularly relevant for comparing phosphorus recovery between PAO and GAO. The amount of biodegradable carbon in the kitchen waste leachate may be high, but the availability of this carbon, in both type and timing, will determine whether PAOs or GAOs are favored. PAOs need to be provided with an appropriate anaerobic-to-aerobic cycle, as well as readily available volatile fatty acids. Phosphorus release and luxury uptake are reduced if anaerobic conditions are insufficient in the system or if there is excessive oxygen during feeding. AGS systems for phosphorus recovery from leachate will therefore need to control the total carbon, carbon form, feeding phase, redox sequence, and sludge retention conditions [38–40].

3.4. Mechanisms of Carbon, Nitrogen, and Phosphorus Transformation

Treatment and recovery potential for AGS depend on the ability to transform carbon, nitrogen, and phosphorus through integrated biotic processes. Organic carbon is first metabolized and mineralized by heterotrophic microorganisms. The readily biodegradable compounds are quickly broken down in the feast phase; more complex organics are either enzymatically hydrolyzed before being broken down or are broken down in the feast phase. For kitchen waste leachate, carbon removal is typically both a discharge requirement and a process control factor. Too high a carbon loading can result in oxygen competition, limiting nitrification, while a low readily biodegradable carbon loading can reduce denitrification and biological phosphorus removal.

N transformation starts with the conversion of organic N to ammonium through ammonification, and subsequently to nitrate in aerobic zones. Ammonia-oxidizing organisms convert ammonium to nitrite, and nitrite-oxidizing organisms convert nitrite to nitrate. Denitrification occurs in anoxic environments where nitrate and/or nitrite serve as electron acceptors. Simultaneous nitrification and denitrification can occur in AGS because nitrifiers are active in the outer regions (high oxygen concentration) and denitrify in the inner regions (low oxygen concentration). This is an attractive mechanism for small systems but is dependent on dissolved oxygen, granule size, carbon availability, and diffusion limitations [41].

The circular bioeconomy conceptually addresses the transformation of nitrogen. Biological N removal via denitrification removes reactive N and leads to a loss of a potentially recoverable nutrient but also a reduction in pollution. Hence, the operation of AGS must be adjusted according to the desired purpose. For discharge compliance, full or complete nitrogen removal may be required. Partial conversion, retention of ammonium or assimilation of biomass or coupling with ammonium recovery technologies may be preferred if nutrient recovery is desired. In the field of wastewater studies, the distinction between the two is frequently overlooked, and removal efficiency is considered the most important measure of success.

Phosphorus transformation in AGS can occur through biological uptake, chemical precipitation, adsorption, and biomass assimilation. When cycling conditions are favorable, PAOs release phosphate under anaerobic conditions, absorb volatile fatty acids, and store them as intracellular polymers. Under aerobic conditions, PAOs use stored polymers and absorb excess phosphate, and store it as polyphosphate. This process may lead to the accumulation of phosphorus in granular biomass and may enable the recovery of phosphorus-rich sludge or the release of phosphate as a sidestream. But phosphorus recovery is not necessarily followed by removing phosphorus. Without phosphorus extraction or reuse, the system is closer to a conventional waste treatment system than to a true resource recovery system [41].

3.5. Operational Parameters Controlling AGS Performance

AGS performance is largely sensitive to the operating parameters. The microbial growth, granule density, and substrate gradients are affected by the organic loading rate. Granulation and nutrient removal will be facilitated by moderate loading, while granules will be unstable, fluffy, or filamentous if the loading is too high. Hydraulic retention time (HRT) is related to contact with the leachate, while sludge retention time (SRT) is related to the ratio of fast-growing heterotrophs to slow-growing nitrifiers or PAOs. Short settling time is one of the primary selection pressures as it will keep the dense granules and remove poorly settling flocs [42].

Another important parameter is dissolved oxygen. High oxygen concentrations favour nitrification and oxidation of organic compounds, but can also decrease anoxic areas for denitrification and inhibit the release of anaerobic phosphorus. Simultaneous nitrification-denitrification is favoured in low oxygen conditions, which can also limit the extent of ammonium oxidation. Oxygen demand can be high for kitchen waste leachate due to high COD, and control of oxygen demand is critical. Aeration should be adequate to supply oxygen and shear force for granule stability and not high enough to demand too much energy or to disturb the desired nutrient recovery routes.

It is also important to provide a feeding strategy. Anaerobic feeding can be beneficial for PAOs and for the accumulation of phosphorus, whereas aerobic feeding can be beneficial for fast heterotrophic oxidation but reduce EBPR. Step feeding can decrease shock loading and help to spread substrate out across the cycle. Leachate pre-fermentation can improve the availability of VFAs but uncontrolled fermentation can produce a higher amount of ammonia, odour and inhibitory compounds. Thus, the design of the operational and engineering aspects of AGS for kitchen waste leachate should not be the same as that of municipal wastewater treatment. **Table 2** summarizes the major operational parameters that regulate the stability of AGS and nutrient recovery, highlighting that each parameter can contribute to both stability and failure in the process of treating kitchen waste leachate [43].

Table 2. Operational parameters affecting AGS stability and nutrient recovery from kitchen waste leachate.

Operational Parameter	Main Function in AGS Systems	Potential Benefit	Critical Risk under Kitchen Waste Leachate Treatment	Recovery-Oriented Control Strategy
Organic loading rate	Controls substrate availability and microbial growth	Promotes granulation and carbon-driven nutrient removal	Excessive loading may cause filamentous growth, oxygen limitation, and granule disintegration	Apply gradual loading increase, dilution during start-up, or step feeding
Hydraulic retention time	Determines contact time between biomass and leachate	Improves organic degradation and nutrient transformation	Short HRT may cause incomplete treatment; long HRT may reduce productivity	Optimize based on COD removal, ammonium conversion, and nutrient recovery targets
Sludge retention time	Controls retention of slow-growing functional microbes	Supports nitrifiers and PAOs	Too short SRT may wash out nitrifiers; too long SRT may reduce phosphorus wastage and recovery	Balance microbial stability with nutrient-rich biomass harvesting
Settling time	Selects dense and fast-settling granules	Enhances granule formation and biomass retention	Excessively short settling may wash out useful biomass during start-up	Gradually reduce settling time as granules mature
Dissolved oxygen	Regulates aerobic and anoxic zones inside granules	Supports nitrification and COD oxidation	Excess DO may suppress denitrification and phosphorus release; low DO may inhibit nitrification	Maintain controlled DO to support simultaneous nitrification–denitrification
Aeration intensity	Provides oxygen and hydrodynamic shear	Strengthens granule compactness and mass transfer	High aeration increases energy demand and may damage granules	Use intermittent or optimized aeration to balance shear and energy use
Feeding mode	Determines substrate exposure and redox sequence	Anaerobic feeding can favor PAOs and EBPR	Aerobic feeding may reduce phosphorus recovery potential	Use anaerobic or step feeding when phosphorus recovery is targeted
Exchange ratio	Controls influent loading per cycle	Increases treatment capacity	High exchange ratio may create shock loading	Adjust exchange ratio according to leachate strength
Pre-fermentation	Converts complex organics into VFAs	Enhances denitrification and biological phosphorus uptake	Uncontrolled fermentation may increase ammonia, sulfide, and odor	Control fermentation time, pH, and VFA profile
Pretreatment for oil/solids	Reduces inhibitory and clogging components	Improves granule stability and downstream recovery	Excessive pretreatment may remove useful carbon	Apply selective removal of fats, oils, and grease (FOG) and coarse solids while retaining soluble carbon

3.6. Advantages of AGS over Conventional Biological Treatment

Advantages of using activated sludge (AS) as compared to conventional activated sludge (CAS) in high-concentration organic wastewater treatment are provided by AGS. It settles very well, enabling the separation of biomass in a fairly short time and achieving higher biomass concentrations. This can help minimize space requirements and enhance process compactness, benefiting decentralized kitchen waste treatment facilities, food markets, campus facilities, restaurants, and municipal organic waste treatment centers. The granular structure also has the advantage of being resistant to hydraulic fluctuations and can be used to remove nutrients in parallel without requiring several separate reactors [44].

AGS also has other benefits for nutrient recovery. Increased biological phosphorus removal can result in granular biomass formation of phosphorus and the transformation of nitrogen to forms that can be removed or recovered. The high biomass also opens the possibility of valorizing granular sludge through anaerobic digestion, biochar production, phosphorus extraction, or recovery of extracellular polymeric substances. This is how AGS is more than just a treatment technology; it can serve as a biological platform for recovering dissolved and particulate pollutants as material streams.

