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Review

Research Advancements in Swine Wastewater Treatment and Resource-Based Safe Utilization Management Technology Model Construction

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Abstract: Swine wastewater contains large amounts of organic matter, nutrients, toxic metal elements, and antibiotics. If it is directly discharged or not properly treated, it poses a significant threat to the environment and human health. Currently, the management of swine wastewater has become a focus of social attention, and it adopts a dual-track parallel model of standard discharge supplemented by resource utilization. If treated properly, it can achieve the recycling of water resources and promote the effective recovery of resources. Based on the pollution characteristics of swine wastewater, this paper analyzes its impact on the environment, society, and the economy in detail and expounds on the research progress of swine wastewater treatment technology. From the perspective of resource utilization and recycling of anaerobic digestion liquid (biogas slurry) from swine wastewater and the carrying capacity of the soil environment and cumulative ecological environmental risks, this study explores new development trends and application prospects for swine wastewater treatment technology.

Keywords: swine wastewater; environmental impacts; resource utilization; efficient processing; technology management mode; combination of planting and breeding

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1. Introduction

With the rise of the global population and the rapid development of the social economy, people's demand for meat, eggs, milk, and other livestock and poultry products has increased dramatically, further promoting the prosperity and development of the livestock and poultry industry, particularly the pig breeding industry. Pigs are among the most widely distributed livestock in the world, and the annual consumption of pork in the world exceeds 128 million tons [1]. In China, pork consumption accounts for 60% of meat consumption [2]. As the world's largest pork producer, China's average annual pork production is as high as 449 million pigs [3]. At the same time, according to different breeding subjects, the livestock and poultry breeding mode is mainly divided into individual breeding and intensive breeding. Obviously, the scale of individual breeding is too small to meet market demand. Therefore, the current breeding mode has been transformed into a large-scale and intensive production mode [4], and the breeding feed has accordingly changed from sporadic waste from family and agricultural production to commercial feed, which is supplied by self-purchasing and self-processing. However, the increase in the number of intensive farms has led to the inevitable production of large amounts of wastewater in areas with limited land, resulting in a contradiction between the development of breeding and environmental protection, which has had a huge impact on the surrounding ecological environment.

The pig industry is the greatest polluter among all livestock and poultry breeding industries, with the discharge of pig manure and wastewater accounting for 76.8% of all livestock and poultry industries [5]. According to previous studies, a pig can produce 4–8 L of swine wastewater (e.g., urine and washing wastewater) every day [6]. That is to say, a large amount of swine wastewater will be produced every year in the world. In addition, the composition of swine wastewater is complex and usually contains high-load pollutants, such as chemical oxygen demand (COD), nitrogen, and phosphorus. Especially in China, the discharge of COD, total nitrogen (TN), and total phosphorus (TP) in swine wastewater accounts for 41.9%, 21.7%, and 37.9% of the total wastewater discharge, respectively, and these proportions are still rising [7].

To improve the efficiency of pig breeding, a certain proportion of additives are usually added to the feed to prevent diseases and increase the growth rate, including high levels of growth hormones, toxic metal elements, and antibiotics [8]. However, pigs have difficulties in absorbing and utilizing these additives, and ~50%–80% is excreted in the form of maternal or secondary metabolites [9]. If not handled properly, it causes great pressure on the safety of the water and soil environments [2]. Thus, swine wastewater has become a non-negligible source of water pollution, and its environmental implications have attracted global attention [10].

Although China has developed and issued a series of policies during the 13th Five-Year Plan period [11], it has attempted to reduce the source, processing, and end use of swine pollutants. At the same time, a series of explorations have been conducted around the treatment and utilization of swine wastewater, resulting in remarkable progress [12]. However, most studies tend to focus only on a certain point in the wastewater treatment process, ignoring the comprehensiveness and integrity of swine wastewater treatment and use. Therefore, constructing a gradient treatment system for swine wastewater is extremely important for the sustainable development of the pig industry and environmental protection.

The aim of this study is to address the critical issue of swine wastewater management, which is of utmost importance for environmental conservation and public health. Although research on the treatment and resource management of livestock and poultry wastewater has been developing rapidly, there still lacks a comprehensive bibliography of research achievements and the establishment of a safe and resourceful technology model. Therefore, this study mainly focuses on the research progress and new trends in the development of swine wastewater treatment technology. The characteristics of swine wastewater are summarized comprehensively, and its impact is discussed from the perspective of the environment, society, and the economy. Moreover, the necessity and urgency of pollution control are emphasized. Subsequently, the current research progress in swine wastewater treatment is expounded. Finally, a critical discussion on the limitations of existing treatment and management methods is presented. The proposed gradient treatment system offers a promising avenue for the sustainable development of the pig industry and environmental protection. The future prospects of efficient treatment and sustainable use of swine wastewater are investigated.

2. Methods

Refer to the introduction of information sources in the methods in the PRISMA 2020 checklist guide to determine the relevant literature included in this review based on the search database, keywords, article publication time, and team expertise. Firstly, the structural outline of this review paper is designed. Starting from the problem of swine wastewater pollution, the theme of the paper to be reviewed is determined, that is, the management of swine wastewater and the construction of a technical model for the safe utilization of resources. After that, the search content was continuously supplemented and improved, and the search terms were expanded (swine wastewater and management, swine wastewater and resource recovery, high-value products, biogas slurry treatment, swine wastewater and biological treatment, etc.), and high-quality papers from the past 5 to 10 years were mainly selected to explore the new trends and application prospects of swine wastewater treatment. In addition, the cited papers and cited papers in some of the literature were searched and considered. The search databases are mainly Web of Science, Elsevier, MDPI, CNKI, and other databases.

A total of 218 papers and reports (including academic papers and book chapters) were found and saved according to the search requirements. After reading step by step, the feasible data sets of 169 publications were screened out for the first time, and 78 papers with low correlation were deleted in the writing process. Finally, the latest research results were selected from 91 publications. The available data set consists of 58 publications, most of which were published in the last three years.

3. Pollution Characteristics of Swine Wastewater and Its Impact on the Environment

3.1. Pollution Characteristics of Swine Wastewater

Livestock and poultry breeding wastewater is a general term for excreta (urine and fecal wastewater), feed residues, and washing wastewater, among others, generated during the production process in livestock and poultry farms [13]. It is generally discharged from farms, manure storage rooms, composting sites, and lagoons [14], and it includes swine wastewater, cattle wastewater, sheep wastewater, and poultry wastewater. Among these, swine wastewater is the most common type. Because of the large differences in the composition of different wastewaters, especially the proportion of pollutants, these mainly depend on animal species, breeding time, feed composition, breeding methods, and environmental factors [15]. Even for the same type of farming, such as swine wastewater, its composition may vary because of the characteristics of the farm (e.g., feed, management of breeding, and manure) [16]. Swine wastewater and other livestock wastewater quality comparisons are shown in Table 1.

There are many types of pollutants in swine wastewater, such as suspended solids (SS), COD, biochemical oxygen demand (BOD), toxic metal elements, antibiotics, and pathogens. Generally, the concentrations of COD, TN, and TP in swine wastewater can be as high as 500–15,000, 100–2100, and 20–350 mg/L, respectively [17]. In addition, swine wastewater is an important source of antibiotic-resistant genes (ARGs), antibiotic-resistant bacteria, and virulence factor genes [18]. Liu et al. [19] studied the ecological risk of toxic metal elements and antibiotics in swine wastewater in Shandong Province and found that the iron and zinc pollution in the wastewater was serious, and the comprehensive pollution indices were 708.94 and 3.13, respectively. At the same time, drug-resistant *Escherichia coli* was detected in all cities of the province, and the genes resistant to quinolones, tetracyclines, sulfonamides, aminoglycosides, and β-lactam antibiotics were all above 60%. Meanwhile, Wu et al. [20] conducted a one-year monitoring of six livestock and poultry farms in eastern China and found that in addition to antibiotics, nonantibiotic substances (e.g., environmental hormones, disinfectants, antistress drugs, and other growth promoters) also have high detection rates, high concentrations, and low removal rates and have high environmental risks.

Therefore, in addition to the treatment of traditional pollutants, toxic metal elements, hormones, and antibiotics must be paid more attention; their research and control must be strengthened; and the use of antibiotics and mineral element additives in the pig industry must be further standardized. Because of the representativeness of swine wastewater, this paper mainly analyzed swine wastewater and discussed the construction of a gradient management system for swine wastewater as a whole.

Table 1. Comparison of wastewater quality between swine wastewater and other livestock wastewater.

