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Research Progress on Algal-Bacterial Symbiotic Systems for the Treatment of Livestock Wastewater

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Abstract: Livestock wastewater is characterized by high organic loading, elevated concentrations of ammonia nitrogen and phosphorus, high suspended solids, and the coexistence of antibiotics, heavy metals, antibiotic resistance genes, and other emerging contaminants. Improper treatment may lead to eutrophication, ecological toxicity, and the dissemination of antimicrobial resistance in aquatic environments. Algal-bacterial symbiotic systems couple organic matter degradation, nitrogen and phosphorus transformation, pollutant adsorption and immobilization, and biomass valorization through the synergistic interaction between microalgal photosynthesis and bacterial heterotrophic metabolism, providing a promising pathway for low-carbon treatment and nutrient recovery from livestock wastewater. This review systematically summarizes the major pollution characteristics of livestock wastewater and the applicability of algal-bacterial systems, and discusses the key mechanisms involved in algal-bacterial symbiosis, including oxygen-carbon dioxide exchange, nutritional complementarity, extracellular polymeric substance-mediated floc formation, and nitrogen transformation driven by aerobic-anoxic microzones. Furthermore, recent progress in the removal of organic matter, nitrogen, phosphorus, antibiotics, antibiotic resistance genes, heavy metals, persistent organic pollutants, microplastics, and other emerging contaminants by algal-bacterial systems is reviewed. The treatment performance of algal-bacterial systems is mainly influenced by algal species and bacterial community composition, algal-bacterial inoculation ratio, light conditions, pH, temperature, dissolved oxygen, wastewater pretreatment, and pollutant loading. Future studies should focus on long-term operation under real livestock wastewater conditions, regulation of algal-bacterial communities, clarification of pollutant migration and transformation among the aqueous phase, biomass, and sediments, and the establishment of safe biomass valorization and comprehensive environmental benefit assessment frameworks. These efforts will promote the transition of livestock wastewater treatment from pollution reduction toward resource recycling.

Keywords: Algal-bacterial symbiosis, livestock wastewater, nitrogen and phosphorus recovery, heavy metals, emerging contaminants.

1. Introduction

With the increasing scale and intensification of livestock production, wastewater discharge from animal farming continues to increase and has become an important component of agricultural water pollution. Compared with domestic sewage, livestock wastewater not only has a high pollution load but also exhibits a clear resource attribute. Approximately 24 billion tons of nutrient-rich livestock wastewater are generated globally each year, in which organic carbon, nitrogen, and phosphorus are both major contributors to water pollution and eutrophication and potential nutrient resources that can be recovered through biotransformation and resource-oriented utilization [1]. However, the complexity of livestock wastewater is not limited to conventional pollutants. This type of wastewater often contains high concentrations of organic matter, ammonia nitrogen, phosphorus, and suspended solids, together with inhibitory components such as high salinity, high turbidity, antibiotics, and heavy metals, resulting in typical composite pollution characteristics [2]. Taking piggery wastewater as an example, effluents released during pork production contain nitrogen, phosphorus, organic matter, and metals simultaneously, indicating that livestock wastewater treatment should not target a single pollution indicator but should address the synergistic reduction of multiple pollutant loads [3]. In addition, the use of antibiotics in livestock production may make wastewater a reservoir and transmission medium for antibiotic resistance genes; if insufficiently treated, it may increase the risk of antimicrobial resistance dissemination in aquatic environments [4]. Therefore, the treatment goal of livestock wastewater has gradually shifted from conventional reductions in COD, nitrogen, and phosphorus toward integrated management that considers nutrient recovery, emerging contaminant control, and environmental risk reduction.

Existing technologies for livestock wastewater treatment mainly include solid-liquid separation, anaerobic digestion, aerobic biological treatment, chemical precipitation, adsorption, and ecological treatment. These technologies play important roles in reducing organic loads, removing suspended solids, and improving effluent quality. Anaerobic digestion can effectively transform organic matter in livestock wastewater and produce biogas, representing an important pathway for energy recovery from organic waste; however, its effluent still contains relatively high concentrations of nitrogen and phosphorus, which require further recovery or advanced removal [1]. Aerobic biological treatment can promote organic matter oxidation and nitrogen transformation, but its operation generally relies on external aeration, and aeration is a major contributor to energy consumption in wastewater treatment systems [5]. Chemical precipitation and adsorption can be used for the removal of phosphorus, heavy metals, and some organic pollutants, but further improvement is needed in terms of nutrient recycling and by-product valorization [1]. As the goal of livestock wastewater management shifts from pollutant removal to resource recovery and composite pollution risk control, increasing attention has been given to biological treatment systems capable of simultaneously achieving organic matter transformation, nitrogen and phosphorus recovery, and emerging contaminant reduction. Microalgae and algal-bacterial symbiotic systems can participate in pollutant removal through photosynthesis, nutrient assimilation, extracellular adsorption, biotransformation, and light-related reactions, while converting nitrogen, phosphorus, and organic carbon in wastewater into usable biomass [4]. Studies on antibiotic removal from swine manure wastewater further show that algal-bacterial systems can remove veterinary antibiotics through adsorption, biodegradation, and phototransformation, demonstrating their potential for treating complex pollution in livestock wastewater [6]. Therefore, developing algal-bacterial symbiotic systems is conducive not only to improving resource recovery efficiency during livestock wastewater treatment but also to advancing low-carbon treatment and circular utilization of animal farming wastewater.

