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# Research Progress and Application Prospect of Food Waste Wastewater Treatment Technology

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## Abstract

**With the acceleration of urbanization and the booming development of the catering industry, the discharge of kitchen waste sewage has increased dramatically. is rich in high-concentration organic matter, oil, nitrogen and phosphorus and other nutrients and a large number of pathogenic bacteria. If it is directly discharged, it will serious pollution to the aquatic environment and soil ecology, and it is also a waste of resources. This paper systematically expounds on the sources and properties of kitchen waste sewage, analyzes its environmental hazards. The research progress, principle, advantages and disadvantages and application status of physical-chemical treatment technology, biological treatment technology and combined treatment technology are reviewed, the problems existing in the current kitchen waste sewage treatment technology are discussed, and the future development directions of resourceization, intelligence and low-carbon are prospected, so as provide reference for the efficient treatment and resource utilization of kitchen waste sewage.**

## Keywords

**Kitchen Waste Sewage; Treatment Technology; Resource Utilization; Ecological Pollution; Research.**

## 1. Research Background and Significance

With the upgrading of consumption in China, especially the rapid development of the takeout industry, the production of food waste has also been increasing year by year [1]. From 2022 to 2025, the annual compound growth rate of food waste in China will continue to grow at an incremental rate of 12% to 15% [2]. By 2025, the daily average amount of food waste collected and transported in urban areas across the country has exceeded 320,000 tons, with an annual total of over 117 million tons. The average annual growth rate has stabilized at 6.2%, making food waste the component with the largest production, the most prominent environmental impact, and the most urgent need for treatment among urban organic solid waste in China [3].

Food waste exhibits typical characteristics such as high moisture content, high organic matter content, high oil and salt content, and rich nutrition [4]. If disposed of through extensive methods like disorderly piling or simple landfilling, it can easily lead to a series of ecological and environmental issues, including leachate infiltration polluting groundwater, unorganized diffusion of odor gases, transmission of pathogenic bacteria, and breeding of mosquitoes and flies. Additionally, there are significant food safety hazards such as waste oil flowing back to dining tables and using swill to feed pigs. Food waste has become a key focus in urban environmental governance, public health safety, and food safety control [5].

The mainstream technical route for large-scale disposal of domestic food waste in China currently involves pretreatment followed by anaerobic digestion to produce biogas. After standardized pretreatment processes such as mechanical crushing, hydraulic slurrying, sand and impurity removal, and three-phase separation and deoiling, food waste is converted into a slurry with a solid content of 5% to 10%. This slurry highly concentrates over 90% of the

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degradable organic matter, water-soluble salts, ammonia nitrogen, and residual oils and fats present in the raw material. It belongs to the typical category of high-concentration, high-salt, high-oil, high-ammonia nitrogen, and difficult-to-stabilize organic special wastewater. Its treatment efficiency directly determines the operational effectiveness of the entire food waste disposal system [6]. The traditional continuous stirred tank reactor (CSTR) is currently the most widely used core equipment in food waste slurry disposal projects. However, over long-term engineering operation, it has revealed a series of technical bottlenecks that are difficult to overcome: the hydraulic retention time (HRT) and sludge retention time (SRT) within the reactor are fully coupled, leading to significant loss of anaerobic functional microorganisms through effluent. This inability to meet the growth and reproduction needs of methanogens results in a low upper limit of organic load and weak shock load resistance in the system. High-concentration substrates entering the system can easily cause excessive accumulation of volatile fatty acids (VFA), leading to system acidification and instability. The sludge-water separation effect is poor, and the concentration of residual pollutants in the biogas slurry remains high, resulting in high loads for subsequent advanced treatment, significant increases in energy and chemical consumption costs. The system has low capacity utilization, requires a large project footprint, and incurs high initial construction investment, making it difficult to adapt to the current development needs of efficient, low-carbon, and intensive treatment [7].