Type of Wastewater	pH	Concentration of Pollutants (mg/L)				Reference
		TN	Ammonia Nitrogen	TP	COD	
Pig	6.77–8.90	210–2100	110–1650	100–620	3000–30,000	[13,21]
Cattle	6.00–8.50	100–830	50–300	9–280	3000–10,500	[11,17]
Poultry	7.1–7.3	56.5–70.7	—	0.2–0.6	480–850	[11]

3.2. Effects of Swine Wastewater on the Environment, Society, and Economy

3.2.1. Impact of Swine Wastewater on the Environment

Because swine wastewater is rich in nutrients, it may have certain benefits to the environment. For example, as a biological fertilizer, it can increase the soil nutrient content and maintain soil fertility. However, once swine wastewater without effective treatment or improper treatment is discharged, it may greatly reduce the local environmental carrying capacity and exceed the environmental capacity of the receiving carrier, resulting in serious non-point source pollution in the regional environment [22]. The production and treatment of swine wastewater are accompanied by the spread and transfer of methane, ammonia, steroid hormones, antibiotics, toxic metal elements, and pathogenic bacteria. These environmental pollutants [13] not only affect soil, groundwater, and air quality but also threaten public health and ecological security (Figure 1).

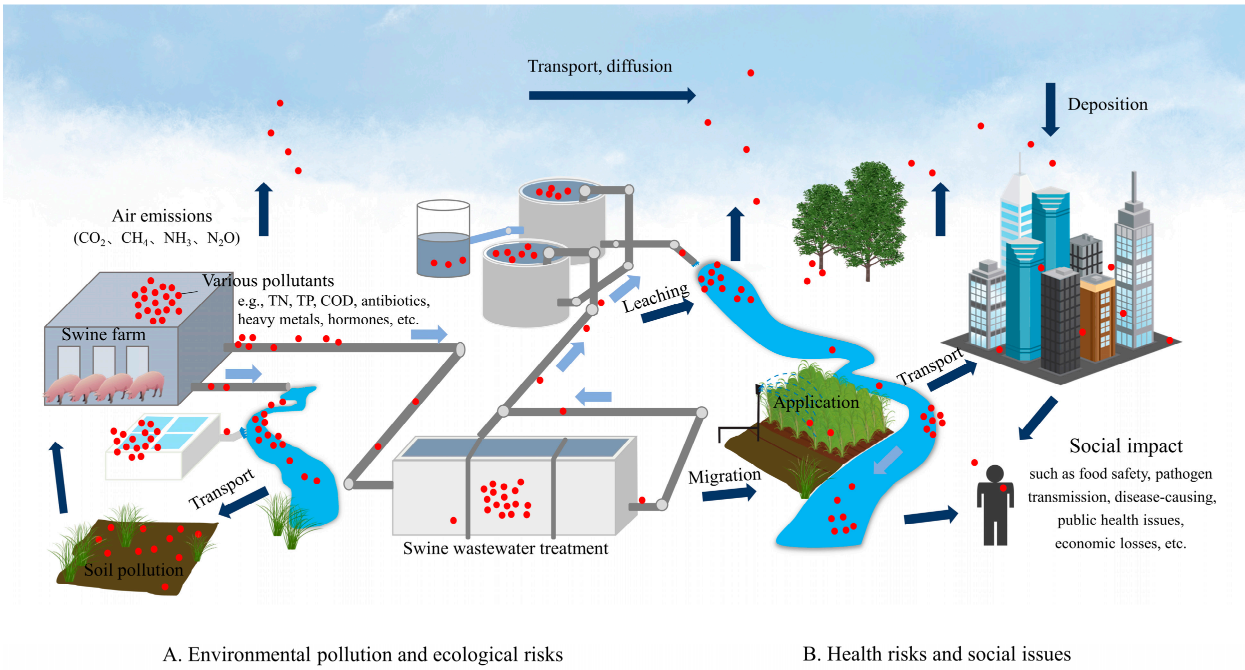

Figure 1. Negative impact of pollutants in swine wastewater.

- Harm to the water environment

The first to be affected by swine wastewater is the water environment, and untreated swine wastewater has become the main source of surface water and groundwater pollution [11]. First, a large number of intestinal parasites, bacteria, and viruses enter the water environment, which is likely to lead to microbial contamination of surface water and groundwater. Second, nitrogen, phosphorus, and water-soluble organic matter abundant in swine wastewater can be transferred to other waters through migration and infiltration, resulting in serious eutrophication of surface water. Studies have shown that swine wastewater containing high concentrations of nitrogen is considered an important source of global eutrophication [23]. Third, antibiotics, toxic metal elements, and steroid hormones cannot be completely removed from swine wastewater by conventional methods. Therefore, these substances may enter the environment with the overflow and leakage of lagoons and the reuse of swine wastewater, thereby polluting groundwater and surface water and affecting the survival of aquatic organisms [2].

- Harm to the soil environment

The emergence of toxic metal elements, antibiotics, and hormones adversely affects soil microbial communities and soil quality, and even pollutants accumulate in the soil, resulting in further degradation of soil functions [15]. In addition, the application of untreated or improperly treated swine wastewater stimulates the proliferation of other soil bacteria, which compete with native bacteria in the soil, thereby changing the soil resistance and virtually increasing the diversity and mobility of ARGs in the soil [18]. In addition, ARGs and resistant bacteria in wastewater change the original soil microbial community structure and diversity and promote the spread of ARGs to cultivated soil and edible crops [24], thus posing a major threat to human and soil health.

- Harm to the atmospheric environment [13]

Ammonia, hydrogen sulfide, nitrous oxide, and other gas pollutants contained in swine wastewater are released with the temporary storage, treatment, and disposal of wastewater [25]. However, farms are often not equipped with sufficient waste gas treatment facilities to purify exhaust gas and thus allow these polluting gases to be discharged into the environment, causing potential atmospheric safety hazards. In addition, the direct application of swine wastewater to increase soil fertility in some places not only emits gas pollutants into the atmosphere but also causes zoonotic pathogens to spread in the air. Finally, greenhouse gases such as CO_2 and methane released during the accumulation of wastewater also aggravate the global greenhouse effect.

- Harm to the ecosystem

Under the influence of swine wastewater, receiving water and soil change significantly. The long-term application of swine wastewater leads to the accumulation of ARGs in deeper soil [26] and then shows a cumulative amplification effect, which affects the structure and function of the ecosystem. Semedo et al. [27] found that the abundance and diversity of ARGs were higher in stream sediments near the discharge of aquaculture wastewater by investigating the drug resistance of the microbial community and the abundance and diversity of nitrogen cycle genes in the stream sediments affected by aquaculture wastewater. The genetic factors of dissimilatory nitrate reduction to ammonia are positively correlated with the total abundance of ARGs. Because of the retention of nitrogen caused by ARGs, the possibility of eutrophication in the ecosystem is increased, which seriously negatively impacts ecosystem health.

3.2.2. Effects of Swine Wastewater on Society

The pollution caused by swine wastewater causes public health problems, threatens public safety, and causes serious negative social impacts. One study [28] found that the more households engaged in pig farming in a certain area, the higher the health risk of the local people; moreover, the larger the proportion of large-scale farming, the higher the health risk of the people. In addition, the development of the pig industry often ignores the ecological recycling of waste, which not only fails to reduce the use of local pesticides and fertilizers but also increases the health risks of people and consumes great amounts of social resources, causing social security problems [13].

3.2.3. Effect of Swine Wastewater on the Economy

At present, the amount of swine wastewater has greatly exceeded the carrying capacity and safety level of existing land resources [11]. Each year, great manpower, material, and financial resources are needed to deal with these huge amounts of swine wastewater, and the direct economic losses caused by the ensuing environmental pollution are immeasurable. In addition, it leads to indirect losses, such as a decline in real estate value and a reduction in tourism.

4. Research Progress on Swine Wastewater Treatment Methods

In the past few decades, various physical, chemical, and biological treatment methods have been successfully developed and applied to treat swine wastewater. These methods mainly include solid–liquid separation (e.g., filtration and membrane treatment), adsorption, advanced oxidation, electrochemical methods, aerobic treatment, anaerobic treatment, constructed wetlands, and microalgae cultivation. Each method has its unique advantages and limitations, and the treatment effect mainly depends on the process characteristics and economic and environmental conditions. The comparison of various treatment methods for swine wastewater is shown in Table 2. Of course, the choice of the most appropriate method depends mainly on the nature of the wastewater and the treatment objectives.