Algal-bacterial symbiotic systems provide a biological pathway for livestock wastewater treatment that integrates pollution reduction, nutrient recovery, and biomass valorization. Unlike conventional aerobic treatment processes that depend on external aeration, algal-bacterial systems use the metabolic complementarity between microalgal photosynthetic oxygen production and bacterial heterotrophic degradation to promote organic matter oxidation and biomass formation, thereby reducing dependence on external oxygen supply to some extent [7]. In this process, microalgae assimilate nitrogen and phosphorus from wastewater while absorbing CO_2 and releasing O_2 through photosynthesis; bacteria decompose complex organic matter and release inorganic carbon, small-molecule organics, and growth-promoting substances, thereby providing favorable conditions for microalgal growth and nutrient transformation [8]. This symbiotic relationship, based on material exchange and metabolic feedback, enables algal-bacterial systems to remove conventional pollutants such as COD, ammonia nitrogen, total nitrogen, and total phosphorus, while also promoting the reduction of some emerging contaminants through adsorption, biodegradation, phototransformation, and cometabolism [9]. Studies using real piggery wastewater have shown that microalgae-bacteria systems can simultaneously remove nitrogen, phosphorus, organic matter, and some metal pollutants, highlighting their applicability to composite pollution control in livestock wastewater [3]. In addition, algal-bacterial systems show advantages in the treatment of antibiotics in livestock and aquaculture wastewater, with removal mechanisms involving extracellular adsorption, cellular uptake, photodegradation, biodegradation, and cometabolism [10]. This review systematically discusses the pollution characteristics of livestock wastewater, algal-bacterial symbiotic mechanisms, progress in pollutant removal, key influencing factors, and future perspectives, aiming to provide a reference for low-carbon treatment, nutrient recycling, and composite pollution risk control in livestock wastewater management.

2. Characteristics of Livestock Wastewater and Its Compatibility with Algal-Bacterial Treatment

2.1. Main Characteristics of Livestock Wastewater

Livestock wastewater has complex sources, including feces and urine discharge, barn washing water, feed residues, farm runoff, slaughterhouse and meat-processing wastewater, and anaerobic digestion effluent. Wastewaters from different sources vary in the composition of organic matter, nitrogen, phosphorus, and suspended solids, but they generally show high pollution loads and nutrient enrichment. For example, meat-processing and slaughterhouse wastewater is rich in recoverable nutrients and can support nitrogen and phosphorus uptake and biomass production through microalgal cultivation, indicating that livestock-related wastewater is not only a pollution carrier but also a potential nutrient resource [11]. Anaerobically treated slaughterhouse wastewater still contains residual organic matter, nitrogen, and phosphorus that can be utilized by microalgae and can support the growth of Chlorella, Scenedesmus, and their co-cultures [12].

In terms of water quality, livestock wastewater is typically characterized by high COD, high ammonia nitrogen, high total phosphorus, and high suspended solids. Nitrogen in piggery wastewater and pig manure digestate is mainly present as ammonium, which can serve as a preferred nitrogen source for microalgae after appropriate dilution. In pig manure liquid digestate cultivation, when NH3 concentrations were controlled at relatively low levels, microalgae such as Chlorella vulgaris and Isochrysis galbana reached high cell densities within 3-7 days, indicating that nitrogen, phosphorus, and trace elements in pig manure digestate can support algal growth [13]. In dairy lagoon wastewater, Chlorella sp. can grow mixotrophically under different dilution ratios and simultaneously remove ammonium, nitrate, and phosphate, indicating that dairy wastewater also has potential for nutrient recovery [14].

In addition to conventional nutrients, livestock wastewater exhibits composite pollution characteristics. Veterinary antibiotics, disinfectants, and metallic elements from feed additives can enter the wastewater with feces and urine, creating combined risks associated with organic pollution, nutrient pollution, and trace contaminants. Studies on swine manure wastewater have focused on the removal of veterinary antibiotics such as tetracycline, ciprofloxacin, and sulfadiazine, indicating that antibiotic residues have become an important indicator for evaluating treatment performance [10]. In high-rate algal ponds treating piggery effluent, variations in zinc concentration affected micropollutant removal by microalgal systems, suggesting that metals are not only water quality constituents but may also influence subsequent biological treatment processes [15]. Therefore, livestock wastewater should be understood as a composite pollution system rather than merely a matrix with excessive COD, nitrogen, and phosphorus.