The Anaerobic Membrane Bioreactor (AnMBR) deeply couples anaerobic microbial degradation technology with efficient membrane separation technology for solid-liquid separation. Through the high-precision retention effect of microfiltration/ultrafiltration membrane components, it achieves complete separation of hydraulic retention time and sludge retention time within the reactor. This allows almost all anaerobic functional microorganisms to be retained inside the reactor, significantly extending the sludge age and effectively enriching methanogenic archaea with slow growth rates. This fundamentally solves the core industry problem of microbial loss in traditional anaerobic processes [8]. This process can maintain extremely high sludge concentration and microbial activity under short hydraulic retention time conditions, with an organic volumetric load up to 3 to 5 times that of traditional anaerobic processes. At the same time, it achieves complete mud-water separation, with the effluent suspended solids concentration approaching zero, significantly reducing the subsequent treatment load. It combines multiple advantages such as efficient pollutant removal, clean energy recovery, small footprint, and high reduction degree, providing a new technological path for the efficient, stable, and low-carbon disposal of high-concentration kitchen waste slurry [9].

Based on this, this study closely focuses on the special water quality characteristics of kitchen waste slurry and the pain points of traditional treatment processes. It systematically investigates the operational efficiency, pollutant degradation patterns, microbial community succession mechanisms, and membrane pollution prevention and control characteristics of treating kitchen waste slurry with an anaerobic membrane bioreactor (AnMBR). At the theoretical level, the aim is to reveal the anaerobic degradation mechanism, functional bacterial community interaction mechanism, and membrane pollution formation and evolution rules of AnMBR under complex substrate environments with high salt, high oil, and high ammonia nitrogen content. This aims to improve the theoretical system of anaerobic membrane biotreatment for high-concentration organic wastewater and enrich the basic research results of resource recovery treatment for special organic wastewater [10]. At the application level, the goal is to optimize the optimal operating parameters of AnMBR for treating kitchen waste slurry, propose engineering-friendly membrane pollution prevention and control strategies, break through the operational bottlenecks of traditional anaerobic processes, and provide technical support and data reference for the upgrading of kitchen waste resource recovery disposal processes and large-scale engineering promotion. This aligns with China's policy direction for low-carbon, resource recovery, and harmless disposal of organic solid waste

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under the "dual carbon" goals, and holds significant academic value and broad engineering promotion prospects [11].

## 2. The Current Status of Disposal of Kitchen Waste Slurry

### 2.1. Source and Characteristics of Kitchen Waste Slurry

The kitchen waste slurry is derived from food residues, waste edible oils and fats, rice and flour residues, vegetable scraps, and other kitchen waste generated by catering outlets, unit canteens, and households. It is processed and prepared through standardized pretreatment units. The kitchen waste is first manually sorted to remove large non-degradable impurities, and then processed through mechanical crushing, hydraulic cyclone slurrying, sand and impurity removal, and three-phase centrifugal separation for oil removal, resulting in a highly homogeneous kitchen waste slurry that is easy for pipeline transportation and biological treatment[12].

It is the core feed substrate for the anaerobic resource recovery disposal of kitchen waste, and its water quality characteristics directly affect the operational stability of the subsequent anaerobic system [13].

Compared to ordinary municipal sewage and general industrial organic wastewater, kitchen waste slurry exhibits strong water quality specificity and treatment difficulty. Its core characteristics can be summarized as follows:

Ultra-high biodegradable organic matter content: The slurry COD concentration ranges from 80,000 to 120,000 mg/L, with a stable BOD5/COD ratio between 0.65 and 0.80, indicating excellent biodegradability. The organic matter content in the dry basis is as high as over 95%, mainly composed of starch, polysaccharides, proteins, cellulose, hemicellulose, and residual animal and vegetable oils. It has extremely high biogas conversion potential, but at the same time, it places extremely high demands on the load-bearing capacity of the anaerobic system [14].

The inhibitory characteristics of high salinity and high ammonia nitrogen are significant: influenced by China's catering and cooking habits, the NaCl content in the slurry is generally between 2500 and 5000 mg/L, which is classified as moderately salty wastewater. High-salt environments can disrupt the osmotic pressure balance of anaerobic microbial cell membranes, inhibit the activity of key metabolic enzymes, significantly reduce methane production efficiency, and even lead to system collapse. At the same time, protein degradation in the slurry produces a large amount of ammonia nitrogen, with the influent ammonia nitrogen concentration reaching between 500 and 2500 mg/L and the total nitrogen concentration exceeding 3000 mg/L. Free ammonia exerts strong toxicity and inhibition on methanogens, which is one of the core causes of operational instability in traditional anaerobic processes [15].