4.1. Physicochemical Treatment Technology

Because of their high efficiency and less time consumption, physicochemical methods have been commonly used in swine wastewater treatment in the past. The common physical and chemical methods mainly include membrane treatment, adsorption, advanced oxidation processes (AOP) (Fenton catalytic, ozone catalytic oxidation, photocatalytic oxidation, and electrochemical oxidation), and so on.

4.1.1. Membrane Processing

Membrane treatment (or membrane filtration) is based on a physical separation process that uses a filter membrane to effectively separate the solid (concentrate or residue) and liquid parts (i.e., permeates) in swine wastewater. Through a series of membrane treatment steps [29], rough solid–liquid separation (pretreatment) is first performed, and then the pretreated wastewater is fed into a microfiltration device and passed through a membrane with a pore size of >0.1 μm at a pressure of 0.1–3 bar. Subsequently, ultrafiltration (pore size > 0.001 μm, pressure 2–10 bar) is performed to remove all SS and microorganisms. Finally, the remaining small molecules and ions are removed by reverse osmosis (pore size < 1 nm, pressure 10–100 bar) steps to obtain nutrient-rich osmotic residues and clean water that can penetrate the membrane [30]. Membrane technology has unique advantages, such as low energy consumption and continuous separation, and has been widely used in many industries [11].

In addition to single membrane filtration, the combination of membrane and other technologies is also a research hotspot. For example, membrane bioreactors are combined with biological treatment units. Although the membrane treatment method has many advantages over other traditional methods, it also faces high operating costs because membranes are easily contaminated and clogged and require frequent cleaning and replacement to ensure sufficient separation performance to maintain stable operation of the system [31], thus limiting the application of this treatment method. Some scholars have proposed that gas permeation membrane technology, as a new type of membrane treatment method, can minimize the NH_3 emission of swine wastewater and recover nutrients such as nitrogen while removing ammonia from wastewater [32].

4.1.2. Adsorption

As a traditional method widely used in the field of wastewater treatment, the adsorption method uses adsorbents with porous structures and large specific surface areas (e.g., diatomite, zeolite, activated carbon, and biochar) to effectively adsorb and retain pollutants in wastewater and remove pollutants. For example, He et al. [33] applied biochar prepared from chitosan-modified birch sawdust to the synergistic removal of vanadium and sulfamethoxazole in aquaculture wastewater. The adsorption capacity of the biochar to vanadium was found to be as high as 110 mg/g, and the adsorption capacity could be increased to 150 mg/g when sulfamethoxazole and vanadium were simultaneously removed. Meanwhile, Zhao et al. [34] used alkali-modified biochar (surface area of 130.520 m^2/g and pore volume of 0.128 cm^3/g) to adsorb and purify antibiotics in swine wastewater. Batch adsorption experiments showed that the adsorption process was mainly determined by chemical adsorption. The biochar had a synergistic effect on the adsorption of Zn^{2+}/Cu^{2+} and antibiotics, and the presence of Zn^{2+}/Cu^{2+} in wastewater was beneficial to the removal of antibiotics. In addition, some researchers began to focus on the adsorption and crystallization of recyclable nutrients in swine wastewater, such as the use of the magnesium ammonium phosphate crystallization method to combine NH_4^+, PO_4^{3-}, and Mg^{2+} in wastewater to form magnesium ammonium phosphate precipitation [35]. The combination of adsorption technology and struvite precipitation can not only improve the removal efficiency but also simultaneously recover nutrients abundant in swine wastewater [36]. Notably, the recycled final product has a much lower production cost than those of other traditional slow-release fertilizers on the market with the same efficacy.

4.1.3. AOP

AOP are commonly employed to treat various types of wastewater. That is, they generate hydroxyl radicals (·OH) using various catalysts like ozone, chlorine oxidants, and hydrogen peroxide [5] to convert refractory organics into easily degradable organics or completely oxidize them into CO_2 and H_2O. AOP have unique advantages in the treatment of swine wastewater containing high concentrations of organic matter (including most refractory organic matter), which can rapidly promote the mineralization and decomposition of organic matter in wastewater [1] and may be the most suitable method for removing refractory organic matter in swine wastewater [4]. Currently, AOP that have been widely studied and applied can be divided into Fenton, ozone catalytic oxidation, electrochemical oxidation [37], UV/hydrogen peroxide, photocatalytic oxidation, and so on.

As a commonly used AOP method, the Fenton catalytic oxidation process generates ·OH in an acidic medium through the catalysis of iron-rich compounds and the subsequent decomposition of hydrogen peroxide, among other factors. Its related research progress has been introduced in detail in the literature [1]. In addition, because of the shortcomings of the traditional Fenton method, such as the production of iron-containing sludge and the narrow application range of pH, Fenton-like treatment methods applied to swine wastewater treatment have begun to emerge [38]. In this regard, Qian et al. [39] used a combined process of biodegradation and deep oxidation to treat swine wastewater. Most conventional organic pollutants (the COD removal rate was 75%) were removed by an up-flow anaerobic sludge blanket (UASB) and sequencing batch reactor. Then, the average antibiotic removal rate of 74% was obtained by the Fenton-like oxidation method (with the participation of citric acid). At the same time, the treatment efficiency of the Fenton-like method was higher than that of the traditional Fenton method (74%:5%). This could be attributed to the chelation of citric acid with Fe^{2+}/Fe^{3+}, which led to an increase in the solubility of Fe^{2+}/Fe^{3+} and further promoted the formation of ·OH.

The ozone catalytic oxidation method is divided into homogeneous and heterogeneous catalytic oxidation, which has strong decolorization and organic matter decomposition ability. However, because of the reaction involving multiphase interfaces, the application of the ozone process requires a suitable gas–liquid contactor, which requires huge investment and maintenance costs, and its economic cost is much higher than that of the Fenton method.

Heterogeneous photocatalytic oxidation methods have been successfully explored in the treatment of various polluted air and water bodies [40], but there have been a few studies on swine wastewater, which is speculated to be related to the turbidity and complex pollutant components of swine wastewater. García et al. [41] used the heterogeneous photocatalytic degradation of COD in swine wastewater and found that the removal rate of COD could reach 91.7%. Considering the cost, AOP are generally combined with other technologies to treat swine wastewater, especially as pretreatment or advanced treatment. Compared with traditional processes, AOP can effectively remove organic pollutants and basically do not produce biological sludge; they have short time consumption and high efficiency [1]. However, their construction and operation costs are high, and the toxicity of degradation products (including intermediates) produced in AOP processes may be higher than that of the target degradation products [42].

4.2. Biological Method

Although the physical and chemical methods have the advantages of quick effect as mentioned above, avoiding the possibility of secondary pollution is difficult. In contrast, the biological method has more advantages, such as stable effects and low costs. According to different treatment subjects, biological treatment methods can be roughly divided into aerobic treatment, anaerobic digestion (AD), constructed wetlands, microalgae, and phytoremediation, among others.

4.2.1. Aerobic Treatment

Aerobic treatment (also known as aerobic biological treatment) uses aerobic microorganisms (including facultative microorganisms) to efficiently degrade organic matter in wastewater under aerobic conditions to achieve harmless discharge. At present, the activated sludge process and its variants are the most widely used aerobic biological treatment methods. However, the traditional activated sludge process is not ideal for nitrogen and phosphorus removal. Thus, it is not suitable for the treatment of swine wastewater. For high-concentration swine wastewater with a COD of 10,000 mg/L, pretreatment is required before aerobic treatment, and flocculant-assisted solid–liquid separation is usually used [5]. In recent years, the aerobic granular sludge sequencing batch reactor (AGSBR), which is superior to the traditional activated sludge method, has become the first choice for wastewater treatment [4]. AGSBR is operationally highly flexible, can maintain a high biomass concentration, has strong adaptability to impact load, and has high nitrogen and phosphorus removal efficiency, which is especially suitable for the treatment of high-concentration swine wastewater. In addition, Zheng et al. [43] conducted a pilot study (5 m^3/d) on the application of a multistage biological contact oxidation system to treat high-concentration livestock and poultry breeding wastewater. The removal rates of COD (89.2%), ammonia nitrogen (69.6%), and TN (57.3%) in the primary contact oxidation tank were dominant, but the method usually required a long hydraulic retention time and a large space.

