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Review

Resource and Energy Utilization of Swine Wastewater Treatment: Recent Progress and Future Directions

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Abstract: Livestock and poultry farming, as a crucial component of agricultural production, poses a substantial threat to the ecological environment due to the discharge of wastewater. In recent years, researchers have proposed various resource treatment technologies for livestock and poultry breeding wastewater. However, a comprehensive discussion regarding the limitations and avenues for optimizing resource utilization technologies for livestock and poultry farming wastewater treatment is notably absent in existing literature. This paper takes swine wastewater as an illustrative case and undertakes a review of the advantages, disadvantages, and optimization directions of resource treatment technologies, including physical and chemical technology, microbial metabolism, microbial electrochemistry, constructed wetlands, and microalgae-based techniques. Based on mass balance, the recovery rates of various treatment technologies are estimated, and it was found that microbial electrochemistry and constructed wetland techniques may become the mainstream for resource utilization in the future. Furthermore, this paper emphasizes that in addition to resource efficiency, the optimization of resource utilization technologies for swine wastewater should also focus on the following aspects: (1) striking a balance between environmental impact and economic benefits; (2) reducing the cost of resource and energy utilization; and (3) safeguarding environmental and ecological security.

Keywords: wastewater treatment; swine wastewater; resource utilization; energy utilization

1. Introduction

The livestock and poultry breeding industry is currently experiencing rapid growth due to the increasing demand for meat consumption. However, as the scale of livestock and poultry farming continues to expand, it generates a substantial volume of waste and pollutants, particularly in the form of breeding wastewater. This environmental issue poses a significant threat to the ecological landscape [1]. Swine wastewater (mainly including swine manure water, swine washing wastewater, etc.) is the primary contributor to pollution in the livestock and poultry breeding industry, accounting for a significant portion of the total wastewater discharge, particularly in China, where swine wastewater discharged from pig breeding makes up a staggering 76.8% of all livestock and poultry wastewater [2]. Therefore, it is crucial for environmental protection and ecological governance to treat swine wastewater in a rational and efficient manner.

Currently, many nations have implemented policies to encourage the treatment and resource recycling of swine wastewater [3]. Researchers also primarily focused on two perspectives in studying the resource utilization of swine wastewater. On one hand, from the perspective of resource recycling, researchers primarily employ physical, chemical, and other methods to recover carbon, nitrogen, phosphorus, and other essential nutrients from swine wastewater [4–8]. These reclaimed nutrients can be used as long-lasting and slow-release fertilizers to provide vital nourishment for crops [9]. On the other hand,

from the perspective of energy generation, researchers employ various methods, such as thermochemical conversion and anaerobic fermentation, to produce methane, hydrogen, ethanol, and other energy substances [10]. It is noteworthy that different resource and energy treatment methods result in different resource and energy efficiencies [11]. Within the context of resource and energy scarcity, recycling from swine wastewater emerges as a promising avenue for the sustainable development of human society [12].

In particular, swine wastewater treatment technology can be broadly categorized into three main types: physical technology, chemical technology, and biotechnology [2,13,14]. Physical and chemical techniques are effective in removing contaminants and recovering nutrients from swine wastewater [15]. For instance, the ammonium magnesium phosphate crystallization method can recover over 92% of the phosphorus in swine wastewater. Nevertheless, the construction and operational costs of physical and chemical technologies often tend to be relatively high. Moreover, these methods may inadvertently lead to secondary pollution of the environment. In contrast, biological treatment technology offers the benefits of cost-effectiveness, sustainability, and high resource recycling efficiency, making it a more promising choice [14]. However, the practical implementation of biological treatment technology for swine wastewater primarily remains limited to laboratory-scale research and lacks industrial-scale applications [2]. These limitations significantly hinder the development of biotechnology in the resource recycling of swine wastewater.

This paper focuses on reviewing the swine wastewater treatment technologies that have gained prominence in recent years. It provides a comprehensive overview of the research status, pollutant removal efficiency, resource utilization, and energy efficiency associated with various technologies, including the ammonium magnesium phosphate crystallization method, anaerobic fermentation, constructed wetlands, electrochemistry, and other innovative technologies. Via a review of the advantages, disadvantages, and existing optimization measures of various resource utilization technologies, we have identified potential areas for future optimization and improvement in these technologies. Different from the percentage-based representation of the resource recovery rate used in the existing literature, this paper uses mass balance to make a more intuitive comparison of the effect of resource recovery. This paper also aims to furnish valuable insights for researchers and engineers engaged in the study and enhancement of swine wastewater treatment processes.

2. Research Status of Wastewater Treatment in Swine Wastewater

Currently, the prevailing treatment technologies for swine wastewater primarily include physical methods such as physical adsorption and electrodialysis, as well as chemical methods like flocculation and ammonium magnesium phosphate crystallization technology. While these technologies have shown some effectiveness in treating swine wastewater, they still face challenges due to limited removal performance and high maintenance costs. In contrast, biological treatment technologies, including anaerobic fermentation and constructed wetlands, are gaining increasing attention from researchers due to their cost-effectiveness and sustainability. A cluster analysis using the keyword "swine wastewater" affirmed that the most significant cluster in the literature on swine wastewater treatment revolves around the "microbial community". This indicates that research on swine wastewater treatment mainly focuses on topics like "microbial community". In addition, the clustering of the keyword "denitrification" is also prominent, indicating that nitrogen is a key element for the efficient treatment of swine wastewater. On the one hand, swine wastewater treated via anaerobic fermentation technology cannot be directly discharged since there are still residual nitrogen elements in the effluent. On the other hand, the denitrification efficiency of constructed wetlands is limited due to the lack of a carbon source for denitrification. These phenomena confirm that the removal of nitrogen elements is a key constraint for the efficient treatment of swine wastewater. Furthermore, it highlights that biological treatment technology is the leading direction in contemporary swine wastewater treatment research. In Figure 1a, the contribution network comprises 223 nodes and 388 connecting lines, with