But these benefits should be taken with a pinch of salt. Reported benefits of AGS have been derived from controlled laboratory or municipal wastewater situations. Kitchen waste leachate is a more complex mixture, and results obtained from diluted synthetic wastewater may not directly apply to actual leachate. Moreover, high removal efficiency does not necessarily indicate high recovery efficiency. A system can effectively remove nitrogen and phosphorus, but cannot generate a useful recovered product. Hence, the assessment of AGS performance should not be limited to pollutant elimination but should also consider nutrient retention, product quality, operational stability, energy demand, and compatibility with downstream recovery [45].

3.7. Limitations and Technical Bottlenecks

The use of AGS technology in kitchen waste leachates has some drawbacks. Slow start-up, in particular, may be required when inoculated biomass needs to adapt to high organic strength, ammonia, lipids, and salinity. Sudden changes in loading, lack of shear, settling selection, or toxic shock can cause granule disintegration. Overgrowth of filamentous forms may result in low densities and poor settling ability. The inhibition of nitrification can be due to free ammonia and/or heterotrophic oxygen competition, and the reduction of phosphorus removal can be attributed to poor PAO selection or GAO competition.

The nutrient removal vs. nutrient recovery is another key limitation. Typical AGS applications are designed to maximize the removal of COD, nitrogen, and phosphorus from effluent. Circular bioeconomy systems, however, need nutrients to be captured as reusable nutrients. This can make necessary changes to the process to promote more phosphorus storage, less ammonium recovery, or more biomass harvesting with high nutrient content. It is possible that such objectives will be incompatible with the stringent effluent-polishing requirement, unless the system is engineered as an integrated treatment/recovery chain [46,47].

Although operational control can improve AGS resilience, these limitations cannot always be overcome by simple parameter optimization. For real kitchen waste leachate, maintaining granule stability may require upstream pretreatment, dilution, equalization, or selective removal of oil, grease, and suspended solids. These measures may improve biological stability but can also dilute nutrients, increase reactor volume, increase cost, or reduce the concentration of streams available for downstream recovery. Thus, AGS design must balance treatment stability with recovery efficiency rather than assuming that both can be maximized simultaneously.

3.8. Implications for Nutrient Recovery from Kitchen Waste Leachate

The advantage of AGS for kitchen waste leachate is that it stabilizes a complex organic stream while guiding the recovery of specific nutrients through specific pathways. It has a microbial stratification that allows carbon oxidation, nitrogen conversion, and phosphorus accumulation to take place concurrently, and its excellent settling facilitates biomass retention and harvesting. However, it is important to consider AGS system design based on the leachate composition of kitchen waste and the desired recovery product. An optimized denitrification reactor can reduce nitrogen pollution but lose the ability to recover nitrogen. Specific aerobic/anaerobic sequencing and control of VFAs may be needed in a reactor optimized for phosphorus accumulation. Product safety, pathogens, heavy metals, and contaminant accumulation must be taken into account in a system used for biomass valorization [33].

Thus, AGS is considered a biological core to be integrated into a wide-band resource recovery system. Upstream treatment can be used for the removal of oils, equalization of loading, or production of VFAs. The AGS reactor can then convert and stabilize organic matter and concentrate or convert nutrients. Specific products can be recovered from the downstream processes, including struvite precipitation, ammonia stripping, ion exchange, membrane concentration or anaerobic digestion. This holistic approach is necessary, as the AGS alone cannot realize the full potential of the circular bioeconomy and must be linked to recovery, product refinement, and reuse routes [32].

Overall, the AGS technology offers a scientifically robust and practically promising foundation for recovering nutrients from leachate produced by kitchen waste. Not only is this because it is compact with regard to its treatment performance, but it is also because of its ability to facilitate the recoverability of carbon, nitrogen and phosphorus through biological transformations. The main challenge is to go beyond proof of pollutant removal, and develop stable, recovery-oriented AGS systems that can use real leachate variability and produce safe, useful and economically viable products.

4. Case Studies and Experimental Evidence on AGS Treatment of Kitchen Waste Leachate

4.1. Overview of Experimental Systems and Evidence-Based Performance Evaluation

In contrast to the extensive literature on the use of AGS for the treatment of municipal wastewater, landfill leachate, slaughterhouse wastewater, brewery wastewater, and other high-strength organic effluents, experimental data on the treatment of kitchen waste leachate using aerobic granular sludge remain relatively limited. This imbalance is significant because the composition of leachate from kitchen waste differs markedly, containing high concentrations of biodegradable organic matter, ammonium, phosphate, suspended solids, fats, oils, and grease, as well as fermentation-derived compounds. Thus, performance trends from other wastewater streams may provide useful reference points, but they cannot be transferred without accounting for the specific characteristics of kitchen waste leachate that can inhibit and/or facilitate recovery [48].

The majority of experimental systems available for this topic are sequencing batch reactors, since the natural sequencing batch reactor operation generates the feast–famine regime, settling selection, and alternating redox conditions necessary for the development of AGS. The operational parameters (organic loading rate, exchange ratio, aeration intensity, settling time, hydraulic retention time, and feeding mode) in these systems are adjusted to facilitate granule formation and nutrient conversion. Continuous-flow AGS systems have also been of interest but are not as well developed as batch-process systems for use with complex leachate, because it is more challenging to sustain stable selection pressure and granule retention under continuous-flow hydraulic conditions.

One of the main problems in case study analysis is distinguishing between removal-oriented and recovery-oriented experiments. High removals for COD, ammonium, total nitrogen, or phosphorus are reported in many studies on AGS, and fewer studies quantify removals of nitrogen and/or phosphorus in recoverable forms. The difference is key in the light of a circular bioeconomy. Nitrogen that is denitrified to nitrogen gas is a good environmental option, but is not available for reuse. The same applies to the removal of phosphorus in waste sludge, which is not recovered unless the waste sludge can be valorized or phosphorus extracted. Thus, besides tracking effluent quality, the nutrient mass balance, product yields, sludge composition and downstream recovery potential must all be taken into consideration in determining experimental evidence [49].

4.2. AGS Treatment of Raw or Diluted Kitchen Waste Leachate

The direct treatment of raw kitchen waste leachate by AGS is conceptually attractive, as it reduces the need for pretreatment and allows concentrated nutrients to be introduced into the biological system. The high levels of biodegradable carbon may provide sufficient support for rapid heterotrophic activity, denitrification, and potentially PAOs, provided that proper anaerobic/aerobic cycling is implemented. Raw leachate may also be an organic and ammonia shock load, which could affect granule morphology and the functional stability of microorganisms. Thus, many experimental methods employ dilution or gradual acclimation prior to exposing AGS to the full-strength leachate [50].

Dilution is often blamed for decreases in the efficiency of resources, but it can be a vital experimental and operational technique at start-up. Dilution also decreases the concentration of COD, ammonium, salinity, and oil, which means fewer acute inhibitions and a gradual adaptation of granules. This constraint is that dilution also reduces nutrient levels, which may result in lower recovery efficiency and higher hydraulic volume. Therefore, dilution will be useful for start-up or decentralized systems that can blend wastewater, but cannot be considered a long-term solution unless the combined stream achieves greater treatment stability and nutrient recovery.

Reported instability under high-strength leachate should be considered a realistic operational outcome rather than only a start-up problem. When loading exceeds the adaptive capacity of the granules, the system may shift from dense granules to fluffy aggregates or flocs, reducing settleability and causing washout. Dilution or gradual acclimation can reduce acute inhibition, but this strategy also lowers nutrient concentrations and may compromise the economics and material efficiency of nutrient recovery. Therefore, direct treatment of raw leachate should be regarded as a high-risk configuration unless supported by careful influent characterization, shock-load control, and contingency strategies [51].

Typical experiments with raw or diluted leachate will typically show an inherent balance between a higher-strength influent resulting in higher recovery potential but higher instability potential. AGS can degrade organic matter efficiently and exhibits good settling performance when moderately loaded. In cases of heavy loading, the granules may swell, decrease in density, become roughened, grow filaments, or partially break apart. These changes will diminish the solid–liquid separation and may lead to biomass washout. This indicates the need to control the loading of kitchen waste leachate, not just the maximum influent concentration, for successful treatment. The most promising systems are designed to gradually strengthen the leachate and to measure the granule size, settling velocity, extracellular polymeric substances, nitrification activity, and capacity for the uptake of phosphorus [51–53].

4.3. AGS Coupled with Pre-Fermentation or Anaerobic Pretreatment

Kitchen waste leachate can be treated in the same manner as the garbage residue, using pre-fermentation and/or anaerobic pretreatment, thereby enhancing compatibility with AGS by converting complex organic content into VFAs. This is particularly important for enhanced biological phosphorus removal, as the preferred food for the P-accumulating organisms is short-chain volatile fatty acids (VFAs) such as acetate or propionate. The fermented leachate can thus be an added source of pollution, but also as an effective carbon source to remove and recover nutrients.