2.2. Applicability of Algal-Bacterial Systems for Livestock Wastewater Treatment

Livestock wastewater is rich in nitrogen, phosphorus, organic carbon, and trace elements that can be utilized by microalgae and bacteria; therefore, it can serve as a nutrient matrix for algal-bacterial growth and pollutant transformation [16]. Microalgae can assimilate inorganic nutrients such as NH_4^+, NO_3^-, and PO_4^{3-} and convert them into cellular components, including proteins, chlorophyll, nucleic acids, and lipids, thereby linking wastewater purification with biomass production [17]. Bacteria can release CO_2, low-molecular-weight organic compounds, and inorganic nutrients through organic matter hydrolysis, mineralization, and respiration, providing substrates for microalgal photosynthesis and cellular synthesis [18]. This nutritional complementarity enables algal-bacterial systems to participate simultaneously in COD reduction, nitrogen and phosphorus transformation, and biomass accumulation, making them suitable for the treatment and recovery of nutrient-rich livestock wastewater [19].

From the perspective of real wastewater applications, algal-bacterial systems show good adaptability to piggery wastewater, anaerobic digestion effluent, and mixed livestock wastewater [20]. In piggery wastewater, *Chlorella vulgaris* cultured in a membrane photobioreactor can continuously remove NH_4^+, PO_4^{3-}, and COD, indicating that microalgal systems can utilize nutrients in piggery wastewater and improve effluent quality [16]. Farm-scale studies have demonstrated that algal-bacterial consortia can be applied to piggery wastewater treatment while providing value for pollutant reduction and techno-economic evaluation, supporting their potential translation into practical application scenarios [21]. Wastewater-derived algal-bacterial communities can still treat real wastewater under short hydraulic retention times, indicating the feasibility of constructing algal-bacterial systems using microorganisms originating from the wastewater itself [18].

The applicability of algal-bacterial systems is also reflected in their consistency with resource-oriented utilization goals. Nitrogen, phosphorus, and organic carbon in livestock wastewater can be incorporated into algal-bacterial biomass, which can subsequently be used for anaerobic digestion, fertilizer production, biofuel generation, or other bio-based products depending on biomass composition [22]. The cultivation of *Chlorella vulgaris* JSC-6 in swine wastewater showed that microalgal treatment not only reduced COD and nutrient levels but also produced carbohydrate-rich biomass, providing a potential feedstock for fermentation products or energy recovery [23]. Therefore, the advantage of algal-bacterial systems for livestock wastewater treatment lies not only in pollutant removal, but also in their capacity to convert wastewater nutrients into harvestable and further utilizable biomass resources [24].

2.3. Limiting Factors in Real Wastewater

The composition of real livestock wastewater is strongly affected by animal type, manure collection method, washing water volume, anaerobic digestion conditions, and seasonal variation; therefore, suitability assessment based on ammonia nitrogen, organic matter, turbidity, and salinity is required before introducing wastewater into algal-bacterial systems [1]. High ammonia nitrogen is one of the most typical limiting factors in piggery wastewater and anaerobic piggery digestate, because excessive NH_3/NH_4^+ concentrations can inhibit microalgal growth and reduce nutrient transformation efficiency [25]. High COD and particulate organic matter can intensify heterotrophic bacterial competition and oxygen consumption, requiring algal-bacterial systems to maintain a balance among organic loading, photosynthetic oxygen supply, and bacterial degradation [26]. High color and suspended solids reduce light penetration and restrict microalgal photosynthesis and O_2 release, making transparency improvement an important regulation strategy before high-strength livestock wastewater enters algal-bacterial systems [27].

Pretreatment and loading regulation are key steps for improving the compatibility of real wastewater. For undiluted piggery wastewater, stepwise treatment can reduce the inhibitory effects of high ammonia nitrogen and high COD on microalgae, allowing ammonia-tolerant microalgae to progressively achieve organic matter and nutrient removal [26]. Integrated ammonia stripping and flocculation pretreatment can reduce NH_4^+-N, turbidity, and part of the organic load in anaerobic digestion piggery effluent, thereby creating more suitable conditions for subsequent microalgal cultivation and nutrient recovery [28]. Pretreatment methods such as electrocoagulation, ammonia stripping, photo-Fenton oxidation, and constructed wetlands can reduce ammonia and organic toxicity in piggery wastewater, thereby decreasing dependence on large volumes of freshwater dilution [27]. Ozonation pretreatment can reduce the color of digested swine manure and improve photosynthetic oxygen production, indicating that oxidative pretreatment can alleviate light-utilization limitations caused by dark-colored wastewater [29].