a modularity value of Q = 0.5848 and a weighted mean silhouette score of S = 0.8708, suggesting that the clustering results are reasonably well defined.
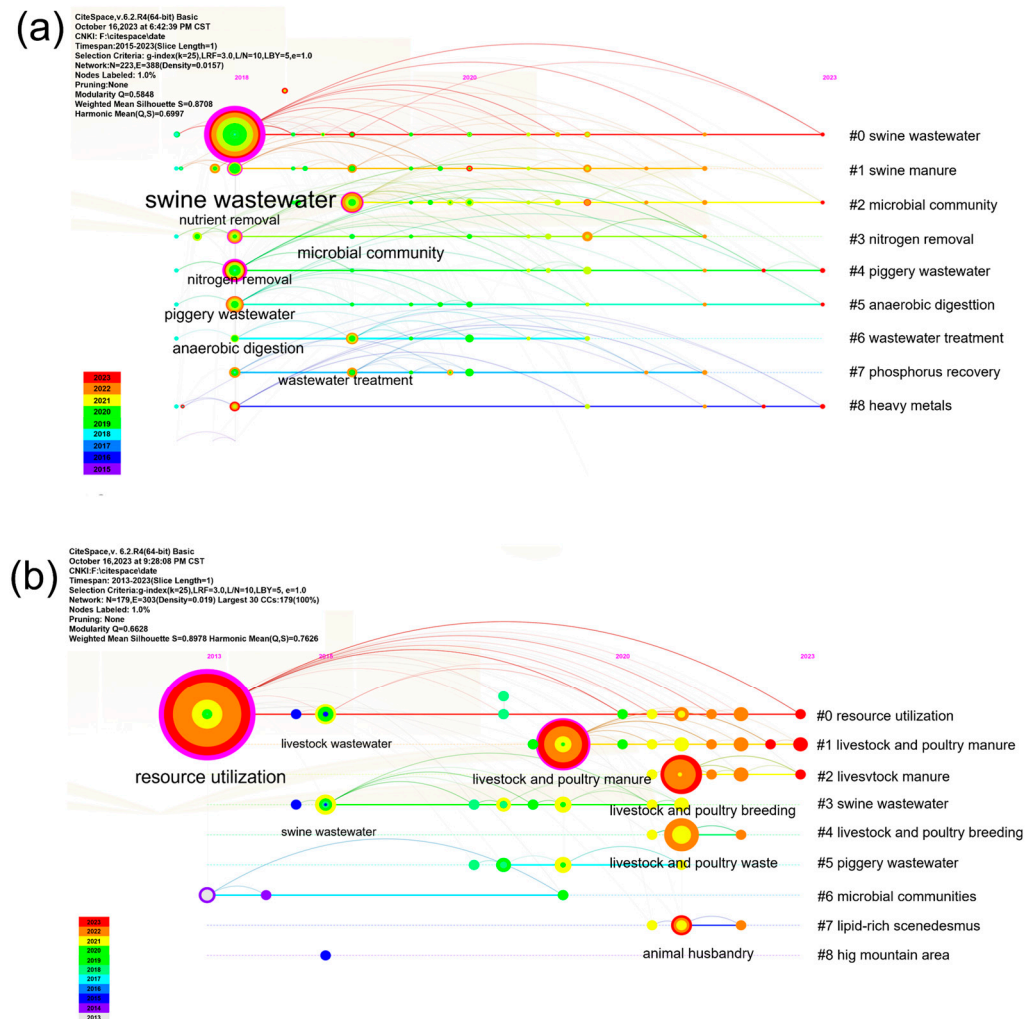

Figure 1. Collinear mapping of keywords related to (**a**) swine wastewater treatment and (**b**) resource utilization.

A timeline analysis revealed that "swine wastewater" and "livestock wastewater" gradually emerged as the dominant clusters in the literature related to swine wastewater resource treatment after the year 2020 (Figure 1b). This development can be attributed to the implementation of policies by several countries to promote the resource treatment of swine wastewater. Consequently, biological treatment technology for swine wastewater resource management holds promising prospects. Nevertheless, it is essential to note that research on biological treatment technology remains confined to laboratory-scale experiments, and the lack of large-scale practical application hinders the advancement of research in this field.

3. Physical and Chemical Technology Treating Swine Wastewater

3.1. Optimization of Materials for Enhancing Physical Adsorption Technology

Physical adsorption has gained significant recognition due to its inherent advantages, such as simplicity and high efficiency (Figure 2) [16,17]. The mechanism behind phosphate adsorption mainly involves surface precipitation, ligand exchange, and electrostatic attraction [18]. Currently, active carbon, zeolite, nanoparticles, and resins are extensively utilized in physical adsorption technology [19]. In recent years, there has been a concerted research

focus on discovering more efficient adsorbent materials to enhance the resource recovery efficiency of nitrogen and phosphorus from swine wastewater.
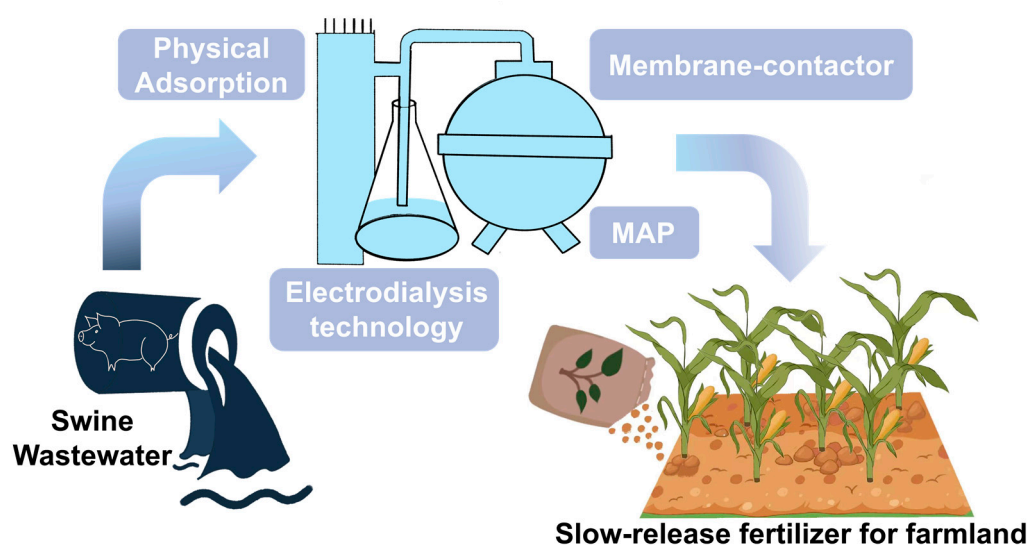

Figure 2. Conceptual diagram of the physical and chemical treatment and reclamation of swine wastewater.