The importance of anaerobic pretreatment is largely dependent on process control. Controlled fermentation can increase the ratio of readily biodegradable COD and improve denitrification and phosphorus uptake. It also reduces particulate solids and partially hydrolyzes proteins, carbohydrates, and lipids. But in uncontrolled fermentation, excessive quantities of ammonia, sulfide, odor, acid, or inhibitory intermediates can be produced. High levels of free ammonia (FA) or volatile fatty acids (VFA) in the fermented stream could inhibit nitrifiers and create AGS instability. For this reason, fermentation would be best optimized as a conditioning step and not as a general pretreatment [46].

Sequential carbon and nutrient management is a significant benefit of anaerobic pretreatment and AGS. Biogas or volatile fatty acid production can be used for energy recovery in anaerobic units, and AGS can be used to polish the liquid fraction and direct nutrients toward biomass or recoverable minerals. However, one of the main drawbacks is that most anaerobic digestion processes do not recover organic nitrogen but instead convert it into ammonium. Significant amounts of this N may be lost as N gas once the next stage of AGS is completed with full nitrification and denitrification. Hence, an integrated anaerobic AGS system should be designed with a clear nutrient strategy, either to maximize nutrient removal for compliance or to retain nutrients such as ammonium and phosphate for downstream recovery [54].

4.4. AGS Integrated with Struvite Precipitation

Precipitation of struvite has been identified as one of the most promising recovery options for AGS-treated kitchen waste leachate, as it recovers ammonium and phosphate as magnesium ammonium phosphate, a slow-release fertilizer. The raw kitchen waste leachate could contain sufficient ammonium and phosphate to form struvite, but may also contain high concentrations of organic matter, suspended solids, and competing ions that could affect the purity and crystallization rate of the product. In this way, AGS can be used as a biological conditioning step to remove soluble organic matter, reduce the number of solids, and convert nutrients into other species prior to precipitation.

The difference between biological nutrient removal and nutrient recovery is demonstrated with the integration of AGS and struvite precipitation. Under normal AGS conditions, biomass can absorb phosphorus, thereby reducing its concentration in the liquid phase. However, to recover struvite, the liquid phase of the ammonia solution needs to be sufficiently concentrated in phosphate, or the phosphate needs to be liberated from the phosphate-rich sludge in a sidestream. Therefore, increasing phosphorus removal in the main reactor does not necessarily maximize struvite production. Controlled phosphorus release, sludge fermentation, or sidestream treatment can be used to crystallize phosphate, and may be needed for a recovery-oriented configuration.

Other factors that affect the success of struvite recovery include pH, magnesium availability, the ammonium-to-phosphate ratio, alkalinity, calcium competition, and organic matter levels. Kitchen waste leachate can give ammonium, but not necessarily enough magnesium. This may then necessitate chemical addition, and this impacts cost and sustainability. Also, calcium can compete with the struvite reaction if it is present in large quantities. The nutrient mass balances and product characterization indicate that assessment of AGS struvite systems should be based on these parameters, not solely on precipitation efficiency. Key requirements for the implementation of circular bioeconomy are the agronomic value, contaminant content, crystal morphology, and economic viability of recovered material [55].

4.5. AGS Combined with Membrane, Ion Exchange, or Adsorption Systems

Hybrid systems using AGS with membrane filtration, ion exchange, or adsorption can help to enhance effluent purity and to recover nutrients. Membranes can be used to retain suspended solids, leading to an effluent that can be clarified; selective membranes can concentrate ammonium and/or phosphate. Ammonium can be removed from treated effluent by ion exchange materials, including zeolite-based media. The removal of phosphate, ammonium, or residual organics can be done by adsorption of biochar, modified minerals, or activated materials, depending on their surface chemistry.

The major benefit of such hybrid systems is that AGS decreases the organic and solids loading prior to the physicochemical recovery step. This can reduce fouling, increase the adsorbent's selectivity, and increase nutrient concentration. This conditioning function is especially significant for kitchen waste leachate due to its complexity in many cases, which prevents the direct use of a membrane or adsorption treatment. There are, however, trade-offs in the complexity of the process, capital cost, and maintenance requirements when it comes to hybridization. The biggest constraint in treating streams containing fats, colloids, extracellular polymers, and fine suspended solids is membrane fouling. The management of regenerant solutions needs to be considered, and regenerants and ion exchangers need to be replaced or regenerated.

While improved removal efficiency is an important consideration, a hybrid AGS system must also be evaluated critically. A membrane that filters nutrients but generates a nutrient-rich concentrate without a reuse route is just moving the problem. Likewise, an adsorbent that can bind the phosphate is useful only if regeneration, nutrient recovery, or direct use in agriculture is possible. Thus, future experiments should take into account recovery efficiency, regeneration performance, product safety, and life-cycle impacts. If these assessments are not conducted, hybrid systems can easily evolve into sophisticated pollution-transfer processes instead of circular recovery systems [56].

4.6. AGS Biomass Valorization as a Case-Study Direction

AGS biomass could be a recoverable product due to its potential to contain organic carbon, nitrogen, phosphorus, EPS, and mineral precipitates. Excess granules in phosphorus-removing AGS systems can accumulate high concentrations of phosphorus within the granules as intracellular polyphosphate or inorganic precipitates. This provides direct applications as a soil amendment post-stabilization, for phosphorus extraction, for energy recovery by anaerobic digestion, for biochar production, or for recovery of alginate-like extracellular polymers.

The valorization of biomass is especially relevant for kitchen waste leachate, since the substrate may accumulate large amounts of biomass and assimilate nutrients. But the safety and uniformity of biomass from AGS should be thoroughly considered. Depending on how kitchen waste is collected and processed, pathogens, salts, trace metals, microplastics, residues of cleaning chemicals, and emerging contaminants may be present in the leachate. If recovered biomass is to be used in agriculture, stabilization, hygienization, monitoring for contamination, and compliance with fertilizer regulations are required. The nutrient value of AGS biomass should also be compared with other products, such as struvite or ammonium sulfate, since the nutrients might be released more slowly into the substrate and these products might have different compositions [11,15,57].

Another constraint is that biomass production and sludge management may conflict to reduce excess sludge production. AGS has been marketed as a process that produces less sludge than activated sludge; however, nutrient recovery through biomass harvesting may necessitate intentional sludge removal. This allows an operating equilibrium between maintaining a reasonable level of biomass for reactor operation and removing sufficient nutrient-laden biomass for recovery. Thus, the valorization of biomass needs to be combined with sludge age control, nutrient mass balance, and product-use planning.

4.7. Comparative Interpretation of Case Evidence

Earlier, I described some common patterns across the case studies' directions. First, AGS is better suited as a platform for controlled biological conversion than as a universal solution for raw kitchen waste leachate. It works better if the influent loading, oil content, solids concentration, and redox sequencing are controlled. Secondly, the most promising configurations are combinations of upstream conditioning and AGS-based biological transformation, with downstream nutrient recovery. Third, high pollutant removal does not necessarily mean circularity. Experiments should be able to differentiate between removal, transformation, concentration, and real recovery [58].

Characterization of inflows is also significant, as recommended by comparative analysis. Studies reporting only COD, ammonium, and phosphorus do not provide a complete basis for process interpretation. The parameters required for kitchen waste leachate are the composition of volatile fatty acids, the ratio of soluble to total COD, concentration of oil and grease, alkalinity, salinity, calcium, magnesium, and free ammonia potential. These parameters decide whether the system promotes nitrification, denitrification, phosphorus accumulation, struvite precipitation, or inhibition. Likewise, only the final effluent quality can be reported. In a study conducted for recovery, nutrient partitioning should be quantified as effluent, biomass, gaseous losses, precipitates, and sidestreams.

Another constraint is the level of experimentation. Laboratory-scale reactors are useful for elucidating the mechanism, but they operate under controlled conditions that may differ from those in kitchen waste collection systems. Leachate streams can be intermittent and variable, and may include cleaning chemicals or other contaminants, whereas full-scale streams are present. Therefore, pilot-scale studies are critical to assess long-term granule stability, operational robustness, energy requirements, and product quality. If this is not so, statements about the implementation of a circular bioeconomy are only preliminary. **Table 3** provides a comparative overview of the main categories of case studies presented in this paper, highlighting the reactor configuration, experimental objective, contribution to the circular bioeconomy, and main limitations [59].

4.8. Research Implications and Future Case-Study Priorities

Ideally, future case studies will shift from proof of treatment to proof of recovery. The need for such designs entails nutrient mass balance, characterization of recovered products, microbial community analysis, and operational stability under realistic variability in leachate composition. Removal percentages are not the only aspect of a study to consider; the transformation of nitrogen and phosphorus, and whether they remain in recoverable forms, should also be examined. For nitrogen, this includes the separation of ammonium recovery, biomass assimilation, nitrate accumulation, and gaseous losses. For phosphorus, the assessment involves determining whether it is stored biologically, chemically precipitated, adsorbed, and/or discharged [60].