High residual oil and grease content, and difficulties in degradation and control: After pretreatment through three-phase separation, the residual oil and grease content in the slurry can still reach 3% to 8%. The long-chain fatty acids (LCFA) produced by the hydrolysis of oil and grease in an anaerobic environment will adsorb onto the surface of microbial cell walls, blocking the transfer of substrates and nutrients and inhibiting microbial metabolic activity. At the same time, they are highly prone to adsorbing onto the membrane surface, forming a dense fouling layer, which is an important factor exacerbating membrane fouling and leading to a decrease in system treatment efficiency [16].

Significant component fluctuations and high impact load resistance requirements: The components of kitchen waste slurry are greatly influenced by regional dietary structures, seasonal changes, and consumption scenarios. The physicochemical indicators of kitchen waste slurry vary significantly across different regions in eastern, western, southern, and northern

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China, as shown in Table 1 below. High risk of spoilage and operational hazards: The slurry is rich in small molecular organic matter that is easily utilized by microorganisms, which can rapidly spoil and acidify at room temperature, leading to the growth of pathogenic bacteria such as Escherichia coli and Salmonella, and the production of malodorous volatile gases. During storage and transportation, acidification and spoilage are prone to occur, directly affecting the stable operation of subsequent anaerobic treatment systems [21].

**Table 1.** Main indicators of kitchen waste slurry in different regions

| Area | pH | COD (mg/L) | SS (mg/L) | $NH_3$-N (mg/L) | TN (mg/L) | TP (mg/L) | VFA (mg/L) | TS/Solids content (%) | References |
|---|---|---|---|---|---|---|---|---|---|
| East | 3.4~4.8 | 67,000~76,000 | 4,000~11,000 | 600~850 | 1,400~2,300 | - | - | - | [17] |
| West | 4.3 | 266,000±31,000 | - | 220±16 | 1,300±90 | 130±20 | - | 24.0±3.7 | [18] |
| South | 4.9 | 220,500 | - | 3,508 | 5,583 | 1,730 | 15,720 | - | [19] |
| North | 4.5 | 150,960 | - | 733.8 | 2,246 | - | - | 7.5 | [20] |

## 2.2. Disposal Technology for Kitchen Waste Slurry

1) Development trend of disposal technology

After more than three decades of development, China's food waste disposal industry has undergone three core transformations in disposal concepts and technical routes, transitioning from extensive and disorderly discharge to standardized, resource-oriented, and low-carbon utilization [22]. The current core development trends of the industry can be summarized into the following five aspects:

Source reduction and refined pretreatment have become the core priorities: the industry is gradually shifting from "end-of-pipe treatment" to "source control". Through mandatory waste sorting and precise source reduction, the pretreatment process is simultaneously optimized. By employing efficient slurry preparation, deep impurity removal, and graded deoiling, the impurity and oil content in the slurry are reduced, homogenizing the water quality. This approach reduces the subsequent biological treatment load from the source and enhances the operational stability of the system.

Resource recovery and energy utilization have become the absolute dominant approach: Under the guidance of the "dual carbon" goal policy, the disposal of kitchen waste has completely abandoned the purely harmless end-of-pipe disposal mode. Instead, it focuses on the energy recovery of organic matter (biogas purification, combined heat and power generation, and bio-natural gas preparation) and the resource recovery of by-products (waste oil and fat to biodiesel, and biogas residue and liquid to organic fertilizer), achieving the synergistic goals of "pollutant reduction [23], high energy recovery, and comprehensive resource utilization".