Native microorganisms and complex pollutants in real wastewater also affect the performance of algal-bacterial systems. Indigenous bacteria in non-sterile wastewater can participate in organic matter degradation, nitrogen transformation, and floc formation; therefore, their role should be regarded as part of algal-bacterial system construction rather than merely as external interference [30]. Veterinary drugs, metal elements, and other micropollutants may alter microbial community structures and pollutant migration pathways; thus, real wastewater evaluation should consider not only aqueous-phase reduction but also biomass enrichment and potential ecological risks [31]. Overall, the limiting factors in real wastewater do not weaken the applicability of algal-bacterial systems, but indicate that stable pollutant transformation and resource recovery require wastewater pretreatment, loading matching, algal-bacterial acclimation, and optimization of operating parameters [32].

3. Synergistic Mechanisms of Algal-Bacterial Symbiotic Systems

Algal-bacterial symbiotic systems are not simple mixtures of microalgae and bacteria, but complex biological systems formed by photosynthetic autotrophic metabolism, heterotrophic degradation metabolism, nutrient transformation, and extracellular polymeric substance-mediated spatial structures. In livestock wastewater treatment, microalgae, bacteria, and wastewater pollutants interact through multiple material exchange pathways, including O_2 and CO_2 exchange, nitrogen and phosphorus uptake and transformation, release and utilization of dissolved organic matter and growth-promoting substances, and aerobic-anoxic microenvironments within algal-bacterial flocs. Existing studies have shown that algal-bacterial systems can couple wastewater pollutant removal with resource transformation through microalgal photosynthetic oxygen production, bacterial organic matter degradation, nitrogen transformation, and biomass formation.

3.1. Oxygen-Carbon Dioxide Exchange Mechanism

Oxygen-carbon dioxide exchange is the most fundamental metabolic interaction in algal-bacterial symbiotic systems. Under illumination, microalgae carry out photosynthesis, absorb CO_2, and release O_2; bacteria use the O_2 released by microalgae to oxidize organic matter in wastewater and generate CO_2 through respiration and organic matter mineralization, thereby providing an inorganic carbon source for microalgal photosynthesis. This gas exchange links microalgal photosynthetic autotrophy with bacterial heterotrophic degradation, allowing algal-bacterial systems to maintain organic matter oxidation and nutrient transformation under reduced external aeration [5]. The exchange of O_2, CO_2, and NH_4^+ in microalgae-bacteria consortia is a key basis for their application in wastewater treatment and resource recovery, in which bacteria oxidize organic carbon to CO_2 and microalgae subsequently assimilate CO_2 into cellular biomass, forming a carbon transformation cycle [33].

Livestock wastewater contains abundant organic matter that can be utilized by bacteria, whereas conventional aerobic degradation usually relies on mechanical aeration. In algal-bacterial systems, microalgal photosynthesis can provide oxygen for bacterial organic matter degradation and ammonia oxidation, thereby enhancing organic matter oxidation and nitrogen transformation. Studies on enhanced nitrogen removal by microalgae-bacteria symbiosis show that microalgal oxygen production can support nitrification, while internal organic carbon can serve as an electron donor for denitrification, indicating that gas exchange is closely linked to nitrogen removal [34]. Meanwhile, CO_2 released by bacteria can alleviate inorganic carbon limitation during microalgal cultivation and improve microalgal biomass accumulation and nitrogen and phosphorus assimilation [35].

In addition, microalgae can fix part of the CO_2 into biomass, while bacteria convert wastewater organic carbon into inorganic carbon and small-molecule substrates that are available to microalgae, creating multiple carbon transformation pathways within the system. Algal-bacterial consortia can be used not only for wastewater treatment but also for carbon fixation and resource recovery, thereby reducing the carbon emission pressure of treatment systems [36]. Therefore, O_2-CO_2 exchange is not only the basis for algal-bacterial symbiosis but also an important mechanism that differentiates algal-bacterial systems from conventional heterotrophic biological treatment.

3.2. Nutritional Complementarity and Metabolic Interactions

Microalgae can directly absorb inorganic nutrients such as NH_4^+, NO_3^-, NO_2^-, and $PO_4{}^{3-}$ and assimilate them into proteins, chlorophyll, nucleic acids, and phospholipids, whereas bacteria decompose complex organic matter in wastewater through hydrolysis, acidification, and mineralization, releasing small organic acids, amino acids, CO_2, and inorganic nutrients that facilitate microalgal uptake [19, 37]. In livestock wastewater, large amounts of particulate organic matter and colloids are difficult for microalgae to use directly, while bacterial decomposition can convert them into substances that more readily participate in algal-bacterial metabolic cycles, thereby improving the utilization efficiency of organic carbon and nutrients. In addition to basic nutrient exchange, bacteria can influence microalgal growth by secreting vitamins, siderophores, phytohormone-like compounds, and extracellular enzymes. Many microalgae require micronutrients such as vitamin B12 and iron, and associated bacteria can enhance microalgal nutrient acquisition through metabolite supply or by promoting metal solubilization [38, 39]. Therefore, microalgae-bacteria interactions involve the exchange of inorganic carbon, organic carbon, oxygen, vitamins, and signaling molecules, which collectively influence microalgal growth, pollutant removal, and energy recovery.