Table 3. Comparative framework for AGS-related case studies on kitchen waste leachate and comparable high-strength organic wastewaters.

Case-Study Category	Reactor/System Configuration	Experimental Objective	Expected Performance Indicators	Contribution to Circular Bioeconomy	Limitation
Raw or diluted kitchen waste leachate treatment	AGS sequencing batch reactor	Evaluate direct biological treatment and granule adaptation	COD removal, NH_4^+-N conversion, total nitrogen (TN) removal, total phosphorus (TP) removal, sludge volume index (SVI), settling velocity, granule size	Demonstrates feasibility of AGS for high-strength food-waste-derived liquid streams	Raw leachate may cause shock loading, ammonia inhibition, and granule instability
Pre-fermented leachate with AGS	Anaerobic fermentation followed by AGS-SBR (sequencing batch reactor)	Improve VFA availability for denitrification and phosphorus removal	VFA/COD ratio, PAO activity, phosphate release/uptake, nitrogen removal, granule stability	Links carbon recovery and biological nutrient transformation	Fermentation may increase odor, ammonium, acidity, and inhibitory intermediates
AGS coupled with struvite recovery	AGS reactor followed by a crystallization unit	Recover phosphorus and ammonium as mineral fertilizer	Phosphate release, Mg/P ratio, struvite yield, crystal purity, residual nutrient concentration	Converts nutrients into a slow-release fertilizer product	Requires pH control, magnesium addition, and product-quality assessment
AGS with membrane, ion exchange, or adsorption	AGS plus polishing or concentration unit	Enhance effluent quality and concentrate nutrients	Membrane flux, fouling rate, ammonium adsorption, phosphate adsorption, regeneration efficiency	Produces recoverable nutrient concentrates or polished reusable effluent	Higher cost, fouling, adsorbent regeneration, and concentrate management
AGS biomass valorization	Nutrient-rich AGS harvesting followed by digestion, extraction, or pyrolysis	Recover value from excess granular biomass	Biomass phosphorus content, methane yield, EPS yield, biochar nutrient content, contaminant level	Converts excess sludge into bioenergy, biofertilizer, EPS, or biochar	Product safety, nutrient bioavailability, and regulatory acceptance remain uncertain
Integrated treatment-recovery system	Pretreatment, AGS, nutrient recovery, biomass valorization	Develop full circular bioeconomy pathway	Nutrient mass balance, energy use, recovered product yield, GHG emissions, economic performance	Moves from pollutant removal to resource recovery	Requires pilot-scale validation and system-level optimization

Also, more attention should be paid to dynamic operation. The concentration of the kitchen waste leachate is unlikely to remain constant in a treatment system. Thus, further experiments should involve shock loading, intermittent feeding, seasonal changes in composition, and recovery after inhibition. These tests would provide more real-world information than steady-state performance tests. Furthermore, the effectiveness of pretreatment should be systematically assessed. Not only should these oil removal, equalization, fermentation, dilution, and solids separation be compared for their effects on AGS stability, but their effects on downstream nutrient recovery should also be considered.

The case-study evidence indicates that AGS has strong potential to treat kitchen waste leachate, but integration into systems offers opportunities for circular bioeconomy value. AGS can be used to stabilize the organic matter, aid nitrogen and phosphorus transformations, and generate recoverable biomass or conditioned effluent. But nutrient recovery is not simply an efficient process for removing nutrients. The next generation of experimental trials should thus consider the effect of AGS within the framework of a treatment recovery chain, including the microbial ecology, reactor operation, nutrient chemistry, and product reuse [28].

5. Circular Bioeconomy Integration, Sustainability, and Implementation Challenges

5.1. Integrating AGS-Based Treatment into Circular Bioeconomy Systems

The use of aerobic granular sludge for managing kitchen waste leachate is an alternative approach to wastewater treatment within a circular bioeconomy. In the conventional approach, the main treatment of kitchen waste leachate is for the removal of organic loads, nitrogen, phosphorus, odor, and toxicity prior to discharge. This will effectively safeguard receiving areas, but can cause the receiving environment to be considered as a pollutant instead of a resource for carbon and nutrients. In the context of a circular bioeconomy, however, a different logic must be embraced: organic carbon, nitrogen, phosphorus, and microbial biomass must be recovered, reused, or valorized wherever technically and economically feasible [3].

AGS is an ideal biological component for such a system, as it can concentrate and transform nutrients while stabilizing high-strength organic liquid streams. But AGS does not automatically give rise to a circular process. Circularity relies on the reuse of treated effluents, granulated biomass, nutrient-rich sidestreams, or precipitated minerals. Thus, the function of AGS should be considered a facilitation measure in the overall chain of recovery. Upstream units can consist of source separation, screening, oil/grease removal, equalization or anaerobic digestion. The AGS reactor can then be used to remove excess organic material, transform nitrogen and phosphorus, and produce biomass or effluent to be recovered in downstream processes. Final recovery units can be struvite crystallization, ammonium stripping, ion exchange, membrane concentration, anaerobic digestion or biomass valorization.

This holistic view is significant because many biological treatment systems are still assessed using removal efficiency as a key performance metric. Removal alone is not enough in a circular bioeconomy if the removed material is not recovered safely and used in a useful way. If excess sludge is disposed of without nutrient recovery (such as by landfilling or incineration), the mineral phosphorus will have low value. Likewise, nitrification losses decrease the eutrophication threat, but remove R-N from potential reuse. Therefore, the design of AGS-based kitchen waste leachate treatment needs to have a clear purpose of resource recovery, rather than merely optimizing for effluent polishing [61].

5.2. Nutrient Recovery Pathways and Product Formation

There are several ways to recover nitrogen from kitchen waste leachate, such as recovering ammonium, using microorganisms to assimilate nitrogen, and creating fertilizer solutions. In an AGS system, ammonium can be oxidized to nitrate and then reduced to nitrogen gas, but this is considered nutrient removal rather than nutrient recovery. Process designs should ensure that nitrogen is not unnecessarily lost but is instead retained in recoverable forms, if the target is nitrogen circularity. This could be partial stabilization of organic matter prior to ammonium recovery; stripping ammonia from the sidestream; acid absorption to form ammonium sulfate or ammonium nitrate; selective resin or zeolite ion exchange; or membrane concentration.

The problem is that the goals for nitrogen recovery and biological nitrogen removal may differ. The combination of nitrification and denitrification can be effective in meeting discharge standards, but it cannot be used for fertilizer recovery. On the other hand, it can be challenging to maintain hydraulic residence time, pH, and aeration levels to avoid complete nitrification while preserving ammonium. This helps to define the need for flexible AGS configurations in which treatment intensity is tailored to the downstream use. Depending on the circumstances, partial removal of nitrogen may be desirable to prevent toxicity, with the remainder recovered as a fertilizer product. When no reuse is offered or regulatory requirements are tight, whole removal might be preferred instead [62].

Enhanced biological phosphorus removal can be used for phosphorus recovery in AGS, which is more directly compatible. The harvest of phosphorus-rich AGS can be used as a raw material for phosphorus extraction, biofertilizer production, or thermal conversion. Or phosphates can be leached from sludge into a sidestream and then be settled out as struvite or calcium phosphate. Struvite is especially appealing because it provides nitrogen, phosphorus, and magnesium in a crystalline, slow-release form. But some constraints are necessary for recovering struvite from kitchen waste leachate, including pH, Mg availability, phosphate levels, and the absence of interference from organic matter and other competing ions.

Phosphorus removal efficiency does not necessarily imply that phosphorus recovery efficiency is an important issue. A system can also be designed to remove phosphorus from the effluent and spread it over unstable sludge, inorganic precipitates, or complex waste streams that are hard to reuse. So, phosphorus mass balances and product quality assessments should be incorporated into future AGS systems. The best configurations will be those that not only reduce the amount of phosphates released into the environment but also generate a concentrated, stable, and agriculturally beneficial phosphate product. **Table 4** presents the main nutrient and biomass recovery pathways that could be coupled with the AGS-based kitchen waste leachate treatment, covering the resource to be recovered, the recovered product, the AGS role, and the major implementation challenges [4,11,63].

Table 4. Nutrient and biomass recovery pathways in AGS-based treatment of kitchen waste leachate.