Harmless standards continue to tighten, with full control over secondary pollution: As ecological and environmental standards continue to be upgraded, the requirements for odor control, leachate management, pathogen inactivation, and heavy metal interception throughout the entire process of kitchen waste disposal are continuously increasing. The admission standards for the resource utilization of biogas slurry and residue are becoming stricter, aiming to eliminate secondary pollution during the treatment process and achieve closed-loop harmless control throughout the entire process.

Efficient, compact, and high-load processes have become the direction of technological upgrading: In response to the pain points of traditional anaerobic processes, such as large footprint, low load, and poor stability, the industry is gradually transitioning towards efficient anaerobic processes with high volumetric load, short hydraulic retention time, high microbial concentration, and small footprint. The requirements for equipment integration, automation, and intelligence are continuously increasing.

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Low carbon footprint and energy consumption, coupled with energy efficiency optimization throughout the entire lifecycle, have become core competitiveness: abandoning treatment routes with high energy consumption and high chemical dosage, and giving priority to process technologies with high energy recovery rates, low self-energy consumption, and minimal chemical consumption, to achieve self-balancing of system biogas production energy and reduce carbon emissions and operating costs throughout the entire lifecycle [24].

2) Comparative analysis of mainstream disposal technologies

Currently, the large-scale disposal technologies for food waste slurry both domestically and internationally primarily fall into three categories: physicochemical pretreatment technology, biological treatment technology, and land resource utilization technology. Among these, biological treatment technology serves as the core process for achieving organic matter degradation and energy recovery. The application characteristics, applicable scenarios, and limitations of each technology are as follows [25]:

Physical and chemical treatment technology: Primarily applied in the pretreatment and advanced treatment stages of kitchen waste slurry, it cannot achieve the degradation and energy recovery of organic matter and is only used as an auxiliary supporting process. Coagulation and sedimentation method is simple to operate and has low construction costs, but it incurs high chemical dosing costs, produces a large amount of sludge, and has limited COD removal efficiency; dissolved air flotation technology has high oil removal efficiency, but the equipment has high energy consumption and limited removal effect on emulsified oil; membrane separation advanced treatment technology yields excellent effluent quality, but it requires high investment, consumes large amounts of energy, and is prone to pollution and blockage [26], making it only suitable for advanced treatment of biogas slurry after anaerobic treatment.

Biological treatment technology: Aerobic biological treatment has high degradation efficiency for organic matter and stable effluent quality, but requires extensive dilution for treating high-concentration slurry, high aeration energy consumption, and a large amount of excess sludge, making it only suitable for low-concentration restaurant wastewater. Traditional anaerobic digestion technology is mature and can recover biogas, but it has defects such as microbial loss [27], low load, susceptibility to acidification instability, poor mud-water separation, and large land occupation. The Anaerobic Membrane Bioreactor (AnMBR), which couples anaerobic degradation with membrane separation, can efficiently retain microorganisms, increase organic load, stabilize effluent quality, and reduce excess sludge. It is the most promising cutting-edge technology for the disposal of high-concentration kitchen waste slurry.

Land resource utilization technology: The biogas residue generated from anaerobic digestion is rich in humus and nutrients, and can be used as organic fertilizer after harmless treatment; the biogas slurry can be returned to the field as water and fertilizer after treatment. However, this technology has strict limitations on heavy metals, pathogens, and salt content, and requires a complete supporting testing process. It is only suitable for disposal projects with supporting agricultural and forestry land nearby, and its application scenarios are limited.

## 3. Research Status of Anaerobic Membrane Bioreactor Technology at Home and Abroad

### 3.1. Current Research Status Abroad

In recent years, research on Anaerobic Membrane Bioreactors (AnMBR) abroad has formed a clear trajectory focusing on membrane fouling inhibition, novel membrane materials, multi-process coupling, and differentiated wastewater treatment. In terms of functional membrane material development, Wang et al. optimized the preparation of conductive ceramic