Biochar has gained widespread use as an adsorbent for phosphate owing to its substantial surface area and numerous porous structures [19]. Studies have indicated that the swine manure of wastewater can be thermally decomposed, generating not only energy but also sustainable biochar [20]. The incorporation of metal nanoparticles, such as Ca, Mg, and Fe, into biochar can significantly enhance its adsorption capabilities [21,22]. For instance, biochar modified with nano zero-valent iron (nZVI) achieved a remarkable phosphate adsorption rate of 68.0–83.7% within the first 60 min [23]. Elements such as Ca, Fe, Mg, Si, Mn, and K not only enhanced the adsorption capacity for nitrogen and phosphorus but also contributed beneficial nutrients and metal ions for crops. These phosphorus-enriched biochars can be applied in soil as long-lasting and slow-release fertilizers to promote crop growth [24]. However, although these studies have demonstrated the effectiveness of physical adsorption technology in recovering phosphorus from swine wastewater, it is essential to consider the associated operating and maintenance costs. In addition, the range of applicable phosphorus concentrations for physical adsorption technology is limited [25]. The mass balance results also indicate that the resource recovery rate of the physical adsorption technology is only 0.48–54.0 mg/L/d [26]. Therefore, physical adsorption technology is generally considered suitable as a terminal method for treating swine wastewater.

3.2. Minimum Costs for the Large-Scale Application of Chemical Treatment Technology

Currently, the magnesium ammonium phosphate crystallization (MAP) method stands as the most extensively employed chemical technology in the field of swine wastewater resource treatment, serving as the final stage of swine wastewater treatment (Figure 2) [27]. The MAP method primarily utilizes NH_4^+ and PO_4^{3+} in wastewater to combine with Mg^{2+} to form magnesium ammonium phosphate precipitation, thereby facilitating the recovery of nitrogen and phosphorus from swine wastewater [28]. It is noteworthy that studies have indicated the remarkable efficiency of the MAP method capable of recovering over 98% of phosphorus from wastewater [29]. Furthermore, the magnesium ammonium phosphate crystals obtained during this process can be employed as slow-release and long-lasting fertilizers, providing essential nutrients for plant growth [30].

Nevertheless, the efficiency of the MAP method is influenced by various factors, with pH and molar ratio of $NH_4^+/Mg^{2+}/PO_4^{3-}$ being pivotal in determining MAP formation efficiency [31]. Studies have demonstrated that phosphorus removal efficiency can reach up

to 97% under specific conditions, such as a Mg/P molar ratio of 1.4 and a pH of 9.5 [32]. Li et al. [31] also observed that the total phosphorus removal rate reached an impressive 99.99% under conditions with a pH of 4 and a Mg:N:P ratio of 1.2:1.1:1. Moreover, optimizing the efficiency of crystallization sedimentation in magnesium ammonium phosphate hold the potential to enhance nitrogen and phosphorus recovery in swine wastewater [33]. It is noteworthy that some researchers have raised concerns regarding the maintenance cost of the ammonium magnesium phosphate crystallization method, which is considered to be a critical factor restricting its widespread implementation [34]. Therefore, when considering practical applications, the economic feasibility of the MAP method should be a crucial consideration.

3.3. Optimization of Membrane Materials to Exploit the Resource Potential

Membrane contactor technology proves to be a highly effective and economically efficient technology for ammonia recovery from swine wastewater (Figure 2) [35]. This technology converts NH_4^+ into NH_3 by increasing the pH or temperature of the wastewater, subsequently allowing it to diffuse into H_2SO_4 through the membrane pores. Ultimately, NH_4^+-N is reclaimed in the form of $(NH_4)_2SO_4$ [36]. The membrane contactor not only achieves an impressive NH_4^+-N recovery rate of 98% but the recovered $(NH_4)_2SO_4$ can also be marketed or utilized as agricultural fertilizer [29].

Currently, numerous studies have found that highly hydrophobic membrane materials facilitate ammonia removal and recovery within membrane contactors [37]. As reported by Míriam C [38], the nitrogen removal rate can reach 99.99% with a recovery rate of up to 86.88%. Moreover, it can be observed that the more hydrophobic membrane material utilized in membrane contactor technology, the longer its stable operation duration and the higher ammonia recovery rate [38]. Although membrane contactors hold significant potential for nitrogen recovery, further optimization of membrane materials suitable for treating swine wastewater is still a vital area required.

3.4. Optimization Wastewater Pretreatment Methods

Electrodialysis technology mainly utilizes an electric potential difference as the driving force, inducing ions with varying potentials to traverse selective ion exchange membranes [39]. However, the quality of products recovered via electrodialysis technology is influenced by various factors such as pretreatment methods and the composition of electrolyte solution. Among them, current density plays a key factor in the removal of nitrogen in electrodialysis technology. Lim et al. [40] emphasized that a current density of 1.09 A/m^2 yielded a noteworthy total nitrogen recovery rate of 75.0%. Additionally, the addition of dolomite into wastewater has been shown to enhance the electrolysis performance, resulting in an increased recovery rate of ammonia nitrogen [41]. Consequently, optimizing pretreatment methods for wastewater and regulating the composition of electrolyte solutions will be the key focus areas for future enhancements and enhancement in electrodialysis technology.