Microalgae can also influence bacterial community structures through the release of dissolved organic matter. During growth, microalgae release polysaccharides, amino acids, organic acids, and other extracellular metabolites that can be utilized by heterotrophic bacteria and promote the enrichment of specific bacterial taxa [40, 41]. Nutritional feedback and extracellular product exchange in algal-bacterial consortia are important for maintaining symbiotic relationships and can promote the conversion of wastewater pollutants into resources such as biofuels, biofertilizers, and animal feed [42]. In livestock wastewater treatment, such metabolic interactions help transform organic matter, nitrogen, and phosphorus in the influent into algal-bacterial biomass, thereby achieving the dual goals of pollutant reduction and nutrient recovery.

3.3. Extracellular Polymeric Substances and Algal-Bacterial Floc Formation

Extracellular polymeric substances are important media for the formation of spatially stable algal-bacterial structures. Both microalgae and bacteria can secrete EPS, which mainly include polysaccharides, proteins, humic-like substances, nucleic acids, and lipids. These substances contain functional groups such as carboxyl, hydroxyl, amino, and phosphate groups, which can promote adhesion between algal and bacterial cells through electrostatic adsorption, hydrogen bonding, hydrophobic interactions, metal ion bridging, and complexation, thereby forming algal-bacterial flocs or biofilm structures [42, 43]. In livestock wastewater, EPS not only contribute to cell aggregation but also interact with suspended particles, organic pollutants, phosphate, and metal ions, influencing pollutant migration and immobilization.

Compared with dispersed suspended microalgal cells, floc structures have larger particle sizes and stronger settling ability, which can reduce the difficulty of subsequent algal biomass harvesting [7]. In microalgae-bacteria consortia, bacteria can promote microalgal flocculation and thereby improve biomass recovery efficiency, which is an important advantage of algal-bacterial systems for wastewater resource recovery. Studies on microalgal-bacterial biofilms also show that these biofilms improve cell retention and biomass collection while providing more complex microenvironments for pollutant transformation [43].

EPS also serve as important interfaces for pollutant removal. Protein, polysaccharide, and humic-like components in EPS can immobilize heavy metal ions through complexation or adsorption [44], and their functional groups can also interact with phosphate, antibiotics, and some hydrophobic organic compounds [45-47]. EPS-mediated interfacial interactions facilitate the transfer of pollutants from the aqueous phase to the biomass phase and create conditions for subsequent biodegradation or resource-oriented disposal. Thus, EPS are not only the “glue” that supports algal-bacterial structural formation but also a key reactive interface for multi-pollutant removal in algal-bacterial systems.

3.4. Aerobic-Anoxic Microzones and Nitrogen Transformation

Oxygen concentration gradients can form within algal-bacterial flocs, biofilms, and granular structures, enabling different nitrogen transformation processes to occur simultaneously in distinct spatial regions of the same biological aggregate [48]. Under illumination, microalgae-rich outer layers release O_2 through photosynthesis, forming aerobic microenvironments favorable for organic matter oxidation, ammonia oxidation, and nitrite oxidation [49]. Because oxygen diffusion into the interior is limited and heterotrophic bacteria continuously consume O_2, the inner zones of flocs or biofilms readily become low-oxygen or anoxic, providing spatial conditions for denitrification [50]. Such spatial stratification enables algal-bacterial systems to couple microalgal assimilation, bacterial nitrification, denitrification, and partial shortcut nitrogen transformation processes, thereby forming a multi-pathway nitrogen removal network [43].

During nitrogen transformation, microalgae can directly absorb NH_4^+, NO_3^-, and NO_2^- and convert them into nitrogen-containing cellular components such as proteins, chlorophyll, and nucleic acids [17]. Photosynthetic oxygen released by microalgae can support the activity of ammonia-oxidizing and nitrite-oxidizing bacteria, gradually converting NH_4^+-N into NO_2^--N or NO_3^--N [51]. In low-oxygen or anoxic regions, denitrifying bacteria can use residual organic carbon in wastewater or endogenous carbon released from decayed algal-bacterial biomass as electron donors to reduce NO_3^--N or NO_2^--N to N_2, thereby transferring nitrogen from the aqueous phase to the gas phase [52]. Therefore, nitrogen removal in algal-bacterial systems is not solely dependent on microalgal uptake but is jointly driven by assimilatory uptake, nitrification, denitrification, and biomass harvesting [53].