Recovery Pathway	Target Resource	Possible Recovered Product	Role of AGS	Advantages	Key Challenges
Biological phosphorus accumulation	Phosphorus	Phosphorus-rich granular sludge	Enriches PAOs and stores phosphate as intracellular polyphosphate	Enables phosphorus concentration within biomass	Requires stable anaerobic–aerobic cycling and PAO dominance
Struvite precipitation	Ammonium and phosphate	Magnesium ammonium phosphate fertilizer	Reduces organic interference and conditions effluent or sidestream	Produces crystalline slow-release fertilizer	Requires pH adjustment, magnesium supply, and product purity control
Ammonia stripping and absorption	Ammonium nitrogen	Ammonium sulfate or ammonium nitrate solution	Converts organic matter and stabilizes liquid before recovery	Generates a liquid fertilizer product	Energy and chemical demand may be high
Ion exchange	Ammonium or phosphate	Regenerant nutrient solution or nutrient-loaded media	Lowers solids and organics before adsorption/exchange	Suitable for selective nutrient capture	Regeneration and spent solution management are required
Membrane concentration	Ammonium, phosphate, and soluble nutrients	Nutrient-rich concentrate	Reduces fouling potential compared with raw leachate	Can produce reusable water and concentrated nutrients	Fouling, pressure demand, and concentrate treatment remain barriers
AGS biomass digestion	Organic carbon and nutrients	Biogas and digestate	Supplies nutrient-rich granular sludge	Recovers energy and reduces sludge volume	Dense granules may resist hydrolysis
Sludge-derived biochar	Carbon and phosphorus	Nutrient-enriched biochar or adsorbent	Provides biomass feedstock	Stabilizes organic matter and may retain phosphorus	Nutrient bioavailability and contaminant risks must be evaluated
EPS recovery	Extracellular polymers	Bioflocculants, adsorbents, or alginate-like polymers	AGS produces structurally important EPS	Adds high-value product pathway	Extraction cost, purity, and product consistency are uncertain
Direct effluent reuse	Treated water and residual nutrients	Irrigation or fertigation water	Removes excess organics and stabilizes nutrients	Supports water and nutrient recycling	Requires strict pathogen, salinity, and contaminant control

5.3. Valorization of AGS Biomass and Organic Carbon

AGS biomass is not only a waste by-product, but it can also be a recoverable biological material that contains nutrients, organic carbon, extracellular polymeric substances, and microbial storage compounds. Over-granulated nutrient-rich leachate treatment can be used as a biosolid with high phosphorus content, an anaerobic digestion feedstock, a biochar precursor, or as a source of extracellular polymeric substances. This represents another pathway for recovering resources other than dissolved nutrients [64].

Excess AGS can be reduced, and its sludge can be used to recover energy through anaerobic digestion to produce biogas. The digestibility of granular biomass, however, may differ from that of conventional activated sludge, as dense granules and extracellular matrices can reduce hydrolysis. The digestibility of the products may be enhanced by pretreatments such as thermal, alkaline, ultrasonic, or enzymatic processes, but these processes are also energy-intensive and expensive. Net energy recovery and nutrient fate, rather than just methane yield, should be used to decide whether to digest AGS biomass.

An alternative route is to produce biochar from AGS biomass, especially if it contains mineral and phosphorus constituents. The biochar made from sludge can be used as a soil amendment, as an adsorbent and/or as a nutrient carrier. However, the route must be evaluated regarding contaminants, salinity, heavy metals and possible toxic substances. Thermal treatment can reduce pathogen levels and stabilize organic matter; it can also affect nutrient availability. The mineral interactions and pyrolysis conditions can affect the solubility of phosphorus in biochar. Therefore, biochar valorization can be considered from both the waste-reduction point of view and the agronomic performance and environmental safety points of view [57].

Other uses for extracellular polymeric substances from AGS include their use as bioflocculants, adsorbents, hydrogels, or even alginate-like substances. It is an emerging field with the potential to enhance the economic viability of AGS systems. Regrettably, the extraction of EPS remains technically demanding because it must be recovered with sufficient yield and purity to be worthwhile, while minimizing chemical use. Furthermore, the composition of the EPS depends on the substrate, microbial community, and operating conditions. This variability may be both an opportunity and a challenge for the kitchen waste leachate: the rich substrate can be used to increase EPS production, while ensuring product consistency may be more challenging [13].

5.4. Environmental Sustainability Assessment

The potential environmental benefits of AGS-based treatment of kitchen waste leachate are great, but can't be assumed unless assessed at the system level. The primary environmental benefits are decreased organic pollution, reduced nutrient discharge, lower eutrophication potential, a smaller reactor footprint, and the potential for fertilizer substitution through nutrient recovery. AGS can recover phosphorus and/or ammonium, potentially reducing reliance on mined phosphate rock and on energy-intensive nitrogen fertilizer production [59].

But there are environmental costs to AGS systems, too. Aeration is typically the highest energy-demand part of the operation, particularly if the leachate is high-strength and has a high oxygen demand. Highly aerated operation can also lead to higher operating expenses and reduced net nutrient recovery benefits. Furthermore, biological N transformation can generate nitrous oxide (N_2O), a highly potent greenhouse gas. Nitrite accumulation, incomplete denitrification, or oxygen-limited nitrification resulting from AGS operation can increase N_2O emissions. Hence, monitoring greenhouse gases (GHGs) should be part of sustainability assessments, especially when AGS is used to treat leachate from nitrogen-rich waste.

Another factor to consider is the fate of carbon. While complete aerobic oxidation of the organic carbon to carbon dioxide confers COD removal, it may result in loss of carbon that can be used to form biogas, volatile fatty acids, microbial products or soil amendments. This means optimal systems could be anaerobic. Rather, they can employ anaerobic processes for carbon recovery, together with AGS, to transform nutrients and stabilize effluent. Hybrid systems, which distribute functions across various treatment stages, better align with the principles of the circular bioeconomy [65,66].

Life cycle assessment is necessary to evaluate the performance of AGS-based systems versus the activated sludge, anaerobic digestion, chemical precipitation, membrane treatment and direct fertilizer recovery systems. A life cycle assessment (LCA) should contain energy consumption, chemical use, GHG emissions, sludge management, avoided fertilizer production, recovered product credits, and infrastructure. If one does not have this broader view, AGS might seem very efficient at the reactor scale but have a questionable benefit at the system scale [7].

5.5. Economic and Techno-Functional Considerations

For the practical implementation the economic feasibility is crucial. AGS has the potential to be more cost-effective due to its small installation size, high settling velocity, elimination of secondary clarifiers, and ability to remove nutrients simultaneously. They can be a desired option for decentralized food waste facilities, markets, campuses, restaurants, and urban organic waste hubs where space constraints are an issue. In addition to these benefits, however, there are costs associated with the equalization, pretreatment, aeration, monitoring, and handling and recovery of sludge from kitchen waste leachate treatment processes [67].

The economic value of the recovered nutrients is low compared with treatment costs. Revenue from fertilizer products like struvite or ammonium sulfate may be available, but it may not be sufficient to cover operational costs unless it is offset by regulatory fines, waste disposal charges, energy recovery, or avoided disposal charges. Hence, the economic justification for AGS-based recovery needs to take into account several benefits and not product sales. The benefits can include reduced discharge penalties, reduced sludge disposal costs, improved process stability, reduced demand for chemical fertilizer, and decentralized waste management capacity.

Product consistency is another techno-functional challenge. Recycled fertilizers should meet market expectations and quality criteria. The composition of the leachate can vary, which can result in different nutrient concentrations, impurities, salinity or levels of contaminants in the leachate. Predictable nutrient composition and safe handling properties are largely required by farmers and on fertilizer markets. Therefore, the nutrient recovery system should incorporate product refinement, quality control, and certification in accordance with regulatory requirements. If not, the recovered products might be technically viable but not economically desirable [68].

5.6. Regulatory, Safety, and Social Acceptance Barriers

Recycling of kitchen waste leachate nutrients poses regulatory and safety issues. Depending on source separation and collection, pathogens, salts, trace metals, microplastics, cleaning agents, antibiotics or emerging organic contaminants (EOCs) may be present in kitchen waste streams. AGS treatment can reduce organic pollution and help stabilize the microflora, but it does not ensure product safety. Evaluations of pathogen inactivation, contaminant buildup, phytotoxicity, and agronomic performance should be conducted on any recovered fertilizer, biomass, or soil amendment.

The recovered fertilizers are regulated differently by various regions. Some jurisdictions require more approval than for traditional fertilizers for products that use waste streams, even if nutrient levels are similar. This can slow market entry and undermine investor confidence. To overcome this barrier, evidence for product safety, nutrient availability, contaminant levels, and environmental impacts needs to be generated from reliable AGS-based recovery systems. Standardized testing and certification will be required [69].