4. Microbial Metabolism for Treating Swine Wastewater

4.1. Optimization of Resource Efficiency to Meet Emission Standards

Anaerobic fermentation refers to the biochemical degradation of organic matter under anaerobic or anoxic conditions, harnessing the metabolic activities of anaerobic and facultative anaerobic bacteria to produce energy-rich gases such as methane and hydrogen [42]. Anaerobic fermentation consists of four stages, namely hydrolysis stage, acidogenesis stage, acetogenesis stage, and methanogenesis stage. These stages are facilitated by microorganisms with specialized functions [43]. At present, anaerobic fermentation technology has been widely used in large-scale swine wastewater treatment owing to its numerous advantages including low energy consumption, reusability of clean production, and utilization of biological resources (Figure 3) [2].
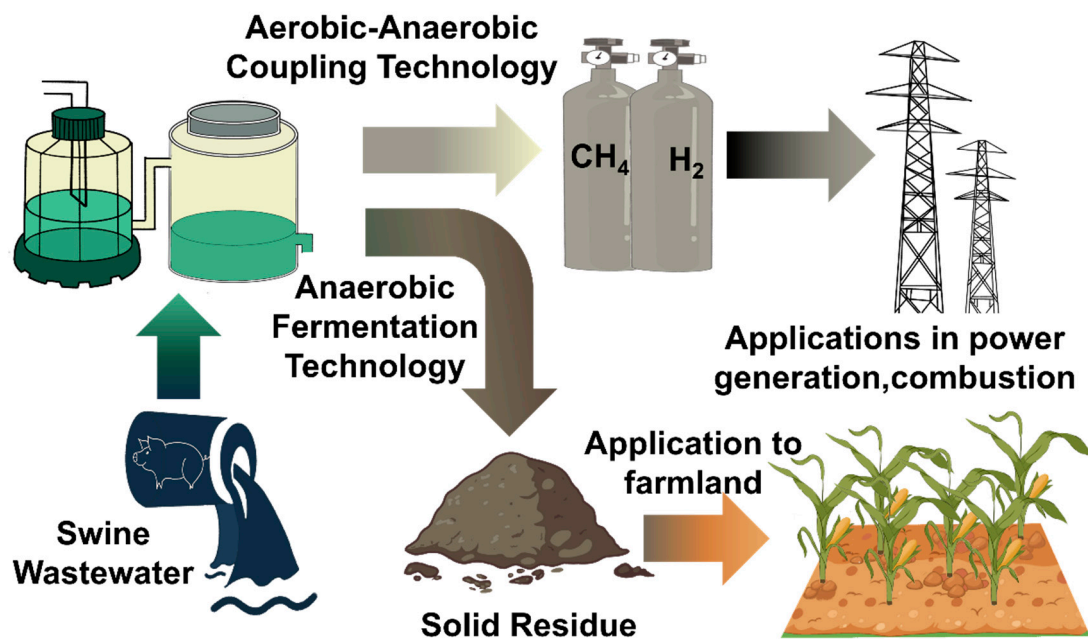
Figure 3. Concept diagram of microbial metabolism for treating swine wastewater and resource utilization process.

However, despite its extensive use, anaerobic fermentation technology still faces practical challenges. Notably, the efficiency of methane production during anaerobic fermentation is relatively low. The mass balance results indicated that the resource recovery efficiency of anaerobic fermentation was only 47.9–95.5 mg/L/d [44].To enhance methane production, researchers have implemented various improvements. For instance, the addition of straw to livestock and poultry manure for anaerobic fermentation has resulted in a consistently stable methane production rate exceeding 55% [45]. Additionally, the addition of exogenous biochar has increased the gas production rate during anaerobic fermentation of livestock and poultry manure, thus aiding in enhancing the metabolism of methanogenic bacteria [46]. Nonetheless, swine wastewater treated by anaerobic fermentation technology still contains a large amount of nutrients, falling short of meeting emission standards [47]. Consequently, the primary focus of research in this field is directed toward optimizing resource recovery while simultaneously meeting swine wastewater discharge standards.

4.2. Further Optimizing the Resource Efficiency of Anaerobic–Aerobic Coupling Technology

Anaerobic–aerobic coupling technologies can be used for nutrient recovery in the swine wastewater resource management process (Figure 3) [48]. Among them, various methods are applied, including internal circulating anaerobic reactor (IC) and anaerobic migration sludge bed reactor (AMBR) [49]. By employing anaerobic–aerobic coupling technology, NH_4^+-N removal efficiencies can reach up to 99% for concentrations exceeding 200 mg/L [50].

In addition, the coupled aerobic–anoxic nitrous decomposition operation (CANDO) is an innovative wastewater treatment technology that not only removes nitrogen from wastewater but also harnesses energy via microbial nitrification and denitrification processes [51]. However, the efficacy of CANDO in wastewater treatment is influenced by several factors, with nitrite concentration in the anoxic reaction stage considered a crucial factor affecting the production of N_2O [52]. Despite the potential of anaerobic–aerobic coupling technology to enhance the production of energy substances such as CH_4 and N_2O, substantial amounts of nutrients persist in swine wastewater [53]. Consequently, exploring ways to further improve the resource utilization efficiency of anaerobic–aerobic coupling technology via deliberate optimization represents a valuable direction for future research.