For livestock wastewater, the formation of aerobic-anoxic microzones can improve the diversity of nitrogen transformation pathways in high-ammonia wastewater. Livestock wastewater often contains high levels of NH_4^+-N and organic nitrogen; if nitrogen enters biomass mainly through microalgal assimilation, subsequent removal still depends on harvesting algal-bacterial biomass. Oxygen gradients formed inside algal-bacterial flocs or biofilms can further promote nitrification-denitrification processes, allowing nitrogen to be removed from the aqueous phase through both biomass fixation and gaseous conversion [34]. Therefore, aerobic-anoxic microzones are not incidental features of algal-bacterial systems but key mechanistic foundations linking microalgal photosynthesis, bacterial nitrogen metabolism, and high-nitrogen wastewater purification [54].

4. Research Progress in Pollutant Removal from Livestock Wastewater by Algal-Bacterial Systems

4.1. COD Removal

Organic matter in livestock wastewater mainly originates from feces and urine, feed residues, washing water, proteins, lipids, and volatile fatty acids. It is typically characterized by high COD and a substantial biodegradable organic load, making organic matter reduction a fundamental objective of algal-bacterial treatment of livestock wastewater [16]. In algal-bacterial systems, complex organic matter is primarily hydrolyzed, acidified, and oxidatively decomposed by heterotrophic bacteria, while microalgae release O_2 through photosynthesis to provide oxygen for bacterial organic matter degradation, forming a coupling between photosynthetic oxygen supply and heterotrophic degradation [18]. Pilot-scale piggery wastewater studies have demonstrated that algal-bacterial consortia can significantly reduce soluble COD and validate the applicability of this system for treating high-organic-load livestock wastewater at farm scale [21]. In anaerobically treated slaughterhouse wastewater, Chlorella, Scenedesmus, and their co-cultures can all reduce COD, with co-culture systems generally showing better organic matter removal and biomass accumulation [12]. In raw swine wastewater cultivation, appropriate supplementation with external carbon sources can promote microalgal growth and COD removal, indicating that the form and availability of organic carbon influence organic matter transformation efficiency in algal-bacterial systems [55].

4.2. Nitrogen Removal

Nitrogen in livestock wastewater mainly occurs as NH_4^+-N, organic nitrogen, and small amounts of NO_2^--N and NO_3^--N, among which NH_4^+-N is both a preferred nitrogen source for microalgae and an important loading parameter affecting system operation [13]. Microalgae can directly absorb NH_4^+, NO_3^-, and NO_2^- and convert them into nitrogen-containing cellular components such as proteins, chlorophyll, and nucleic acids; therefore, biomass harvesting is an important pathway for nitrogen removal in algal-bacterial systems [17]. Photosynthetic oxygen released by microalgae can support the activity of ammonia-oxidizing and nitrite-oxidizing bacteria, further converting NH_4^+-N into NO_2^--N or NO_3^--N and linking algal assimilation with bacterial nitrification [56]. Low-oxygen microzones formed inside algal-bacterial aggregates or biofilms can provide suitable environments for denitrifying bacteria to reduce NO_2^--N or NO_3^--N to N_2, thereby increasing nitrogen removal pathways from the aqueous phase [56]. In the cultivation of indigenous *Chlorella sorokiniana* using mixed domestic and livestock wastewater, appropriate adjustment of influent nutrient ratios promoted nitrogen removal and biomass accumulation, indicating that water quality composition is an important regulatory condition for improving nitrogen transformation efficiency [57].

4.3. Phosphorus Removal

Phosphorus in livestock wastewater mainly exists as orthophosphate, particulate phosphorus, and organic phosphorus, among which soluble phosphate can be directly absorbed by microalgae and used for ATP, nucleic acids, phospholipids, and polyphosphate granule synthesis [58]. Microalgal photosynthesis consumes CO_2 and can increase system pH, promoting phosphate precipitation with Ca^{2+} and Mg^{2+}; therefore, phosphorus removal in algal-bacterial systems generally involves both biological assimilation and chemical precipitation [59]. Mixotrophic cultivation of *Chlorella* sp. in dairy wastewater showed that algal growth can simultaneously remove ammonium, nitrate, and phosphate, converting part of these nutrients into usable biomass [14]. In anaerobically treated slaughterhouse wastewater, *Chlorella* and *Scenedesmus* co-cultures showed high removal capacity for total phosphorus and orthophosphate, indicating that algal co-cultures can be used for advanced purification of high-phosphorus livestock-related wastewater [11]. In algal-bacterial systems, functional groups such as carboxyl, hydroxyl, amino, and phosphate groups in EPS can further promote phosphate immobilization and particle settling through adsorption, complexation, and bridging [60].