4.2.2. AD

AD can be cost-effective and energy-recycling in the treatment of swine wastewater with high organic matter content [44]. It converts organic matter into methane-rich biogas using anaerobic microorganisms and uses the heat and electricity converted by biogas to offset the energy loss during the treatment process. Therefore, AD has also become a widely used biological method in swine wastewater treatment [45]. Common AD reactors include traditional digesters, covered lagoons, continuously stirred tank reactors, UASB, sequencing batch anaerobic reactors, and anaerobic membrane bioreactors [5]. In addition to a single AD, it can also be combined with other methods (especially the various physicochemical methods mentioned above), such as the formation of anaerobic membrane bioreactors combined with membranes, which can simultaneously achieve methane production and the removal of multiple pollutants (especially antibiotics and toxic metal elements) [11]. In this respect, Thao et al. [46] found the removal rates of COD, BOD, total SS, TN, TP, and total organic carbon could reach 84.2%, 92.7%, 80.8%, 93.3%, 76.0%, and 90%, respectively, when the swine wastewater after AD was filtered by biochar (prepared from mango leaf biomass residue) and treated by ozone catalysis. In addition, new breakthroughs have been made in the treatment of antibiotics and ARGs in swine wastewater by anaerobic digesters. Zhang et al. [47] found that the total removal rates of antibiotics, ARGs, and mobile genetic factors in the three reactors were 65.1%–98.1%, 3.5%–71.0%, and 26.9%–77.2%, respectively, when the antibiotics and ARGs in swine wastewater were removed by buried biogas digesters, UASB, and high-density polyethylene membrane-covered biogas digesters. The removal rates of UASB and high-density polyethylene membranes were higher than those of buried biogas plants, but the three digestion reactors could not effectively remove the pathogens.

Chen et al. [48] used UASB and an anaerobic membrane bioreactor to treat swine wastewater, which operated continuously for 137 days. With the increase in influent concentration (TP 22–93 mg/L, COD 2–7 g/L), the removal rates of TP and COD were 63% and 96%, respectively. However, it must be noted that refractory substances such as antibiotics, toxic metal elements, and hormones may persist after the AD process [4]. AD has been used as a pretreatment method in the treatment of swine wastewater using biological methods. Because AD requires a long hydraulic retention time to effectively stabilize the wastewater, it cannot efficiently remove nitrogen and phosphorus in aquaculture wastewater, and some refractory organics can inhibit the microbial activity in the AD process, which may lead to a reduction in process performance [37,49]. Therefore, it can be combined with natural treatment, biological denitrification technology, planting, and breeding at the back end to achieve standard discharge and resource utilization.

4.2.3. Anaerobic Ammonia Oxidation Treatment

Because of the difficulty of traditional treatment methods such as the activated sludge process in reducing the ammonia concentration in swine wastewater to a level that meets discharge standards, the anaerobic ammonia oxidation (anammox) method, a new, green, economical, and efficient nitrogen removal process for wastewater treatment, has emerged as a promising option. This process can directly convert NH_3–N and NO_2^-–N to N_2 under anaerobic conditions. It requires no additional organic carbon source and has a low sludge yield. Moreover, it reduces the occurrence of secondary pollution. Li et al. [50] proposed that micro-aeration and a low influent C/N ratio are key environmental factors for achieving anammox in livestock and aquaculture wastewater treatment plants. However, the growth time of ammonia-oxidizing bacteria is approximately 10–14 days, which slows down the wastewater treatment process. If there is a loss of activated sludge, the recovery time for the bacteria is even longer [11]. In addition, as this method mainly targets nitrogen in the wastewater, it is difficult to adapt to the interference of antibiotics, toxic metal elements, hormones, and other pollutants in swine wastewater. Therefore, the anaerobic ammonia oxidation process cannot be used directly to treat swine wastewater. If the nitrogen content remains high after pretreatment and other processes such as AD treatment, consideration can be given to combining this process.

4.2.4. Constructed Wetlands

Constructed wetlands are artificial equivalents of natural wetlands for the treatment of diluted wastewater. They consist of shallow ponds, vegetation, soil, microorganisms, and substrates that promote the adsorption and removal of pollutants and nutrients [51]. They are mainly divided into free surface flow and subsurface flow wetlands and are promising methods for the advanced treatment of swine wastewater. In this regard, Zhao Wei [8] constructed a horizontal subsurface flow constructed wetland to remove the characteristic pollutants in livestock and poultry breeding wastewater. The experiment found that the removal rates of total organic carbon, TN, NH_3–N, and TP in aquaculture wastewater were 84.3%, 78.6%, 82.1%, and 88.0%, respectively. At the same time, it also had high removal rates for antibiotics, toxic metal elements, and ARGs. Meanwhile, Brienza et al. [52] established a new combined system of ammonium recovery and aerated constructed wetland. The core of the system was to recover nitrogen from swine wastewater using an NH_3 stripping process and then purify it using an aerated constructed wetland. This method can be used as an alternative method of biological nitrification–denitrification treatment in traditional systems. However, regardless of the kind of constructed wetland process, further research is needed. At present, there is still a lack of comprehensive life-cycle assessment analysis for constructed wetlands [53]. The most critical thing is solving the problem of intensive land use and optimizing process parameter settings to improve the economic feasibility and environmental sustainability of these technology combinations.

4.2.5. Microalgae Cultivation

The microalgae cultivation treatment of swine wastewater has mainly focused on treatment effectiveness and biomass accumulation [54]. Because of their strong adaptability, microalgae are commonly employed in various wastewater treatment processes [55]. After the pretreatment of swine wastewater, the use of microalgae can not only easily achieve discharge standards but also contribute to environmental sustainability and economic growth. In this regard, Chen et al. [56] studied the growth of three native microalgae strains (*Chlorella AK-1*, *Chlorella MS-C1*, and *Chlorella TJ5*) in untreated swine wastewater. They found that *Chlorella AK-1* had the best tolerance and could grow in 50% concentration of swine wastewater. It removed 90.1%, 97.0%, and 92.8% of COD, TN, and TP in the wastewater, respectively, and produced significant biomass (5.45 g/L) and protein yield (0.27 g/L/d). Nevertheless, significant differences existed among microalgae species, necessitating the selection of appropriate microalgae based on the target water body's (e.g., pollutant type and concentration) compatibility. For instance, López-Sánchez et al. [15] mentioned in their review that mixed-nutrition microalgae, particularly those from the Chlorophyta phylum, such as *C. vulgaris*, *C. regularis*, and *H. pluvialis*, have demonstrated effective nutrient removal capabilities in aquaculture wastewater while producing marketable valuable products (e.g., biomass rich in protein, pigments, and carotenoids). Notably, the combination of microalgae with other technologies (e.g., algae–bacteria symbiosis, artificial wetlands, and physical–chemical treatment methods) holds great promise. For example, the utilization of a low-cost, high-efficiency, environmentally friendly algae–bacteria symbiosis system to treat pretreated swine wastewater significantly enhances system stability, efficiently removing nitrogen, phosphorus, toxic metal elements, antibiotics, and other substances from the wastewater [55]. Nevertheless, as a circular biological economy approach, employing algae–bacteria symbiosis systems to manage swine wastewater and its posttreatment slurry remains a challenge because of three primary obstacles: enhancing biomass productivity, improving pollutant removal efficiency, and increasing the production of high-value compounds.

Although the biological treatment methods mentioned above are effective in removing contaminants from swine wastewater to some extent, the limitations of requiring significant treatment time and space and constraints when dealing with organic pollutants such as antibiotics cannot be ignored [1]. Therefore, seeking collaborative treatment through multiple technologies, achieving economic and environmental benefits (by fully considering the environmental carrying capacity and achieving sustainable economic development), and constructing a convenient method system for gradient treatment is particularly important.

Table 2. Comparison of wastewater treatment technologies for the pig industry.