5. Microbial Electrochemical Technologies for Treating Swine Wastewater

5.1. Optimization Electrode Cost and Durability for Optimized Microbial Fuel Cells (MFCs)

Microbial fuel cells (MFCs) stand as an environmentally friendly technology that directly converts the chemical energy found in swine wastewater into electricity (Figure 4) [54]. MFCs have captured the attention of numerous researchers owing to their key attributes, including access to diverse raw materials, minimal secondary pollution, and efficient resource recycling, making them highly valuable in the context of swine wastewater resource utilization [55]. MFC technology offers several distinct advantages when compared to traditional wastewater treatment methods. Firstly, MFC will significantly reduce reliance on external energy inputs, as it can produce electricity. Secondly, the raw materials of MFC come from a wide range of sources. Thirdly, the working principle of MFC is relatively straightforward compared to traditional treatment technologies [56]. However, the processes of resource recovery and contaminant removal are influenced by several factors, such as electrode potential, pollutant concentration, HRT, and pH [57]. Studies have shown that different HRT operating conditions can affect COD removal. For instance, the COD removal rate at an HRT of 13d ranges from 59% to 71%, while at an HRT of 14d, the COD removal rate falls within the range of 60–73% [58]. Moreover, in MFCs with air as the cathode, phosphorus in swine wastewater tends to be adsorbed on the cathode surface in the form of suspended solids, with some precipitation observed in the liquid phase on the cathode side. The X-ray diffraction analysis revealed that the primary constituent of the precipitate on the liquid side of the cathode is struvite [59]. Currently, researchers have successfully achieved the resourceful treatment of swine wastewater from small-scale farms using MFC technology. In this study, a large-scale MFC system achieved a maximum COD removal rate of 5.0 kg COD/m^3 d^{-1}, with an energy generation efficiency of approximately 310–414 mW/m^3 [60]. This confirmed the viability of MFCs technology in the large-scale treatment of swine wastewater.
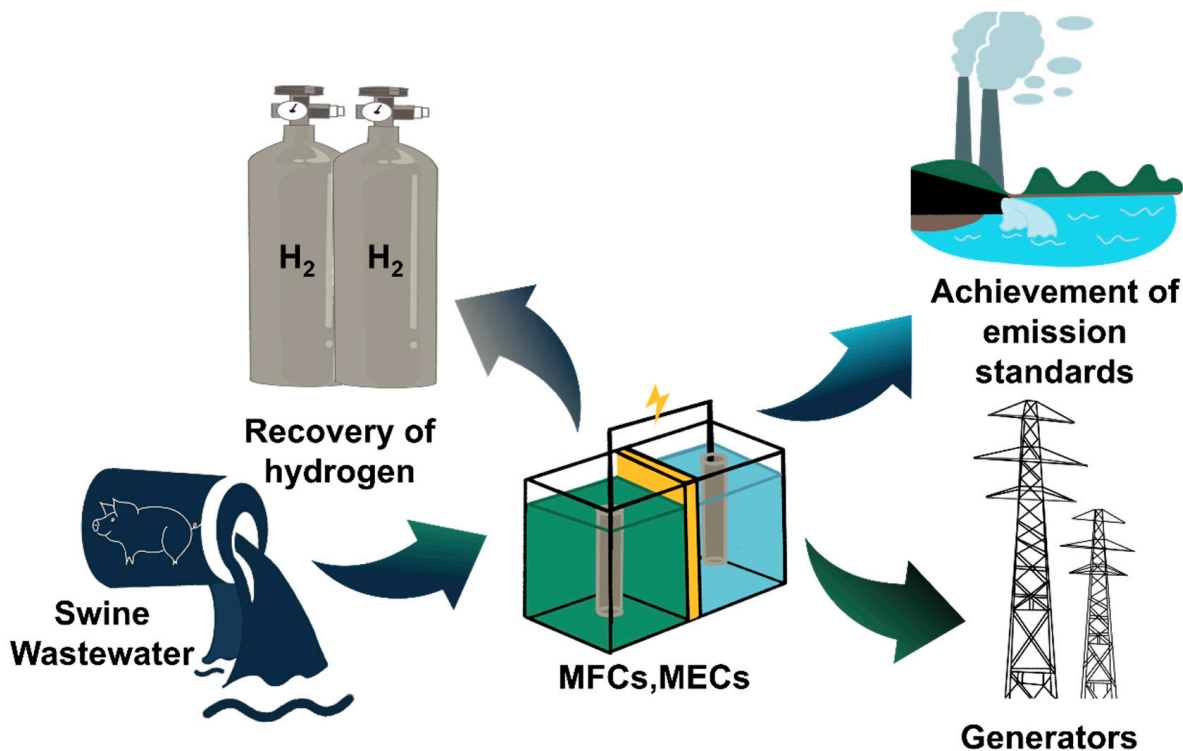

Figure 4. Concept diagram of a microbial electrochemical method for swine wastewater treatment and recycling.

Although MFCs showed promising results in small-scale applications, they still faced challenges in terms of the cost of reactor materials [61]. Additionally, concerns regarding the cost and durability of the electrodes, the enhancement of hydrogen production efficiency, the balancing of voltage and hydrogen production efficiency, and the maximization of economic benefits necessitate further exploration.

5.2. Optimization of Electrode Materials for Microbial Electrolytic Cells (MECs)

Microbial Electrolysis Cells (MECs) represent an emerging bio-electrochemical technology, initially discovered by Wageningen University [62] and Pennsylvania State University [63]. MECs harness electricity-producing microorganisms immobilized on the surface of the anode to oxidize organic matter under an applied voltage. The process results in the generation of electrons, which combine with protons diffusing from the cathode to produce hydrogen, concurrently yielding energy or valuable chemicals from wastewater [64,65]. In recent years, MECs have gained significant attention as a research hotspot due to their advantages of minimal secondary pollution, high removal rates, and low energy consumption (Figure 4) [66]. When treating highly concentrated swine wastewater using MECs, COD removal rates could reach 69–75% after 184 h, while the hydrogen production rate was approximately 66–88% [55]. Additionally, research has demonstrated that the effectiveness of the MEC-AD system, which involves a stainless-steel mesh encasing a Fe/Ni-MOF electrospun film composite cathode, in efficiently treating swine wastewater and recovering energy. The MEC-AD system achieved a COD removal of 82.92% and an alkane yield of 213.47 mL CH_4/g COD [67]. Previous researchers have confirmed that the resource recovery rate of MEC is approximately 190–285 mg/L/d via mass balance estimation [68]. However, the abundance of microorganisms in swine wastewater can reduce the lifespan of the proton exchange membrane in the MECs [69]. Therefore, a key focus for future research in MEC technology lies in the identification of substances that can be used as electrodes to enhance hydrogen recovery efficiency. Furthermore, in practical applications, the energy conversion cost of MEC also needs to be considered. Existing research has shown that the cost of hydrogen production via MECs needs to be reduced to below USD 0.30 per kilogram to achieve commercial viability compared to traditional gasoline energy prices [70].