Community acceptance is also important. Fertilizers obtained from the leachate of kitchen waste could result in negative perceptions due to the association with waste, odor, and hygiene hazard. Better acceptance may be achieved through transparent product labeling, quality assurance, odor control, and showing agronomic benefits. In this regard, the use of struvite or ammonium salts purified from sludge might be preferred to the use of untreated sludge products, which are considered cleaner, more standardized and easier to control.

5.7. Scale-Up Challenges and Implementation Strategies

It is very difficult to transfer AGS-based kitchen waste leachate treatment from laboratory studies to actual plants. Real leachate streams are variable, intermittent, and may contain oils, solids, and cleaning residues. To achieve stable granulation under these conditions, comprehensive reactor control is essential, as is equalization of the inflowing water, and monitoring of the COD, ammonium, phosphate, alkalinity, salt content, pH, dissolved oxygen, and sludge settleability. Long-term operation is of particular interest, as granules might perform well in a short experiment but become unstable under prolonged shock loading or seasonal changes [70].

Laboratory testing helps establish mechanisms and operating windows, but a pilot is required to assess hydraulic performance, energy consumption, maintenance needs, odor management, and the quality of recovery products. For best practice, demonstration projects at food markets, university campuses, restaurants, or municipal food waste centers could help to provide realistic evidence. These facilities are appropriate where there is a high concentration of kitchen waste and/or where there is local demand for recovered products or waste management solutions.

Scale-up possibilities could be enhanced through digital monitoring and process control. More responsive operation can be supported using dissolved oxygen, oxidation–reduction potential, pH, conductivity, ammonium, nitrate, phosphate, and sludge blanket behavior sensors. But for decentralized applications, the advanced control should be affordable and resilient. While a process train may be complex, the most practical ones can combine simple pretreatment, stable AGS operation, and targeted nutrient recovery.

The concept of recovering nutrients from kitchen waste leachate using AGS has great potential, but is not dependent on the efficiency of the reactors themselves. The technology should aim for stable leachate, recovery of nutrients into useful products, safe production, and economical operation under variable conditions. The most significant change is from a "removal" to a "recovery" design paradigm. This implies the necessity of monitoring nitrogen and phosphorus throughout the system, from influent to effluent, biomass, gas emissions, precipitates, and final products.

Future experiments should focus on mass balance, long-term pilot experiments, LCA, techno-economic analysis, and product safety validation. The full potential of AGS to contribute to circular bioeconomy systems can only be realized if upstream source management and downstream recovery routes are connected. With proper integration, AGS can not only reduce KWL pollution but also serve as a medium for nutrient recycling, supporting bioenergy and sustainable fertilizer production [48,58,71].

6. Conclusion

The kitchen waste leachate is a complex but valuable liquid stream in the food waste management chain. It is higher in biodegradable organic matter, ammonium, phosphate, suspended solids, oils and grease, and industrial fermentation products, all of which pose significant challenges for treatment. These attributes, in turn, make them excellent for resource recovery. The major problem is not only to remove pollutants from kitchen waste leachate, but also to recover carbon, nitrogen, and phosphorus as useful, safe products. This review concludes that this transformation must be grounded in circular bioeconomy systems rather than conventional removal-based treatment.

Aerobic granular sludge is a feasible biological basis for this. Because of its small size, good settling properties, high biomass retention, and stratified microenvironment, it is possible to achieve simultaneous degradation of organic matter, nitrification, denitrification, and phosphorus accumulation. These are all important characteristics that can make AGS particularly well-suited for high-strength, variable wastewater streams. With respect to kitchen waste leachate, AGS can be used as a treatment technology and as a biological conditioning step to stabilize organic matter, transform nutrient species, and generate recoverable biomass or nutrient-rich effluents. The operational control, however, is critical to the performance of AGS. Too much organic loading, too much ammonia inhibition, too much salinity, too much fat, oil, and grease, and too much influent variability can affect granule stability, nitrification, and the efficiency of phosphorus recovery.

One key lesson of this review is the need to differentiate nutrient removal and nutrient recovery. Nitrogen exported via denitrification reduces eutrophication risk, but is not nutrient cycling. In the same way, phosphorus lost in sludge is not recovered unless sludge is reused or processed, or it can be made into a recoverable product. As a result, AGS systems for kitchen waste leachate should be designed using nutrient mass balances that include N and P in both the effluent and biomass, gaseous emissions, precipitates, and sidestreams. The recovery-oriented configurations can involve pre-fermentation, struvite recovery, ammonia stripping, ion exchange, membrane concentration, anaerobic digestion, biochar production, or extracellular polymeric substance recovery, coupled with AGS.

Based on the evidence in the case, AGS shows great promise but is still in its early stages of implementation. Most of the information comes from laboratory-scale or similar high-strength wastewater tests, and few long-term pilot-scale or full-scale demonstration projects have been conducted using kitchen waste leachate. The realistic variability of the influents, the ability to withstand shock loads, microbial community dynamics, product safety, greenhouse gas emissions, and techno-economic feasibility should be studied in the future. Special consideration should be given to the trade-off between reactor stability and resource recovery, as conditions that maximize pollutant removal may not maximize fertilizer production or nutrient retention.

Overall, AGS should be presented not as a standalone solution for all kitchen waste leachates, but as a biological core within an integrated treatment–recovery chain whose feasibility depends on pretreatment needs, influent variability, stability under shock loads, and possible trade-offs between process robustness and nutrient recovery.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or generated in this study. As this is a review, it is based on data and information from previously published sources, which are cited in the reference list.

Conflicts of Interest

The author declares no conflict of interest.

AI Use Statement

The author declares that no artificial intelligence (AI) tools were used in the preparation of this manuscript.

References

[1] Kehrein, P., van Loosdrecht, M., Osseweijer, P., et al., 2020. Exploring resource recovery potentials for the aerobic granular sludge process by mass and energy balances—Energy, biopolymer and phosphorous recovery from municipal wastewater. Environmental Science: Water Research & Technology. 6(8), 2164–2179. DOI: https://doi.org/10.1039/D0EW00310G

[2] Yadav, B., Atmakuri, A., Chavan, S., et al., 2021. Role of bioeconomy in circular economy. In: Pandey, A., Tyagi, R.D., Varjani, S. (Eds.). Biomass, Biofuels, Biochemicals: Circular Bioeconomy—Current Developments and Future Outlook. Elsevier: Amsterdam, The Netherlands. pp. 163–195. DOI: https://doi.org/10.1016/B978-0-12-821878-5.00022-2

[3] Paul, T., Yee, J.-J., Park, S.H., 2025. Biochar-assisted aerobic granulation in enhanced biological treatment of landfill leachate with municipal wastewater for sustainable resource recovery: A biorefinery approach. Journal of Environmental Chemical Engineering. 13(2), 115330. DOI: https://doi.org/10.1016/j.jece.2025.115330

[4] Guzmán-Fierro, V., Quiroz, M., Moscoso, K., et al., 2026. Aerobic granular sludge as a regenerative system for nutrient removal and metal recovery from landfill leachate. RSC Advances. 16(2), 1121–1133. DOI: https://doi.org/10.1039/D5RA05817A

[5] Mehta, C.M., Khunjar, W.O., Nguyen, V., et al., 2015. Technologies to recover nutrients from waste streams: A critical review. Critical Reviews in Environmental Science and Technology. 45(4), 385–427. DOI: https://doi.org/10.1080/10643389.2013.866621

[6] Cydzik-Kwiatkowska, A., 2021. Biopolymers in aerobic granular sludge—Their role in wastewater treatment and possibilities of re-use in line with circular economy. Energies. 14(21), 7219. DOI: https://doi.org/10.3390/en14217219

[7] Hamza, R., Rabii, A., Ezzahraoui, F.-Z., et al., 2022. A review of the state of development of aerobic granular sludge technology over the last 20 years: Full-scale applications and resource recovery. Case Studies in Chemical and Environmental Engineering. 5, 100173. DOI: https://doi.org/10.1016/j.cscee.2021.100173

[8] Sijan, A.H., Zhang, B., 2025. Accelerating the formation of aerobic granular sludge (AGS): Advances, challenges, and future perspectives. Water-Energy Nexus. 9, 75–84. DOI: https://doi.org/10.1016/j.wen.2025.08.004

[9] Vydehi, P., Ravindran, G., Shyamala, G., et al., 2025. Aerobic granular sludge-based wastewater treatment: Current trends, formation, applications, granulation, efficiency, and bottlenecks. Journal of Water Process Engineering. 70, 107075. DOI: https://doi.org/10.1016/j.jwpe.2025.107075

[10] Smoot, L., 2021. A Molecular-Level Interrogation of Ammonia Oxidizing Bioreactors: Comparing and

Contrasting Nitritation and Nitrification [Master's Thesis]. University of Idaho: Moscow, ID, USA.