4.4. Antibiotic Removal

Common antibiotics in livestock wastewater include tetracyclines, sulfonamides, fluoroquinolones, and macrolides, mainly originating from veterinary drug use, feed additives, and disease prevention and control [61]. Antibiotic removal by algal-bacterial systems is usually not a single biodegradation process but involves the combined effects of extracellular adsorption, cellular uptake, photodegradation, biotransformation, and cometabolism [62]. Pilot-scale photobioreactor studies on swine manure wastewater have shown that microalgae-bacteria consortia can remove not only organic matter and nutrients but also veterinary antibiotics such as tetracycline, ciprofloxacin, sulfadiazine, and sulfamethoxazole [10]. Comparative studies of open photobioreactors have shown that both microalgae-bacteria systems and purple phototrophic bacterial systems can remove various veterinary drugs from piggery wastewater, although removal efficiencies vary with hydraulic retention time, illumination, and pollutant properties [63]. Studies on algal-bacterial granular sludge show that microalgae can promote antibiotic removal and simultaneously decrease the abundance of some antibiotic-resistant bacteria and antibiotic resistance genes, suggesting the potential of algal-bacterial structures for coordinated antibiotic and ARG control [64]. Studies on sulfamethoxazole removal in algal-bacterial membrane-aerated biofilm reactors further demonstrate that antibiotic removal is accompanied by bacterial community responses and ARG changes; therefore, evaluations of antibiotic reduction should simultaneously consider target pollutants, microbial communities, and resistance risks [65].

4.5. Heavy Metals and Other Pollutants Removal

Metal elements such as Cu, Zn, Mn, Fe, and As in livestock wastewater mainly originate from feed additives, veterinary drug use, feces and urine discharge, and washing of farming facilities. Among them, Cu and Zn are relatively common in piggery wastewater and its treatment residues [31]. Metal ion removal by algal-bacterial systems mainly depends on cell wall functional group adsorption, EPS complexation, ion exchange, bioprecipitation, and intracellular accumulation, with carboxyl, hydroxyl, amino, and phosphate groups serving as important metal-binding sites [66]. In photobioreactors treating piggery wastewater, microalgal biomass, bacterial EPS, and particle settling jointly influence the migration and distribution of Cu and Zn between the aqueous and biomass phases [67]. High-rate algal pond studies treating piggery effluent showed that Scenedesmus sp. systems can effectively reduce aqueous Zn concentrations, but high Zn exposure may also alter the metabolic status of algal-bacterial systems and the removal performance of micropollutants [15]. Because heavy metals cannot be completely mineralized by biological processes, their removal is mainly manifested as adsorption and immobilization, speciation transformation, and phase transfer. Therefore, the fate of metals in effluents, sediments, and algal-bacterial biomass and the associated risks of biomass valorization should be carefully evaluated [15].

In addition to heavy metals, livestock wastewater and its receiving environments may contain persistent organic pollutants, endocrine-disrupting compounds, microplastics, and their combined contaminants. These pollutants are usually present at low concentrations but have high environmental persistence, complex migration pathways, and potential interactions with organic matter, metal ions, or microbial biofilms [68]. The removal of persistent organic pollutants by algal-bacterial systems generally involves biosorption, bioaccumulation, cometabolic transformation, and enzymatic degradation, in which bacterial degradation capacity can be complemented by oxygen supply, organic metabolites, and attachment interfaces provided by microalgae [69]. For hydrophobic organic pollutants such as polycyclic aromatic hydrocarbons, microalgae-bacteria co-cultures can promote pollutant transfer from the aqueous phase to the biotic phase and further transformation through algal cell surface adsorption, bacterial degradation, and algal-bacterial interactions [70]. Endocrine disruptors such as bisphenol A, benzophenones, and parabens can be reduced in microalgal systems through adsorption, absorption, photodegradation, and biotransformation, with removal efficiency affected by pollutant structure, algal species composition, and light conditions [71]. After entering algal-bacterial systems, microplastics can form heteroaggregates with algal cells, bacteria, and EPS, enabling aqueous removal through bioflocculation, surface adhesion, and settling [72, 73]. Meanwhile, biofilms formed on microplastic surfaces may enrich bacteria, antibiotic resistance genes, and organic micropollutants; therefore, evaluation of microplastic removal by algal-bacterial systems should also consider their environmental behavior as composite pollution carriers [74]. Overall, the reduction of heavy metals, POPs, endocrine disruptors, and microplastics by algal-bacterial systems is mainly reflected in the combined effects of adsorption/immobilization, biotransformation, and phase transfer, and future studies should integrate pollutant fate, transformation product toxicity, and safe disposal of algal-bacterial biomass [4].