6. Microalgal-Based Technology for Treating Swine Wastewater

6.1. Selection of Microalgal Species and Optimization of Biomass Recovery Methods

Microalgae, known for their short maturation period and ease of cultivation, hold substantial economic potential for resource utilization, particularly in the domains of wastewater treatment and resource utilization (Figure 5) [71]. In recent years, the exploration of cultivating microalgae from swine wastewater for biomass energy production has generated considerable interest, opening up new possibilities in biomass energy production [47]. Microalgae such as *Chlorella*, *Chlamydomonas*, *Scenedesmus*, *S. obliquus*, etc., have been successfully cultivated in wastewater for biodiesel production, as demonstrated in Table 1. Existing studies have summarized the resource recovery rates of different types of microalgae in swine wastewater based on mass balance results. The results indicated that the resource recovery rates of microalgae in swine wastewater range from 0.54 to 505 mg/L/d [72]. This finding suggested that the resource recovery efficiency of microalgae was highly dependent on the specific type of microalgae used.
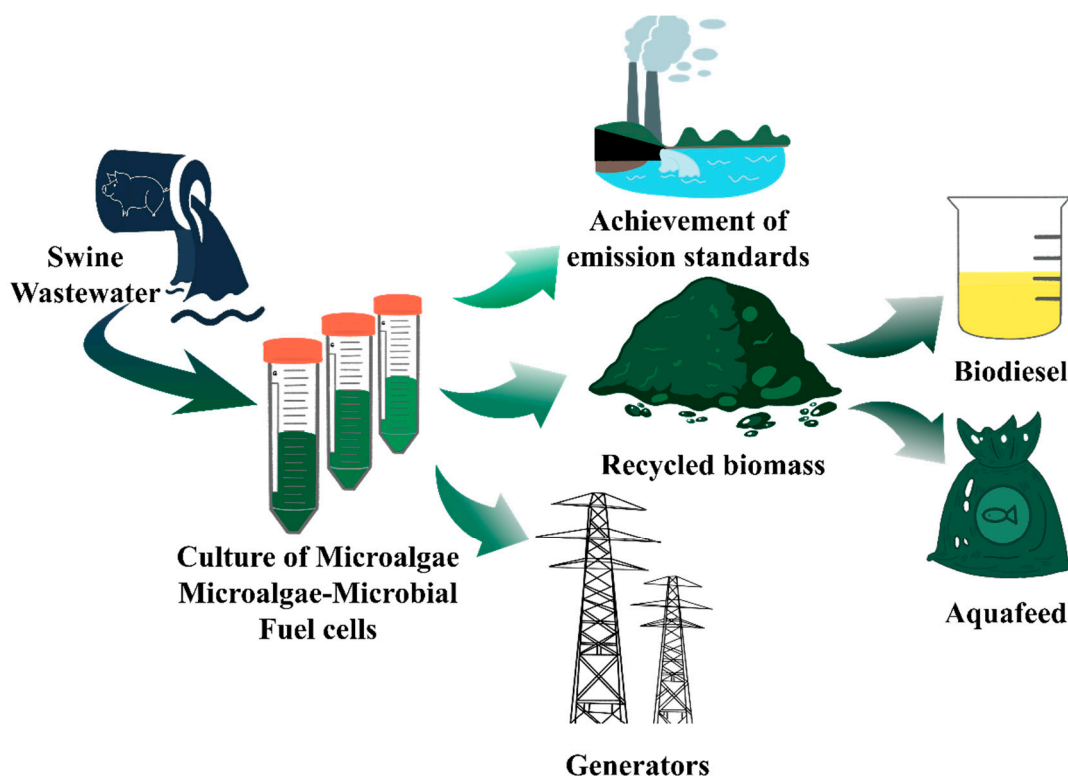
Figure 5. Conceptual diagram of swine wastewater treatment and recycling process in microalgae-based reactor.

Nonetheless, several studies have reported challenges in sustaining microalgae growth in swine wastewater, attributed to the high concentration of ammonia-nitrogen and low light transmission [73]. To resolve this issue, researchers have successfully addressed the problem of low light transmittance in swine wastewater by employing the ultraviolet irradiation acclimation method. This innovative approach resulted in recovery rates of 89.5% for total nitrogen and 85.3% for total phosphorus [74]. Therefore, while the use of swine wastewater to generate biomass energy from microalgae proves to be efficient and environmentally sustainable, it is important to acknowledge that challenges persist, particularly in the selection, cultivation, and harvesting of microalgae [75].

Table 1. Wastewater treatment efficiencies and biomass yield by microalgae.

Species	Biomass Productivity (mg L^{-1} d^{-1})	TN Removal (%)	NH_4^+-N Removal (%)	TP Removal (%)	COD Removal (%)	References
C. sorokiniana	23.4–408.9	60–98.6	79.1–85	64.7–96.4	36–93.7	[76–78]
C. subellipsoidea	860	75.3	–	78	–	[79]
C. vulgaris	86.1–101.7	69.6–80.9	91.2	64.4–94	72.2–95.7	[80–82]
Chlamydomonas	28	62.00	–	28.00	–	[83]
Chlorella	48–130	74.2–97.6	92–95	28–97.1	66.7–75	[83–85]
Diplosphaera	–	54.5	–	82.5	70.7	[86]
Monoraphidium	860	65.8–76.7	–	37.8–75.2	81.5–84	[86,87]
Oleoabundans	5.1	–	37.5	26.9	–	[88]
Pyrenoidosa	7.7–29.9	–	65.8–97.6	75.4–85.3	–	[88,89]
S. abundans	970	81	–	65.9	77	[90]
S. obliquus	11.8	–	72.4	80.9	–	[88]
S. quadricauda	–	95.5	–	96.4	81.9	[91]
Scenedesmus	7.1–211	77.8	80–95	86.7–94.1	26.4–83.3	[84,92,93]
Spirulina	48.4–115	75	80	86.7	68.8	[84,94]

Furthermore, efficiently harvesting microalgal biomass from swine wastewater poses another major challenge. When compared to traditional methods like centrifugation and filtration, flocculation and gravity sedimentation are more cost effective and convenient for collecting algal biomass [95]. Similarly, various technologies for lipid extraction, such as organic solvents, supercritical fluids, pulsed electric field-assisted methods, and subcritical fluids, can be utilized to recover lipids from algal biomass with considerable economic benefits [96–98]. It is important to emphasize that the harvesting and lipid extraction phases may result in secondary pollution due to the introduction of foreign flocculants or organic solvents [97]. Therefore, the exploration of innovative lipid extraction methods that can not only enhance lipid recovery but also mitigate pollution stemming from lipid extraction is a crucial area that warrants attention.

6.2. Coupling Microbial Fuel Cells Technique

With the advancement of microalgae-related research, microalgae–microbial fuel cells (M-MFCs) have emerged as a promising solution for concurrent electricity generation and wastewater treatment (Figure 5). They offer substantial advantages and hold the potential to address concerns related to energy, cost, and the environment [99]. Relevant studies have illustrated the remarkable potential of combining *Chlorella* vulgaris (FACHB-26) with microbial fuel cells. This synergy has resulted in impressive removal rates, including a COD removal rate of 93.2%, NH_4^+-N removal rate of 95.9%, TN removal rate of 95.1%, PO_4^{3-} removal rate of 82.7%, and maximum power density of 466.9 mW/m^3 [100]. Furthermore, M-MFCs have also demonstrated their capability to enhance battery performance [101]. For example, the utilization of immobilized or suspended yeast as a biocatalyst, combined with microalgae *Spirulina* on the cathode side, has yielded higher average power density and current density in suspended yeast M-MFC when compared to immobilized yeast. The average power density and current density are found to be 1.69 mW m^{-2} and 1.38 mA m^{-2}, respectively [102]. Based on this, microalgae-based microbial fuel cells present an environmentally friendly and sustainable approach; however, the technology still confronts the challenges such as high installation costs and energy consumption associated with microalgae acquisition.