Treatment Technology		Advantages	Disadvantages	Future Development Direction
Physical chemical method	Membrane treatment [29]	Simple operation, small footprint, efficient interception and removal of most pollutants, and resource recovery	The membrane is easily blocked and lost, thus requiring regular replacement and high costs	(1) Research and development of new membrane materials; (2) improving the efficiency and stability of membrane treatment; (3) cost reduction
	Adsorption [57]	The process is simple; the operation is flexible; and the maintenance is convenient, economical, and efficient	The adsorption efficiency is affected by the type of adsorbent and the characteristics of the adsorbate, and most of the adsorbents have poor regeneration	Low-cost, high-adsorption capacity, and good regeneration of new adsorption materials, such as modified carbon nanotubes, graphene-based materials, and functional covalent organic framework materials

Table 2. *Cont.*

Treatment Technology		Advantages	Disadvantages	Future Development Direction
Physical chemical method	Advanced oxidation [1]	Fast reaction speed and good treatment effect	The operation cost is high, and it may produce a large number of harmful intermediate products	(1) Improve the choice of oxidant; (2) improve the processing efficiency; and (3) reduce operating costs
Aerobic treatment [4]		Good stability, mature research	Long hydraulic retention time, large area, narrow scope of application	(1) Combine with other processes; (2) design new reactors
Anaerobic digestion [4]		Convert pollutants into biogas and organic fertilizer to achieve resource utilization; the operating cost is relatively low	Regular maintenance, high maintenance costs	New attempts to combine bioaugmentation, molecular biology, nanomaterials, artificial intelligence, and other new technologies
Anaerobic ammonia oxidation [4]		High-efficiency denitrification, low cost, and broad prospects for engineering applications	The growth rate of anaerobic ammonia-oxidizing bacteria is slow, the culture time is long, and the reaction conditions are harsh	(1) Combination with anaerobic digestion and physical and chemical methods; (2) in the case of high ammonia nitrogen, efficient treatment of pollutants and resource recovery are achieved
Constructed wetlands [13]		No secondary pollution, low treatment and maintenance costs, and high efficiency	The treatment efficiency is greatly affected by climatic conditions, and the stability and treatment effect must be improved	(1) Improve the design and operation mode of constructed wetlands to improve their treatment efficiency and stability; (2) combine with other wastewater treatment technologies, such as biofilm reactors and microalgae cultures, to form a combined process; (3) use the Internet of Things, big data, artificial intelligence, and other means to achieve remote monitoring and intelligent operation
Microalgae cultivation [55,58]		Various pollutants can be removed simultaneously; low cost, high efficiency, environmental friendliness, and energy	The growth rate of microalgae is slow and has certain requirements for environmental conditions (to a certain extent, it is inhibited by antibiotics, toxic metal elements, and other pollutants in aquaculture wastewater)	(1) Microalgae and other microbial symbiosis cultivation; (2) biomass biofuels

5. Discussion and Outlook

5.1. Gradient Progressive Treatment and Safe Utilization Management Mode of Swine Wastewater

In the new form of industrialized pig breeding development, swine wastewater exhibits multiple sources and complex composition. Although some studies have shown that the physical and biological treatment methods mentioned above have achieved some success [1], there are still many unresolved issues (such as noncompliance with discharge standards and failure to achieve resource safely utilization). The particularity of swine wastewater determines that it cannot achieve discharge compliance and resource utilization using only a single method. Generally, pig farms apply biological treatment processes such as lagoons, AD tanks, and tertiary A/O in primary and secondary treatment processes. However, because of the limitations of the method itself and the long-term neglect of resource attributes and overall governance of swine wastewater [54], the awareness and management mode for constructing a gradient treatment of swine wastewater and the safe utilization of its AD biogas slurry after treatment must be strengthened.

In recent years, the treatment thinking of swine wastewater has shifted from "pollutant removal" in the past to "resource recovery and reuse." The treatment thinking of wastewater should follow the environmental sustainability and circular economy concepts in the new era [36]. For instance, the combination and balance of breeding and planting is an effective way to alleviate the environmental risks caused by swine wastewater. [10]. As shown in Figure 2, the "fecal output" block in the material flow of the breeding industry (biogas slurry) and the "nutrient supply" block in the planting industry (soil) are the key links in the integration and circulation connection of the "plant–animal" industry. Through the process mechanism of physical and chemical adsorption; retention and precipitation; microbial metabolism; and the transformation of COD, BOD_5, NH_3–N, PO_4^{3-}–P, K^+–K in biogas slurry and the absorption effect of plants, soil can improve or soil quality can even be enhanced and the application of fertilizers for crops can be reduced. This is a convenient path for resource recycling and utilization of biogas slurry. The sustainability and safety of resource recycling and the utilization of biogas slurry can be achieved only under the premise of ensuring the balance of the two circulation links of the "plant–animal circulation system," that is, the balance between the biogas slurry load and the soil environmental carrying capacity.

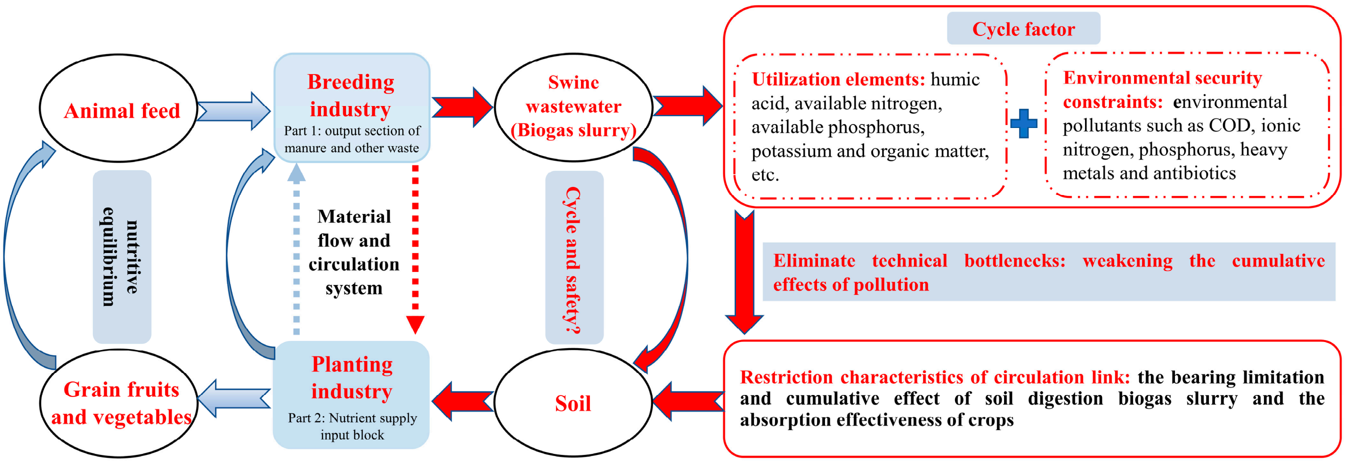

Figure 2. Basic framework of material flow circulation and circulation safety utilization in related blocks of livestock and planting industries.

Soil serves as a crucial link that connects the material flow of the breeding and planting industries. Although soil types may vary, it has certain limitations in terms of environmental carrying capacity for biogas slurry because of its natural characteristics. The other circulation link, livestock and poultry breeding manure or biogas slurry, is a complex of "environmental pollution sources and agricultural resources." It contains not only nutrients that can be used in agricultural production, such as humic acid, available nitrogen, available phosphorus, potassium, and organic matter, but also environmental safety constraints such as COD, BOD_5, ionic nitrogen, phosphorus, toxic metal elements, and antibiotics. During the process of biogas slurry resource utilization treatment or deep treatment for discharge standards, different types of treatment technologies cannot achieve the fundamental removal of "pollutants" in biogas slurry. In particular, the accumulation and retention of refractory organic matter, SS, and colloids on the soil surface inevitably lead to the growth of heterotrophic microorganisms, which can cause fatal inhibition of nitrifying microorganisms by blocking soil pores, reducing water carrying capacity, and competing for oxygen consumption. This destroys the balance of soil environment biodiversity in the utilization and self-purification of biogas slurry and gradually reduces the soil environmental carrying capacity. Further, it directly affects agricultural production by disrupting the effective balance of substrate components such as nitrogen, phosphorus, potassium, and organic matter in the soil. Moreover, COD, BOD_5, TP, NH_3–N, and new pollutants are accumulated through the "latent transfer" of soil carriers, regional water bodies, and groundwater. In particular, the ARGs carried by biogas slurry lead to the enrichment and transfer of antibiotic-resistant bacteria, posing a significant threat to regional soil ecological environments and human health. This forms a technical bottleneck in the process of biogas slurry resource utilization in terms of soil "adsorption-retention–transformation" and cumulative environmental ecological safety. Additionally, during anaerobic fermentation of livestock breeding wastewater, microorganisms metabolize and consume a large amount of carbon sources. The low-carbon–nitrogen ratio and poor biodegradability of the anaerobic effluent (biogas slurry) form a technical barrier to efficient biochemical treatment. Therefore, it is crucial for pollution control in the breeding industry and the safe utilization of its resources to reduce the biogas slurry load to achieve a balance with the soil environmental carrying capacity and eliminate cumulative environmental ecological risks through technical means.