[11] Qu, Z., Zhang, S., Ren, Y., et al., 2026. Resource recovery from aerobic granular sludge: Potential, methodologies and state of the art. Water. 18(5), 540. DOI: https://doi.org/10.3390/w18050540

[12] Ferreira, T.J.T., 2023. Study of emerging aerobic biotechnologies for sewage treatment and resource recovery [Master's Thesis]. Federal University of Ceará: Fortaleza, Brazil.

[13] Dababat, S., Enaime, G., Wichern, M., et al., 2023. Aerobic granular sludge: Perspectives for excess sludge management and resource recovery. Chemie Ingenieur Technik. 95(12), 1881–1896. DOI: https://doi.org/10.1002/cite.202300093

[14] Chen, X., Wang, X., Wang, Q., et al., 2024. Energy and resource recovery from a future aerobic granular sludge wastewater treatment plant and benefit analysis. Chemical Engineering Journal. 487, 150558. DOI: https://doi.org/10.1016/j.cej.2024.150558

[15] Pagliaccia, B., Campo, R., Carretti, E., et al., 2024. Towards resource recovery-oriented solutions in agriculture exploiting structural extracellular polymeric substances (sEPS) extracted from aerobic granular sludge (AGS). Chemical Engineering Journal. 485, 149819. DOI: https://doi.org/10.1016/j.cej.2024.149819

[16] Al-Gheethi, A., Noman, E.A., Alsahari, M., et al., 2024. Potential of complex microbial community in aerobic granular sludge as a bio-startup approach for next-generation wastewater treatment. Applied Water Science. 14(10), 215. DOI: https://doi.org/10.1007/s13201-024-02268-2

[17] Shameem, K.S., Sabumon, P.C., 2023. A review on the stability, sustainability, storage and rejuvenation of aerobic granular sludge for wastewater treatment. Water. 15(5), 950. DOI: https://doi.org/10.3390/w15050950

[18] Wang, H., Xu, J., Sheng, L., 2019. Study on the comprehensive utilization of city kitchen waste as a resource in China. Energy. 173, 263–277. DOI: https://doi.org/10.1016/j.energy.2019.02.081

[19] Yuan, Q., Huang, Y., Chi, J., et al., 2024. Effective treatment of leachate concentrate from waste incineration plant by combination of coagulation and direct contact evaporation. Chemosphere. 349, 140880. DOI: https://doi.org/10.1016/j.chemosphere.2023.140880

[20] Gurjar, R., Behera, M., 2021. Effect of operating parameters on leachate quantity and quality generated during hydrolysis of kitchen waste. In: Kalamdhad, A.S. (Ed.). Integrated Approaches towards Solid Waste Management. Springer: Cham, Switzerland. pp. 255–264. DOI: https://doi.org/10.1007/978-3-030-70463-6_24

[21] Yan, Y., Liang, H., Wang, Z., et al., 2024. Attaining superior nitrogen removal from integrated mature landfill leachate and kitchen waste digestion liquid via a two-stage partial nitrification/anammox (PN/A) process. Chemical Engineering Journal. 480, 148352. DOI: https://doi.org/10.1016/j.cej.2023.148352

[22] Chen, Z., Zhang, S., Li, Y., et al., 2023. Investigating nitrous oxide emissions and mechanisms in kitchen waste composting with leachate reuse. Chemical Engineering Journal. 476, 146813. DOI: https://doi.org/10.1016/j.cej.2023.146813

[23] Ilmasari, D., Nishimura, F., 2025. Algal-bacterial aerobic granular sludge: Applications and future prospects. Journal of Water and Environment Technology. 23(2), 57–70. DOI: https://doi.org/10.2965/jwet.24-080

[24] Zhang, P., Chai, J., Cao, J., et al., 2023. Landfill leachate generation mechanism study: A review. International Journal of Environmental Science and Technology. 20(8), 9271–9290. DOI: https://doi.org/10.1007/s13762-022-04723-6

[25] Abdel-Shafy, H.I., Ibrahim, A.M., Al-Sulaiman, A.M., et al., 2024. Landfill leachate: Sources, nature, organic composition, and treatment: An environmental overview. Ain Shams Engineering Journal. 15(1), 102293. DOI: https://doi.org/10.1016/j.asej.2023.102293

[26] Sharma, V., Nagpal, G., Naveen, B.P., et al., 2026. An updated review on landfill leachate treatment methods. Discover Chemistry. 3(1), 34. DOI: https://doi.org/10.1007/s44371-026-00473-3

[27] Li, W., Liu, H., Deng, L., et al., 2024. Recent advances in treatment refinement of kitchen digested wastewater: Feasibility, prospects, and technicalities. Water Cycle. 5, 20–30. DOI: https://doi.org/10.1016/j.watcyc.2023.12.001

[28] Remmas, N., Manfe, N., Zerva, I., et al., 2023. A critical review on the microbial ecology of landfill leachate treatment systems. Sustainability. 15(2), 949. DOI: https://doi.org/10.3390/su15020949

[29] Babcock-Jackson, L., Konovalova, T., Krogman, J.P., et al., 2023. Sustainable fertilizers: Publication landscape on wastes as nutrient sources, wastewater treatment processes for nutrient recovery, biorefineries, and green ammonia synthesis. Journal of Agricultural and Food Chemistry. 71(22), 8265–8296.

[30] Ahmed, S.M., Rind, S., Rani, K., 2023. Systematic review: External carbon source for biological

denitrification for wastewater. Biotechnology and Bioengineering. 120(3), 642–658. DOI: https://doi.org/10.1002/bit.28293

[31] Shen, N., Zhou, Y., 2016. Enhanced biological phosphorus removal with different carbon sources. Applied Microbiology and Biotechnology. 100(11), 4735–4745. DOI: https://doi.org/10.1007/s00253-016-7518-4

[32] Jun, Z., Fan, Z., Xiaofeng, L., et al., 2025. Insight of biological transformation process in the anaerobic codigestion of kitchen waste with landfill site closure leachate. Scientific Reports. 15(1), 22930. DOI: https://doi.org/10.1038/s41598-025-06866-1

[33] Mei, Z., Wang, J., Luo, J., et al., 2025. Unraveling the mechanism of dissolved organic matter in enhancing nitrogen removal from leachate wastewater treatment via aerobic granular sludge process. Water Research. 287, 124407. DOI: https://doi.org/10.1016/j.watres.2025.124407

[34] Ma, J., Sun, H., Ji, Y., et al., 2025. Niche differentiation drives microbial community assembly in an anaerobic/oxic/anoxic-aerobic granular sludge (AOA-AGS) system: Insights into anammox self-enrichment. Water Research. 288, 124615. DOI: https://doi.org/10.1016/j.watres.2025.124615

[35] da Silva, V.E.P.S.G., de Sousa Rollemberg, S.L., dos Santos, A.B., 2023. Step-feeding in aerobic/anoxic cycles enhanced the performance of aerobic granular sludge (AGS) systems treating effluents with low C:N ratios. Process Safety and Environmental Protection. 171, 1031–1042. DOI: https://doi.org/10.1016/j.psep.2022.10.004

[36] Wang, J., Li, Z., Wang, Q., et al., 2023. Use of photo-driven algal-bacterial aerobic granular sludge system to close carbon cycle in biological nutrients removal and sludge anaerobic digestion units in wastewater treatment plants. Chemical Engineering Journal. 475, 145999. DOI: https://doi.org/10.1016/j.cej.2023.145999

[37] Liu, L., Wang, C., Peng, Y., et al., 2025. Deciphering spatial microbial distribution in aerobic granules: Linking granulation dynamics to nitrogen metabolism in the continuous flow self-circulating reactor. Chemical Engineering Journal. 514, 163111. DOI: https://doi.org/10.1016/j.cej.2025.163111

[38] Rosas-Echeverría, K., Fall, C., Gutiérrez-Segura, E., et al., 2023. Mechanisms of persistence and impact of ordinary heterotrophic organisms in aerobic granular sludge. Bioresource Technology. 384, 129346. DOI: https://doi.org/10.1016/j.biortech.2023.129346

[39] Xiao, H., Wang, K., Wang, Y., et al., 2024. Inhibition of denitrification and enhancement of microbial interactions in the AGS system by high concentrations of quinoline. Journal of Environmental Management. 370, 122837. DOI: https://doi.org/10.1016/j.jenvman.2024.122837

[40] Ni, M., Pan, Y., Zhang, X., et al., 2021. Effects of P/C ratios on the growth, phosphorus removal and phosphorus recovery of a novel strain of highly efficient PAO. Process Biochemistry. 111, 109–117. DOI: https://doi.org/10.1016/j.procbio.2021.08.010