7. Constructed Wetlands for Treating Swine Wastewater

7.1. Optimization of Nitrogen Removal to Improve the Resource Treatment Effect of Constructed Wetlands (CWs)

CWs harness the combined forces of physical, chemical, and biological processes, utilizing substrates, plants, and microorganisms to efficiently purify swine wastewater [76,103,104]. CWs are widely adopted due to their advantages of exceptional treatment efficiency, high shock load resistance, low investment requirement, and high ecological and landscape value (Figure 6) [105]. Furthermore, researchers have also confirmed via the evaluation of mass balance that the resource recovery efficiency of constructed wetlands is approximately 168–262 mg/m^2/d [106]. However, the nitrogen removal effect of CW treatment for swine wastewater encounters limitations arising from the lack of carbon sources. Studies have shown that the addition of microalgae in CWs can significantly enhance denitrification, thereby improving nitrogen removal efficiency while concurrently recovering biomass energy from available resources [107]. Therefore, integrating CWs with other technologies or optimizing the internal configuration of CWs for swine wastewater treatment not only enhances wastewater treatment efficiency but also bolsters both resource utilization and treatment efficiency [108,109].
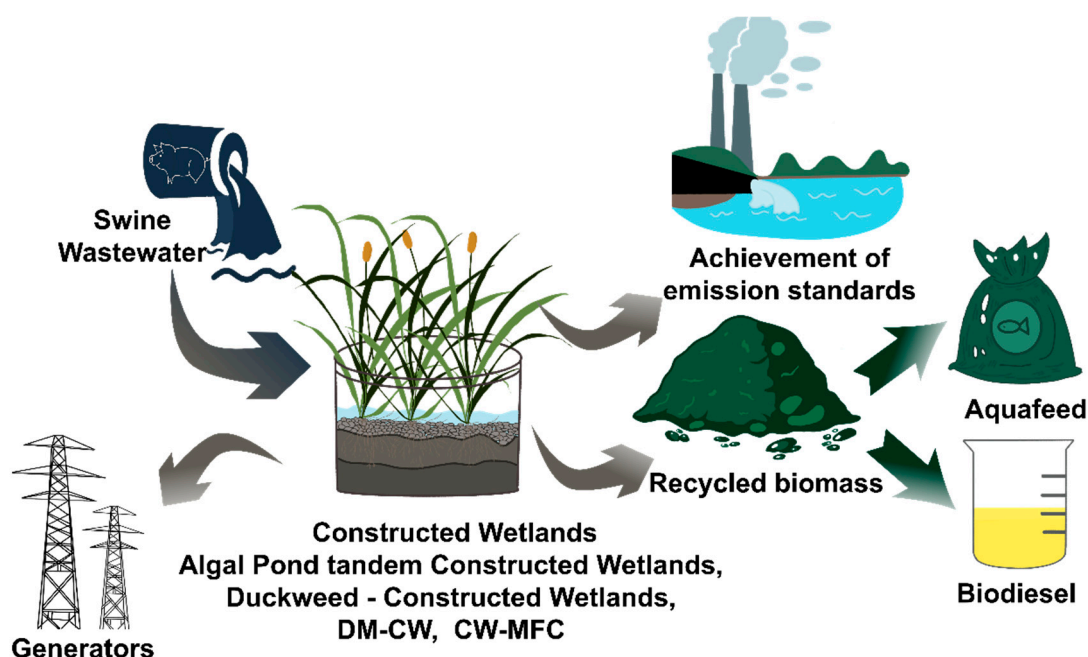
Figure 6. Conceptual diagram of swine wastewater treatment process and resource utilization processes in constructed wetlands.

Constructed wetland–microbial fuel cells (CW-MFCs) are an innovative green power generation technology based on constructed wetlands and microbial fuel cells [102]. A study investigating CW-MFCs using different plant species discovered that the CW-MFCs employing plantain outperformed other plant species in terms of contaminant removal and biopower generation capabilities from swine wastewater [103]. In addition, the arrangement of the electrodes plays a crucial role in determining the decontamination capability of CW-MFCs. Dohert et al. found that simultaneous upstream and downstream feeding of CW-MFCs could reduce internal resistance and enhance electrical performance [104]. Furthermore, employing glass wool spacer as separation materials can effectively narrow electrode spacing, leading to improved power production and pollutant treatment efficacy. However, there is currently a lack of clear explanation regarding the potential reaction principle underlying CW-MFC. This knowledge gap posed a challenge to the practical application and widespread adoption of CW-MFC in mitigating external interference in wastewater treatment.

7.2. Optimization of Microalgae-Based CWs

In recent years, the combination of algal ponds and constructed wetlands has gained recognition as a highly effective method for treating various types of wastewater, including that from agriculture, industry, and municipalities (Figure 6) [110]. This technique is favored for its superior economic efficiency and the capacity to produce treated swine wastewater that aligns with discharge standards [111]. Within the framework of algae pond tandem constructed wetland systems, the algal pools play a pivotal role in overcoming the limited nitrogen removal capacity typical of traditionally constructed wetlands. They achieve this via processes such as assimilation, nitrification, denitrification, and anaerobic ammonia oxidation [112]. However, it is essential to acknowledge that high concentrations of NH^{4+}-N in swine wastewater can severely limit the growth of microorganisms in algal pools and diminish the effectiveness of resource utilization [113]. As a result, appropriate pretreatment of swine wastewater and the careful selection of suitable microalgae are critical aspects of this approach. These steps ensure optimal performance and the sustainable resource recovery capabilities of algae pond tandem constructed wetland systems in the treatment of swine wastewater.

7.3. Choice of Duckweed or Microalgae for the Purpose of Optimizing CW Operation

Duckweed is increasingly recognized as a valuable source of protein and starch, primarily owing to its exceptional nutrient recovery efficiency [111]. Currently, researchers have established duckweed ponds on farms in North Carolina to utilize swine wastewater for producing protein and starch. Under the climate conditions in North Carolina, the protein and starch yields of duckweed in swine wastewater can reach up to 2.68 m^{-2} d^{-1} and 1.88 g m^{-2} d^{-1}, respectively [114]. In addition, the integration of duckweed into CWs has also proven to significantly enhance the removal capacity for dissolved nutrients in swine wastewater [115]. Numerous studies have demonstrated that duckweed-CWs outperform traditional CWs without duckweed, achieving notably higher removal rates of TN and TP [116]. The combined duckweed and CW system for swine wastewater treatment not only effectively eliminate high concentrations of nutrients while maintaining the ecological balance but also provides abundant biological resources for recycling. It is worth noting, however, that the choice of duckweed species exerts a substantial influence on the removal efficiency and biomass in duckweed-type CWs. Therefore, the selection of appropriate duckweed species is important when considering duckweed-type-based CW for resource utilization.