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membranes and applied them to electrochemical-coupled AnMBR for the treatment of kitchen wastewater. The conductive membrane assisted the electric field in alleviating membrane surface fouling and enhancing methane production efficiency [28]. Indian scholars such as Menon developed a green cationic cellulose coating, which achieves long-term pollution control without chemical agents through charge neutralization, meeting the needs of low-carbon water treatment [29]. Bioelectrochemical coupling systems have become a mainstream anti-fouling method. Dlamini et al. in South Africa systematically reviewed the pollution control mechanism of the electrochemical-AnMBR hybrid system, confirming that electric fields can regulate microbial communities and reduce irreversible adsorption of Extracellular Polymeric Substances (EPS), which is a core approach to solving membrane blockage [30]. Xiao et al. further applied electric field-assisted AnMBR to domestic sewage, improving the operational stability of anaerobic systems under low substrate conditions [31]. For wastewater from industries with high organic matter content, extensive pilot-scale optimization has been conducted abroad. When treating kitchen waste wastewater, Yan et al. balanced biogas production and membrane fouling by regulating lipid retention [32]. Tang et al. employed a two-stage shortcut nitrification-anaerobic ammonia oxidation process to deeply remove high-concentration ammonia nitrogen from AnMBR effluent and explored the recovery patterns of system microbial communities under shock loads [33]. For characteristic aquatic product processing wastewater in Southeast Asia, Hang's team constructed an AnMBR-Integrated Chemical-Enhanced Anaerobic Sludge Blanket (ICEAS) pilot system, effectively tolerating high-salt and high-protein water quality shocks, achieving synergistic pollutant removal and energy recovery [34]. Overall, current AnMBR research abroad shows a trend towards the green functionalization of new materials, multi-process coupling, a shift from small-scale mechanism research to pilot-scale engineering verification, and fine-tuning for different wastewaters.

## 3.2. Current Domestic Research Status

In recent years, domestic research on Anaerobic Membrane Bioreactors (AnMBR) has taken into account mechanism analysis, process coupling, engineering adaptation, targeted pollutant removal, and long-term prevention and control of membrane fouling. The research scenarios cover various water bodies such as municipal sewage, industrial wastewater, kitchen waste, landfill leachate, sludge digestion, and high-salt wastewater. Meanwhile, a complete research system has been formed around novel improved configurations such as electrocatalysis, high temperature, vibrating two-phase, and membrane distillation. The overall direction is towards low-carbon resource utilization, shock resistance, and low membrane fouling: In the direction of electrochemical enhanced resource utilization, Cheng Yu et al. reviewed the mechanism of action of electrocatalytic Anaerobic Membrane Bioreactors, systematically summarized the effects of electrode materials, operating voltage, and reactor configuration on methane production and biogas purification efficiency, and compared the operating costs and resource utilization benefits of different electrocatalytic systems, providing a comprehensive theoretical basis for the large-scale biogas recovery of electrochemically coupled AnMBR [35]; facing the complex industrial wastewater treatment needs, Zhang Zhongyi et al. summarized the application cases of AnMBR in various industrial wastewaters such as chemical, food, printing and dyeing, focusing on analyzing the problems of bacterial inhibition and membrane blockage caused by high COD, high salt content, and toxic organic compounds, proposing operation regulation parameters and pretreatment schemes adapted to different water qualities, and expanding the industrial application scenarios of AnMBR [36]; high-temperature anaerobic systems are an important branch for enhancing the degradation rate of organic substrates. Zhang Liangmiao et al. reviewed the removal effect of high-temperature anaerobic membrane bioreactors on refractory organic matter, compared the differences in sludge activity, methane production rate, and membrane fouling under mesophilic and high-temperature conditions, and objectively pointed out the existing shortcomings such as high energy consumption under