On the basis of the technical foundation of the physical–chemical–biological (AD, flocculation, and biological/ecological purification) treatment of swine wastewater mentioned above, combined with the research and demonstration project results of the project team in recent decades on advanced catalytic oxidation, new pollutant reduction and detoxification technologies for livestock and poultry breeding pollution were developed, and from the perspective of soil bearing safety and environmental ecological risk accumulation in biogas slurry resource utilization, a highly efficient management technology mode for safe utilization of biogas slurry resource was constructed, as shown in Figure 3. Through the efficient photocatalytic oxidation and flocculation of high-concentration refractory organic matter in biogas slurry, the cumulative inhibitory effect on the "adsorption–retention–transformation" process of soil slurry absorption is eliminated, ensuring the soil's own purification balance level and environmental carrying capacity and thus, laying a solid technical foundation for the safe utilization of biogas slurry resources. At the same time, it effectively regulates the carbon–nitrogen ratio of biogas slurry; improves the level of the synergistic effect of microorganisms in its biochemical system on COD, BOD_5, NH_3–N, and TP degradation and transformation; and eliminates technical barriers to efficient discharge treatment. By reducing and detoxifying new pollutants, such as antibiotics in biogas slurry, we weaken their biological activity. In the whole process of swine wastewater treatment, whether resource utilization or discharge standards, we can reduce the "cumulative effect" ecological environmental risks of pollutants. This has great practical significance and technical guidance for effectively promoting the efficient treatment of swine wastewater and its safe utilization in agricultural resource circulation with the soil bearing capacity, as well as the integration development of the planting industry.

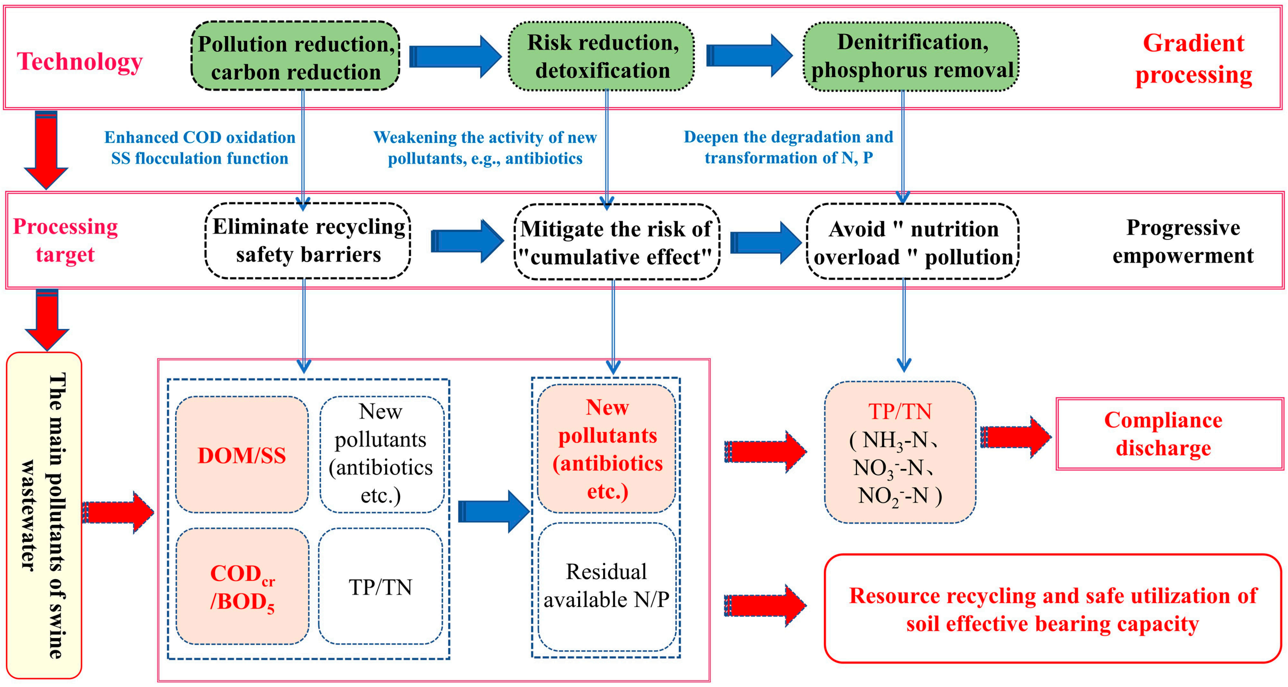

Figure 3. Gradient progressive treatment of swine wastewater and agricultural recycling technology system.

5.2. Future Research Perspectives

Profoundly understanding the development characteristics of the breeding industry (pigs), gradually solving the environmental problems caused by it, and realizing the circular economy are the only ways to construct ecological civilization. The development prospects of the management model for the treatment and safe utilization of swine wastewater mainly include the following aspects:

(1) Prevention and control of emerging pollutants (e.g., disinfection by-products, antibiotics, and ARGs), based on which the development of multifunctional and high-performance biological methods (e.g., microalgae, artificial wetlands, and microbial fuel cells) will further expand the scope and scale of engineering applications.
(2) Using electronic information, big data, artificial intelligence, and other means to identify various pollutants (especially emergency pollutants); optimize the construction of treatment systems (based on accurate energy flow calculation, economic analysis, and carbon balance analysis); and establish automatic control systems, which is the future development trend.
(3) Promoting the construction of a convenient gradient and progressive technology for wastewater treatment; enhancing the resource performance of treatment; strengthening the integration of pollution control, resource reuse, and animal husbandry; achieving the overall goal of discharge standard compliance for wastewater and effective utilization by planting industries; and improving the circular economy system.
(4) With the continuous promotion of the "CO_2 emission peak and carbon neutrality" goal, the pollutant control–animal husbandry cycle model of green, low carbon, and sustainable development is the mainstream of future development, especially the combination of automated swine wastewater treatment and smart agriculture.

6. Conclusions

With the increasing attention paid to the treatment of swine wastewater in China, relevant policies are constantly improving, from emphasizing the emission of pollutants in the initial stages to full-process management and then to harmless treatment and integration of breeding and cultivation. Although China's research on the treatment of swine wastewater has shifted from only focusing on end-of-pipe treatment to source control, there are still relatively few overall research achievements that need further promotion. The main conclusions of this study are as follows:

(1) In terms of source control and reduction, it is necessary to reasonably arrange breeding farms and strictly control the production process; develop environmentally friendly feed (improved feed) and control the addition of veterinary drugs to reduce the entry of pollutants such as toxic metal elements, antibiotics, and ARGs from the source; and improve the breeding method, promote clean production, and reduce the discharge of wastewater to reduce the subsequent treatment difficulty and cost at the source.

(2) In terms of end-of-pipe pollution treatment, although physical and chemical methods can remove most organic and inorganic pollutants, they cannot effectively degrade antibiotics in swine wastewater, and the cost is high; meanwhile, biological treatment methods remain a cost-effective and promising wastewater treatment technology, but its resource utilization must be optimized. Its improvement methods include coupling multiple processes, operating serial reactors, and so on.

(3) It is particularly important to establish a convenient treatment and safe utilization management model for swine wastewater based on the construction of a gradient and progressive treatment system. By integrating individual treatment units into a unified system, large-scale intensive breeding can be organically combined with crop cultivation, achieving a balance between breeding and cultivation.

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References

1. Domingues, E.; Fernandes, E.; Gomes, J.; Martins, R.C. Advanced Oxidation Processes Perspective Regarding Swine Wastewater Treatment. *Sci. Total Environ.* **2021**, *776*, 145958. [CrossRef]
2. Hu, Y.; Cheng, H.; Tao, S. Environmental and Human Health Challenges of Industrial Livestock and Poultry Farming in China and their Mitigation. *Environ. Int.* **2017**, *107*, 111–130. [CrossRef]
3. Duan, N.; Khoshnevisan, B.; Lin, C.; Liu, Z.; Liu, H. Life Cycle Assessment of Anaerobic Digestion of Pig Manure Coupled with Different Digestate Treatment Technologies. *Environ. Int.* **2020**, *137*, 105522. [CrossRef] [PubMed]
4. Chen, N.; Zhang, X.; Du, Q.; Huo, J.; Wang, H.; Wang, Z.; Guo, W.; Ngo, H.H. Advancements in Swine Wastewater Treatment: Removal Mechanisms, Influential Factors, and Optimization Strategies. *J. Water Process. Eng.* **2023**, *54*, 103986. [CrossRef]
5. Deng, L.; Zheng, D.; Zhang, J.; Yang, H.; Wang, L.; Wang, W.; He, T.; Zhang, Y. Treatment and Utilization of Swine Wastewater—A Review On Technologies in Full-Scale Application. *Sci. Total Environ.* **2023**, *880*, 163223. [CrossRef] [PubMed]
6. García, D.; Posadas, E.; Grajeda, C.; Blanco, S.; Martínez-Páramo, S.; Acién, G.; García-Encina, P.; Bolado, S.; Muñoz, R. Comparative Evaluation of Swine Wastewater Treatment in Algal-Bacterial Photobioreactors Under Indoor and Outdoor Conditions. *Bioresour. Technol.* **2017**, *245*, 483–490. [CrossRef] [PubMed]
7. Sun, L.; Zhao, H.; Liu, J.; Li, B.; Chang, Y.; Yao, D. A New Green Model for the Bioremediation and Resource Utilization of Livestock Wastewater. *Int. J. Environ.* **2021**, *18*, 8634. [CrossRef] [PubMed]
8. Zhao, W.; Fan, Z.Z.; Yang, X.P. Removal of Characteristic Pollutants in Livestock Wastewater by Horizontal Subsurface Flow Constructed Wetlands. *Environ. Sci.* **2021**, *42*, 5865–5875.
9. Danner, M.; Robertson, A.; Behrends, V.; Reiss, J. Antibiotic Pollution in Surface Fresh Waters: Occurrence and Effects. *Sci. Total Environ.* **2019**, *664*, 793–804. [CrossRef] [PubMed]