In addition, based on the characteristics of duckweed and microalgae, which grow in the upper layer of water bodies with the highest pollutant concentration, researchers have developed a microalgae–duckweed-type constructed wetland (DM-CW) system [111]. This innovative approach showed that the DM-CW system achieved an average removal rate of 65.9% for ammonia nitrogen and 21.5% for total phosphorus over a 3-day evaluation period [117]. Moreover, the treated swine wastewater from the DM-CW system has been demonstrated to meet the standards required for agricultural reusability. However, it is worth noting that certain reports indicated that the DM-CW system may exhibit a lower pollutant removal capacity in wastewater treatment compared to systems that solely rely on duckweed or microalgae in combination with constructed wetlands [111]. Therefore, selecting the appropriate species of microalgae and duckweed to maximize pollutant removal and efficiency may be the direction of optimization and improvement for the DM-CW technology.

8. Envisioning the Future: Optimizing Resource Utilization Techniques for Swine Wastewater

In the context of energy resources, resource utilization has become an inevitable trend in the treatment of swine wastewater. Numerous resource utilization technologies proposed by researchers can be roughly classified into five categories based on their recovery principles, namely adsorption technology, microbial metabolism, microbial electrochemical, microalgae reactor, and constructed wetland (Figure 7). Among them, adsorption technology is limited by adsorbent materials, resulting in generally low resource recovery rates, ranging from only 0.48–54.0 mg/L/d (Table 2). It is worth noting that microalgae reactors, as a popular resource recovery technology in recent years, have significant fluctuations in resource recovery rates (0.54–505 mg/L/d), which is highly dependent on the type of microalgae. This drawback may greatly influence the potential for large-scale application of microalgae reactors in the future. In comparison, microbial electrochemical and constructed wetlands have higher and more stable resource recovery rates, ranging from 190 to 285 mg/L/d and 168 to 262 mg/m^2/d, respectively, and are expected to become the mainstream technologies for resource utilization of swine wastewater.
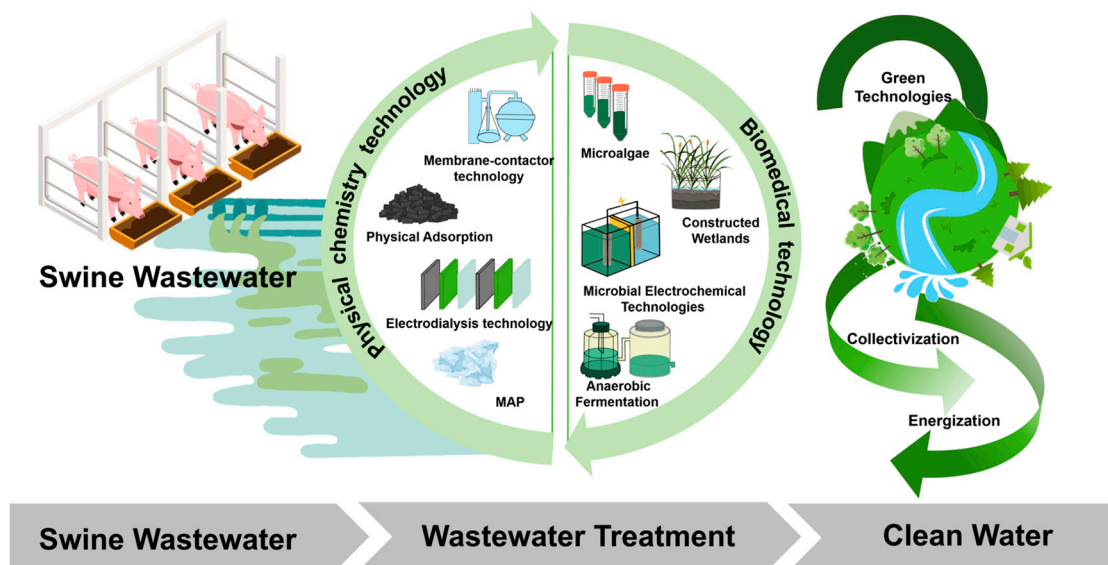
Figure 7. Schematic diagram of resource treatment of swine wastewater.

Table 2. Optimization direction and efficiency of resource treatment technology for swine wastewater.

	Advantage	Disadvantage	Optimization Direction	Resource Recovery Efficiency
Adsorption technology	Lower cost	Recovered element unitary; small scope of application	Optimized adsorption material	0.48–54.0 mg/L/d
Microbial metabolism	Recovery of energy gas	Tailwater cannot be discharged directly	Make tailwater meet discharge standards	47.9–95.5 mg/L/d
Microbial electrochemical	A wide range of raw materials; High productivity	Expensive	Optimize electrode cost	190–285 mg/L/d
Microalgae reactor	Make up for the lower energy density	High environmental load and economic cost	Reduce environmental load and economic cost	0.54–505 mg/L/d
Constructed wetlands	Treatment results are satisfactory	The processing mechanism remains to be studied	Accurately evaluate the operation efficiency of CWs	168–262 mg/m²/d

Additionally, environmental concerns and economic costs emerged as two key factors limiting the rapid and sustainable development of the livestock and poultry farming industry in recent years. In the process of optimizing and developing various resource utilization technologies, a balance needs to be achieved between environmental impact and economics. Previous researchers have utilized response surface methodology to optimize the resource utilization of microalgae in swine wastewater, resulting in a reduction of 48.0% in overall environmental impact and 10.2% in total economic costs during the treatment process [47]. Additionally, the utilization of genetically engineered products in the recycling and energy generation from swine wastewater may inadvertently result in the discharge of these products into the natural environment via water flows, thereby posing an unpredictable risk to the ecological integrity of the natural environment.

9. Conclusions and Implications

This study takes swine wastewater as an example to comprehensively explore the advantages, disadvantages, and optimization directions of resource recycling and utilization

technologies. While resource utilization treatment of livestock and poultry wastewater is theoretically feasible, there are still several issues that need to be addressed during its large-scale implementation: (1) striking a balance between environmental impact and economic benefits has become a key issue; (2) the challenge of reducing the cost associated with resource and energy utilization; And (3) the challenge of averting threats to the ecological security of the environment.

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