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high-temperature conditions and the difficulty in acclimating thermophilic bacteria [37]; aiming at the risk of stress from typical antibiotic trace pollutants in the water environment, Sun Yutong took norfloxacin as the target pollutant to explore the changes in methane production efficiency, key methanogenic enzyme activity, and functional gene abundance of AnMBR under different drug concentrations, elucidating the intrinsic microscopic mechanism of antibiotic inhibition of anaerobic metabolism from the molecular biology level [38]; the treatment of high-solid content materials is extremely prone to inducing severe irreversible membrane fouling. Su Jinghan et al. systematically analyzed the membrane surface blockage and stratification mechanism caused by EPS, organic flocs, and inorganic particles in high-solid systems, summarized multi-level prevention and control methods such as physical cleaning, chemical modification, and operating parameter optimization, and the related research has been pre-published online, with complete experimental data and analysis accessible through CNKI links [39]; To achieve low-carbon energy recovery from municipal sewage, Fan Chenlong established a combined process of coagulation pretreatment coupled with an anaerobic membrane bioreactor. This process utilizes coagulation to remove colloids and suspended impurities from water, reducing membrane surface load. Long-term continuous experiments have verified the engineering feasibility of this entire process in removing COD and simultaneously recovering methane energy [40]. In response to the high-fat and high-suspended solids characteristics of kitchen waste water, Pang Xinran developed a two-phase anaerobic membrane bioreactor with a reciprocating vibration structure. The focus was on exploring the regulation laws of different membrane relaxation durations and vibration frequencies on the growth rate of transmembrane pressure difference, sludge stratification effect, and methane production rate, providing a low-energy consumption and pollution control configuration for kitchen waste liquid treatment [41]. For trace persistent pollutants in water bodies, Liu Yaru conducted trimethoprim degradation experiments relying on an anaerobic membrane system. She analyzed the degradation pathway of pollutants, clarified the response laws of microbial community structure evolution and functional bacteria under different loads, and improved the theory of anaerobic removal of trace organic pollutants [42]. High-salt wastewater can disrupt the osmotic pressure balance of anaerobic bacterial communities and exacerbate salt crystallization pollution on the membrane surface. Jiang Linjiang studied an anaerobic membrane distillation bioreactor, systematically revealing the laws of methane production attenuation and membrane flux attenuation under different salinity gradients. He proposed targeted regulation measures such as dilution pretreatment, salt-tolerant bacterial community acclimation, and salt-resistant modification of the membrane surface [43]. In the field of sludge reduction and resource recovery disposal, Xu Mingzhe introduced AnMBR into the sludge anaerobic digestion unit. He compared the sludge reduction rate, biogas production, and effluent water quality differences between traditional digestion and membrane-coupled digestion, confirming that AnMBR can retain anaerobic functional microorganisms, extend the hydraulic retention time of sludge, and enhance the sludge stabilization effect [44]. In response to the high COD, high ammonia nitrogen, and refractory characteristics of landfill leachate from incineration plants, Wang Ruijing and others conducted pilot-scale experiments to verify the stable removal capacity of anaerobic membrane bioreactors for humic substances and organic pollutants in leachate. They analyzed the characteristics of membrane pollution components and cleaning recovery schemes under long-term operation, providing an efficient treatment technology route for refractory high-concentration organic wastewater [45].

## 4. Conclusion

With the annual increase in domestic kitchen waste output, pretreated kitchen waste slurry features high organic matter, salinity, ammonia nitrogen, oil content and fluctuating water quality. Conventional CSTR anaerobic processes suffer from microbial loss, acidification

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tendency, low load and poor sludge-water separation, failing low-carbon resource disposal needs. Anaerobic Membrane Bioreactor (AnMBR) decouples hydraulic and sludge retention time via membrane separation to retain anaerobic microbes, boosting treatment load, methane production and effluent stability. Global researches focus on novel membranes, electrochemical coupling and microbial succession; overseas studies emphasize new materials and pilot processes, while domestic researches cover kitchen waste, leachate and hypersaline wastewater to build modified AnMBR systems.

As AnMBR boasts high sludge concentration, small footprint, low excess sludge and high energy recovery, membrane fouling caused by oil, salts and extracellular polymeric substances restricts its large-scale application and reduces membrane flux. Its performance is governed by water quality, temperature, pH, membrane modules and microbial consortia. Synergistic metabolism of hydrolytic acidifying bacteria, hydrogen-producing acetogens and methanogens drives pollutant removal and biogas generation. Membrane modification, process coupling and microbial acclimation mitigate fouling. Though theoretical mechanisms are well-established, long-term anti-fouling techniques and low-cost engineering solutions need further research to promote its practical application in kitchen waste resource recovery.

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