10. Li, J.; Yang, W.; Liu, L.; Liu, X.; Qiu, F.; Ma, X. Development and Environmental Impacts of China's Livestock and Poultry Breeding. *J. Clean. Prod.* **2022**, *371*, 133586. [CrossRef]
11. Vaishnav, S.; Saini, T.; Chauhan, A.; Gaur, G.K.; Tiwari, R.; Dutt, T.; Tarafdar, A. Livestock and Poultry Farm Wastewater Treatment and its Valorization for Generating Value-Added Products: Recent Updates and Way Forward. *Bioresour. Technol.* **2023**, *382*, 129170. [CrossRef]
12. Zhang, J.; Han, Z.; Zheng, D.; Wang, W.; Deng, L. Technical Status and Trends in Animal Wastewater Treatment. *J. Agro-Environ. Sci.* **2021**, *40*, 2320–2329.
13. Hu, H.; Li, X.; Wu, S.; Yang, C. Sustainable Livestock Wastewater Treatment Via Phytoremediation: Current Status and Future Perspectives. *Bioresour. Technol.* **2020**, *315*, 123809. [CrossRef]
14. Wang, Y.; Han, M.; Jia, T.; Hu, X.; Zhu, H.; Tong, Z.; Lin, Y.; Wang, C.; Liu, D.; Peng, Y.; et al. Emissions, Measurement, and Control of Odor in Livestock Farms: A Review. *Sci. Total Environ.* **2021**, *776*, 145735. [CrossRef]
15. López-Sánchez, A.; Silva-Gálvez, A.L.; Aguilar-Juárez, Ó.; Senés-Guerrero, C.; Orozco-Nunnelly, D.A.; Carrillo-Nieves, D.; Gradilla-Hernández, M.S. Microalgae-Based Livestock Wastewater Treatment (Mbwt) as a Circular Bioeconomy Approach: Enhancement of Biomass Productivity, Pollutant Removal and High-Value Compound Production. *J. Environ. Manag.* **2022**, *308*, 114612. [CrossRef] [PubMed]
16. Lourinho, G.; Rodrigues, L.F.T.G.; Brito, P.S.D. Recent Advances on Anaerobic Digestion of Swine Wastewater. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 4917–4938. [CrossRef]
17. Zhang, N.; Liu, W.; Peng, Y.; Song, X. Anaerobic Membrane Bioreactors for Livestock Wastewater Treatment and Resource Recovery: Opportunities and Challenges. *Curr. Pollut. Rep.* **2021**, *7*, 277–285. [CrossRef]
18. Ibekwe, A.M.; Bhattacharjee, A.S.; Phan, D.; Ashworth, D.; Schmidt, M.P.; Murinda, S.E.; Obayiuwana, A.; Murry, M.A.; Schwartz, G.; Lundquist, T.; et al. Potential Reservoirs of Antimicrobial Resistance in Livestock Waste and Treated Wastewater that Can be Disseminated to Agricultural Land. *Sci. Total Environ.* **2023**, *872*, 162194. [CrossRef] [PubMed]
19. Liu, C.; Feng, C.; Duan, Y.; Wang, P.; Peng, C.; Li, Z.; Yu, L.; Liu, M.; Wang, F. Ecological Risk Under the Dual Threat of Heavy Metals and Antibiotic Resistant Escherichia Coli in Swine-Farming Wastewater in Shandong Province, China. *Environ. Pollut.* **2023**, *319*, 120998. [CrossRef]
20. Wu, D.; Sui, Q.; Mei, X.; Yu, X.; Gu, Y.; Zhao, W. Non-Antibiotics Matter: Evidence from a One-Year Investigation of Livestock Wastewater from Six Farms in East China. *Sci. Total Environ.* **2022**, *846*, 157418. [CrossRef]
21. Cheng, D.L.; Ngo, H.H.; Guo, W.S.; Chang, S.W.; Nguyen, D.D.; Kumar, S.M. Microalgae Biomass from Swine Wastewater and its Conversion to Bioenergy. *Bioresour. Technol.* **2019**, *275*, 109–122. [CrossRef] [PubMed]
22. Pan, Z.; Dai, R.; Liao, J.; Lin, J.; Hong, Y.; Ling, J.; Xu, Y.; Li, Y.; Peng, J. Spontaneous Formation and Mechanism of Anaerobic Ammonium Oxidation (Anammox) Bacteria in Swine Wastewater Treatment System. *Int. Biodeterior. Biodegrad.* **2020**, *154*, 105058. [CrossRef]
23. Sun, H.; Wu, S.; Feng, S.; Jiang, C.; Wang, R.; Xu, S.; Cui, L.; Zhuang, X. Impact of Influent Strengths on Nitrous Oxide Emission and its Molecular Mechanism in Constructed Wetlands Treating Swine Wastewater. *Environ. Res.* **2022**, *210*, 112957. [CrossRef]
24. Zalewska, M.; Błażejewska, A.; Czapko, A.; Popowska, M. Antibiotics and Antibiotic Resistance Genes in Animal Manure—Consequences of its Application in Agriculture. *Front. Microbiol.* **2021**, *12*, 610656. [CrossRef]
25. Ramírez-Islas, M.E.; Güereca, L.P.; Sosa-Rodriguez, F.S.; Cobos-Peralta, M.A. Environmental Assessment of Energy Production from Anaerobic Digestion of Pig Manure at Medium-Scale Using Life Cycle Assessment. *Waste Manag.* **2020**, *102*, 85–96. [CrossRef]
26. He, L.; He, L.; Liu, Y.; Zhang, M.; Zhao, J.; Zhang, Q.; Ying, G. Microbial Diversity and Antibiotic Resistome in Swine Farm Environments. *Sci. Total Environ.* **2019**, *685*, 197–207. [CrossRef]
27. Semedo, M.; Song, B. Sediment Metagenomics Reveals the Impacts of Poultry Industry Wastewater on Antibiotic Resistance and Nitrogen Cycling Genes in Tidal Creek Ecosystems. *Sci. Total Environ.* **2023**, *857*, 159496. [CrossRef] [PubMed]
28. Fan, D.; Mao, Y.; Xu, L.; Wang, W. Effects of Livestock and Poultry Breeding Pollution on Health Risks: Evidence from a Hog Breeding Case in Rural China. *Chin. J. Popul. Resour. Environ.* **2020**, *18*, 342–349. [CrossRef]
29. Phoon, B.L.; Ong, C.C.; Mohamed Saheed, M.S.; Show, P.; Chang, J.; Ling, T.C.; Lam, S.S.; Juan, J.C. Conventional and Emerging Technologies for Removal of Antibiotics from Wastewater. *J. Hazard. Mater.* **2020**, *400*, 122961. [CrossRef]
30. Rizzioli, F.; Bertasini, D.; Bolzonella, D.; Frison, N.; Battista, F. A Critical Review on the Techno-Economic Feasibility of Nutrients Recovery from Anaerobic Digestate in the Agricultural Sector. *Sep. Purif. Technol.* **2023**, *306*, 122690. [CrossRef]
31. Song, Y.; Wang, G.; Li, R.; Chen, G. Research Progress of Biogas Slurry Treatment and Resource Utilization. *Trans. Chin. Soc. Agric. Eng.* **2021**, *37*, 237–250.
32. González-García, I.; Riaño, B.; Cuéllar-Franca, R.M.; Molinuevo-Salces, B.; García-González, M.C. Environmental Sustainability Performance of a Membrane-Based Technology for Livestock Wastewater Treatment with Nutrient Recovery. *J. Environ.* **2022**, *10*, 107246. [CrossRef]
33. He, Y.; Ifthikar, J.; Yang, L.; Chen, Z. Simultaneous Elimination of Vanadium(V) and Sulfamethoxazole from Livestock Wastewater with Nitrogen-Impregnated Biochar. *J. Environ.* **2023**, *11*, 111105. [CrossRef]
34. Zhao, H.; Wang, Z.; Liang, Y.; Wu, T.; Chen, Y.; Yan, J.; Zhu, Y.; Ding, D. Adsorptive Decontamination of Antibiotics from Livestock Wastewater by Using Alkaline-Modified Biochar. *Environ. Res.* **2023**, *226*, 115676. [CrossRef]
35. Zhao, X.; Zhang, T.; Meng, X.; Ma, X.; Zhang, S.; Jin, M.; Li, C. Research on Resource Utilization and Energy Utilization of Livestock and Poultry Wastewater-Taking Swine Wastewater as an Example. *J. Northeast Agric. Univ.* **2023**, *54*, 88–96.