[41] Su, L., Li, Y., Chao, L., et al., 2023. Enhanced simultaneous nitrogen and phosphorus removal performance of the AGS-SBR reactor based on the effects of the C/N ratio and microbial community change. Sustainability. 15(9), 7691. DOI: https://doi.org/10.3390/su15097691

[42] Min, K.J., Lee, E., Lee, A.H., et al., 2024. Effect of settling time and organic loading rates on aerobic granulation processes treating high strength wastewater. Heliyon. 10(16), e36018. DOI: https://doi.org/10.1016/j.heliyon.2024.e36018

[43] Toja Ortega, S., van den Berg, L., Pronk, M., et al., 2022. Hydrolysis capacity of different sized granules in a full-scale aerobic granular sludge (AGS) reactor. Water Research X. 16, 100151. DOI: https://doi.org/10.1016/j.wroa.2022.100151

[44] Setianingsih, N.I., Hadiyanto, Budihardjo, M.A., et al., 2024. Effective sludge activation in a sequencing batch reactor (SBR) towards aerobic granular sludge (AGS) technology. Desalination and Water Treatment. 320, 100774. DOI: https://doi.org/10.1016/j.dwt.2024.100774

[45] Sarvajith, M., Nandini, D., Nancharaiah, Y., 2024. Comparative evaluation of activated sludge and aerobic granular sludge for biological treatment of real domestic wastewater with oxytetracycline dosing. Journal of Environmental Chemical Engineering. 12(2), 112482. DOI: https://doi.org/10.1016/j.jece.2024.112482

[46] Anjum, M., Anees, M., Qadeer, S., et al., 2023. A recent progress in the leachate pretreatment methods coupled with anaerobic digestion for enhanced biogas production: Feasibility, trends, and techno-economic evaluation. International Journal of Molecular Sciences. 24(1), 763. DOI: https://doi.org/10.3390/ijms24010763

[47] Zhang, Y.-X., Cai, X., Zhang, X.-G., et al., 2024. Periodic injection of liquefied kitchen and food waste in municipal solid waste: Effects on leachate and gas generation. Waste Management. 176, 1–10. DOI: https://doi.org/10.1016/j.wasman.2024.01.020

[48] da Silva, V.E.P.S.G., 2023. Aerobic granular sludge system optimization strategies for landfill leachate treatment and co-treatment with domestic sewage [Master's Thesis]. Federal University of Ceará: Fortaleza, Brazil.

[49] Berenji Rahimzadeh, N., 2024. Impact of the co-treatment of food waste and municipal wastewater on the performance of an aerobic granular sludge system [Master's Thesis]. İstanbul Technical University: Istanbul, Türkiye.

[50] Chen, H., Zhou, W., Xu, Z., et al., 2021. Nitrogen and phosphorus removal by GAOs and PAOs using nitrate and limited oxygen as electron acceptors simultaneously and the impact of external carbon source in the anoxic phase. Journal of Environmental Chemical Engineering. 9(6), 106520. DOI: https://doi.org/10.1016/j.jece.2021.106520

[51] Chen, J., Wang, J., Wang, X., et al., 2022. Strengthening anoxic glycogen consumption in SNEDPR-CW as a strategy to control PAO-GAO competition under carbon limited condition. Chemosphere. 288, 132617. DOI: https://doi.org/10.1016/j.chemosphere.2021.132617

[52] Chen, H.-B., Wang, D.-B., Li, X.-M., et al., 2015. Enhancement of post-anoxic denitrification for biological nutrient removal: Effect of different carbon sources. Environmental Science and Pollution Research. 22(8), 5887–5894. DOI: https://doi.org/10.1007/s11356-014-3755-1

[53] Gong, B., Duan, K., Chen, S., et al., 2023. Enhanced nutrients removal and microbial mechanisms in a pilot-scale anaerobic-oxic-anoxic (A/O/A) system: Synergistic roles of denitrifying polyphosphate accumulating organisms and endogenous denitrifiers. Process Safety and Environmental Protection. 179, 47–56. DOI: https://doi.org/10.1016/j.psep.2023.08.085

[54] Morales-Polo, C., Cledera-Castro, M.D.M., Moratilla Soria, B.Y., 2018. Reviewing the anaerobic digestion of food waste: From waste generation and anaerobic process to its perspectives. Applied Sciences. 8(10), 1804. DOI: https://doi.org/10.3390/app8101804

[55] Siciliano, A., Limonti, C., Curcio, G.M., et al., 2020. Advances in struvite precipitation technologies for nutrients removal and recovery from aqueous waste and wastewater. Sustainability. 12(18), 7538. DOI: https://doi.org/10.3390/su12187538

[56] Podder, A., Reinhart, D., Goel, R., 2020. Integrated leachate management approach incorporating nutrient recovery and removal. Waste Management. 102, 420–431. DOI: https://doi.org/10.1016/j.wasman.2019.10.048

[57] da Silva, V.E.P.S.G., Fiorani Ezequiel, T., Iorhemen, O., et al., 2026. Adaptation and application of methodologies for quantification of xanthan and curdlan in conventional AGS systems and algal-bacterial association. Biomass and Bioenergy. 205, 108558. DOI: https://doi.org/10.1016/j.biombioe.2025.108558

[58] da Silva, V.E.P.S.G., de S. Rollemberg, S.L., da S. e Santos, S.G., et al., 2022. Landfill leachate biological treatment: Perspective for the aerobic granular sludge technology. Environmental Science and Pollution Research. 29(30), 45150–45170. DOI: https://doi.org/10.1007/s11356-022-20451-3

[59] Kazimierowicz, J., Dębowski, M., 2022. Aerobic granular sludge as a substrate in anaerobic digestion—Current status and perspectives. Sustainability. 14(17), 10904. DOI: https://doi.org/10.3390/su141710904

[60] Wang, J., Qiao, Z., 2024. A comprehensive review of landfill leachate treatment technologies. Frontiers in Environmental Science. 12, 1439128. DOI: https://doi.org/10.3389/fenvs.2024.1439128

[61] Gusiatin, M.Z., Kulikowska, D., Bernat, K., 2024. Municipal sewage sludge as a resource in the circular economy. Energies. 17(11), 2474. DOI: https://doi.org/10.3390/en17112474

[62] Karthikeyan, O.P., 2008. Solubilization of ammoniacal nitrogen in landfills under tropical environments—Effects on waste stabilization and struvite recovery [PhD Thesis]. Anna University: Chennai, India.

[63] Mady, E., Oleszkiewicz, J., Yuan, Q., 2026. Phosphorus-rich liquid extraction strategies to enhance phosphorus removal in aerobic granular sludge treating municipal wastewater. Bioresource Technology Reports. 34, 102852. DOI: https://doi.org/10.1016/j.biteb.2026.102852

[64] Pagliano, G., Ventorino, V., Panico, A., et al., 2017. Integrated systems for biopolymers and bioenergy production from organic waste and by-products: A review of microbial processes. Biotechnology for Biofuels. 10(1), 113. DOI: https://doi.org/10.1186/s13068-017-0802-4

[65] Dung, N.P., 2022. Nitrous oxide emissions during wastewater treatment process [Master's Thesis]. Technische Universität Darmstadt: Darmstadt, Germany.

[66] Cavanaugh, S.K., 2021. Nitrous Oxide Emissions from Wastewater Treatment Processes and Process Parameters Affecting Emissions [Master's Thesis]. University of Washington: Seattle, WA, USA .

[67] Sharrer, M., Rishel, K., Taylor, A., et al., 2010. The cost and effectiveness of solids thickening technologies for treating backwash and recovering nutrients

from intensive aquaculture systems. Bioresource Technology. 101(17), 6630–6641. DOI: https://doi.org/10.1016/j.biortech.2010.03.101

[68] Yu, C., Wang, K., 2024. Continuous flow aerobic granular sludge: Recent developments and applications. Water Science & Technology. 89(5), 1155–1178. DOI: https://doi.org/10.2166/wst.2024.055

[69] Upadhyay, S.K., 2026. Composting: Safety and regulatory considerations in sustainable agriculture. In: Singh, R.K., Trindade, H., Sousa, J.R., et al. (Eds.). Composting of Farm Residues by Nature-Based Solutions: A Potential Key towards Sustainable Agricultural Practices. Springer: Cham, Switzerland. pp. 379–409. DOI: https://doi.org/10.1007/978-3-032-12255-1_15

[70] Kazimierowicz, J., Dębowski, M., Zieliński, M., 2022. Microbial granule technology—Prospects for wastewater treatment and energy production. Energies. 16(1), 75. DOI: https://doi.org/10.3390/en16010075

[71] Ahmed, M., Ahmad, S., Fayyaz-ul-Hassan, et al., 2019. Innovative processes and technologies for nutrient recovery from wastes: A comprehensive review. Sustainability. 11(18), 4938. DOI: https://doi.org/10.3390/su11184938