36. Wu, H.; Vaneeckhaute, C. Nutrient Recovery from Wastewater: A Review on the Integrated Physicochemical Technologies of Ammonia Stripping, Adsorption and Struvite Precipitation. *Chem. Eng. J.* **2022**, *433*, 133664. [CrossRef]
37. Reza, A.; Chen, L. Electrochemical Treatment of Livestock Waste Streams. A Review. *Environ. Chem. Lett.* **2022**, *20*, 1863–1895. [CrossRef]
38. Yang, H.; Zheng, X. Application and Research Progress of Advanced Oxidation Process for Degradation of Organic Pollutants. *Technol. Water Treat.* **2021**, *47*, 13–18.
39. Qian, M.; Yang, L.; Chen, X.; Li, K.; Xue, W.; Li, Y.; Zhao, H.; Cao, G.; Guan, X.; Shen, G. The Treatment of Veterinary Antibiotics in Swine Wastewater by Biodegradation and Fenton-Like Oxidation. *Sci. Total Environ.* **2020**, *710*, 136299. [CrossRef] [PubMed]
40. Wang, H.; Zhang, J.; Yuan, X.; Jiang, L.; Xia, Q.; Chen, H. Photocatalytic Removal of Antibiotics from Natural Water Matrices and Swine Wastewater Via Cu(I) Coordinately Polymeric Carbon Nitride Framework. *Chem. Eng. J.* **2020**, *392*, 123638. [CrossRef]
41. Garcia, B.B.; Lourinho, G.; Romano, P.; Brito, P.S.D. Photocatalytic Degradation of Swine Wastewater on Aqueous TiO_2 Suspensions: Optimization and Modeling Via Box-Behnken Design. *Heliyon* **2020**, *6*, e03293. [CrossRef] [PubMed]
42. Wu, S.; Li, H.; Li, X.; He, H.; Yang, C. Performances and Mechanisms of Efficient Degradation of Atrazine Using Peroxymonosulfate and Ferrate as Oxidants. *Chem. Eng. J.* **2018**, *353*, 533–541. [CrossRef]
43. Zheng, T.; Li, P.; Ma, X.; Sun, X.; Wu, C.; Wang, Q.; Gao, M. Pilot-Scale Multi-Level Biological Contact Oxidation System On the Treatment of High Concentration Poultry Manure Wastewater. *Process Saf. Environ. Prot.* **2018**, *120*, 187–194. [CrossRef]
44. Chen, X.C.; Chen, B.; Xiao, L.; Fukushi, K.; Zhang, J.; Niu, J.; Xu, K. Optimisation of an Original CO_2-Enhanced Natural Treatment System for Reclaiming and Reusing Anaerobically Digested Strong Wastewater from Animal Breeding Industry. *J. Clean. Prod.* **2021**, *291*, 125946. [CrossRef]
45. Khalil, M.; Berawi, M.A.; Heryanto, R.; Rizalie, A. Waste to Energy Technology: The Potential of Sustainable Biogas Production from Animal Waste in Indonesia. *Renew. Sustain. Energ. Rev.* **2019**, *105*, 323–331. [CrossRef]
46. Thao, N.T.P.; Nga, N.T.T.; Kim, H.T.T.; Kien, T.T.; Hieu, T.T.; Thang, N.V.; Tri, N.L.M.; Le, T.H. Combination of Biochar Filtration and Ozonation Processes in Livestock Wastewater Treatment and Application for Soil Cultivation. *Case Stud. Chem. Environ. Eng.* **2023**, *7*, 100286. [CrossRef]
47. Zhang, M.; Liu, Y.; Zhao, J.; Liu, W.; Chen, J.; Zhang, Q.; He, L.; Ying, G. Variations of Antibiotic Resistome in Swine Wastewater during Full-Scale Anaerobic Digestion Treatment. *Environ. Int.* **2021**, *155*, 106694. [CrossRef]
48. Chen, H.; Yuan, J.; Xu, Q.; Yang, E.; Yang, T.; Shi, L.; Liu, Z.; Yu, H.; Cao, J.; Zhou, Q.; et al. Swine Wastewater Treatment Using Combined Up-Flow Anaerobic Sludge Blanket and Anaerobic Membrane Bioreactor: Performance and Microbial Community Diversity. *Bioresour. Technol.* **2023**, *373*, 128606. [CrossRef]
49. Zhou, Q.; Li, X.; Wu, S.; Zhong, Y.; Yang, C. Enhanced Strategies for Antibiotic Removal from Swine Wastewater in Anaerobic Digestion. *Trends Biotechnol.* **2021**, *39*, 8–11. [CrossRef]
50. Li, Y.; Pan, Z.; Liao, J.; Dai, R.; Lin, J.; Ling, J.; Xu, Y. Micro-Aeration and Low Influent C/N are Key Environmental Factors for Achieving Anammox in Livestock Farming Wastewater Treatment Plants. *Water Res.* **2023**, *253*, 120141. [CrossRef] [PubMed]
51. Nagarajan, D.; Kusmayadi, A.; Yen, H.; Dong, C.; Lee, D.; Chang, J. Current Advances in Biological Swine Wastewater Treatment Using Microalgae-Based Processes. *Bioresour. Technol.* **2019**, *289*, 121718. [CrossRef] [PubMed]
52. Brienza, C.; Donoso, N.; Luo, H.; Vingerhoets, R.; de Wilde, D.; van Oirschot, D.; Sigurnjak, I.; Biswas, J.K.; Michels, E.; Meers, E. Evaluation of a New Approach for Swine Wastewater Valorisation and Treatment: A Combined System of Ammonium Recovery and Aerated Constructed Wetland. *Ecol. Eng.* **2023**, *189*, 106919. [CrossRef]
53. Bôto, M.L.; Dias, S.M.; Crespo, R.D.; Mucha, A.P.; Almeida, C.M.R. Removing Chemical and Biological Pollutants from Swine Wastewater through Constructed Wetlands Aiming Reclaimed Water Reuse. *J. Environ. Manag.* **2023**, *326*, 116642. [CrossRef] [PubMed]
54. Li, S.; Qu, W.; Chang, H.; Li, J.; Ho, S. Microalgae-Driven Swine Wastewater Biotreatment: Nutrient Recovery, Key Microbial Community and Current Challenges. *J. Hazard. Mater.* **2022**, *440*, 129785. [CrossRef]
55. Chen, B.; Zhu, Y.; Wang, K.; Xiao, Y.; Huang, J.; Zhang, J.; Zhang, X.; Chen, X. Research Progress on the Mechanisms and Influencing Factors for the Microalgae-Bacteria Symbiosis System for Treating Biogas Slurry from Livestock and Poultry Industry. *Trans. Chin. Soc. Agric. Eng.* **2023**, *39*, 14–24.
56. Chen, C.; Kuo, E.; Nagarajan, D.; Ho, S.; Dong, C.; Lee, D.; Chang, J. Cultivating Chlorella Sorokiniana Ak-1 with Swine Wastewater for Simultaneous Wastewater Treatment and Algal Biomass Production. *Bioresour. Technol.* **2020**, *302*, 122814. [CrossRef]
57. Yu, F.; Li, Y.; Han, S.; Ma, J. Adsorptive Removal of Antibiotics from Aqueous Solution Using Carbon Materials. *Chemosphere* **2016**, *153*, 365–385. [CrossRef]
58. Dai, C.; Wang, F. Potential Applications of Microalgae–Bacteria Consortia in Wastewater Treatment and Biorefinery. *Bioresour. Technol.* **2024**, *393*, 130019. [CrossRef] [PubMed]