5. Key Factors Affecting the Treatment Performance of Algal-Bacterial Systems

5.1. Algal Species and Bacterial Community Composition

Algal species and bacterial community composition determine the basic metabolic capacity of algal-bacterial systems and are the primary biological factors affecting livestock wastewater treatment performance [37]. Different microalgae vary in their tolerance to ammonia nitrogen and salinity, photosynthetic efficiency, nutrient uptake capacity, and EPS secretion, so algal strain selection should be matched with specific wastewater characteristics and treatment objectives [75]. Indigenous microalgae isolated from piggery wastewater are often highly adaptable to raw wastewater environments and can be used for nitrogen removal and subsequent algal-bacterial system construction [76]. In liquid anaerobic digestate treatment, *Chlorella*, *Scenedesmus*, *Chlamydomonas*, and other algal species show different adaptability to high-ammonia and dark-colored wastewater, and species selection directly influences biomass accumulation and nutrient removal [77]. Bacterial community composition also influences system functions, as nitrifiers, denitrifiers, heterotrophic organic matter degraders, and algal growth-promoting bacteria participate in nitrogen transformation, organic matter mineralization, and microalgal growth promotion, respectively [51]. Real livestock wastewater contains abundant indigenous bacteria, and appropriate utilization of native microbial communities can facilitate the formation of algal-bacterial interaction systems more compatible with actual wastewater conditions [78].

5.2. Algal-Bacterial Inoculation Ratio

The algal-bacterial inoculation ratio affects photosynthetic oxygen supply, heterotrophic degradation, nutrient competition, and bioflocculation and is an important operational parameter regulating the strength of algal-bacterial interactions [79]. When the algal fraction is too low, photosynthetic oxygen production and nitrogen and phosphorus assimilation are limited; when the bacterial fraction is too high, heterotrophic oxygen consumption and shading may weaken microalgal growth advantages [80]. An appropriate algal-bacterial ratio helps maintain the O_2-CO_2 exchange balance and promotes coordinated organic matter degradation, nutrient uptake, and particle settling [81]. Comparisons of different algae/sludge inoculation ratios show that this ratio significantly affects algal biomass growth, effluent quality, and biomass settling performance [80]. The algal-bacterial ratio can also alter cellular interactions and pollutant removal in membrane bioreactors, indicating that it is not only an inoculation parameter but also a key factor influencing subsequent community succession and reactor operation [82].

5.3. Light Conditions

Light is the core environmental factor driving algal-bacterial system operation because microalgal photosynthesis directly determines O_2 release, CO_2 fixation, and nutrient assimilation rates [83]. Insufficient light limits microalgal growth and photosynthetic oxygen production, thereby affecting bacterial organic matter degradation and nitrification [84]. Excessive light can cause photoinhibition or alter algal cellular energy allocation, reducing biomass accumulation and pollutant removal efficiency [85]. The light-dark cycle also affects algal-bacterial interactions, and suitable alternation between light and dark helps coordinate microalgal photosynthesis, bacterial respiration, and nitrogen and phosphorus transformation [86]. In pig-farming biogas digestate, light intensity, nutrient concentration, and N/P ratio jointly influence DO, pH, electrical conductivity, and algal-bacterial community dynamics; therefore, light regulation should be considered together with wastewater loading [87].

5.4. pH, Temperature, and Dissolved Oxygen

pH simultaneously affects microalgal physiological activity, ammonia nitrogen speciation, phosphate precipitation, and bacterial metabolism, making it one of the most important integrated environmental parameters in algal-bacterial systems [88]. Elevated pH can promote phosphate precipitation with calcium and magnesium ions but can also increase the fraction of free ammonia, increasing stress on microalgae in high-ammonia wastewater [89]. Temperature affects microalgal photosynthesis, bacterial enzyme activity, and community structure; low temperature reduces metabolic rates, whereas high temperature may induce stress in algal cells or functional bacteria [90]. Dissolved oxygen links microalgal photosynthesis and bacterial respiratory metabolism, directly influencing organic matter oxidation, nitrification, and the formation of low-oxygen denitrification microzones [17]. Different combinations of aeration and illumination can alter nitrate and phosphorus removal kinetics in algal-bacterial systems, indicating that DO regulation should be optimized together with light cycles and gas supply [91].

5.5. Wastewater Pretreatment and Pollutant Loading

Real livestock wastewater is often characterized by high ammonia nitrogen, high COD, high color, and high turbidity, and direct introduction into algal-bacterial systems can cause ammonia toxicity, light limitation, and organic loading shocks [26]. Dilution is a common approach to reduce ammonia nitrogen, color, and suspended solids, but excessive dilution increases water consumption and lowers nutrient recovery concentrations [27]. Pretreatments such as ammonia stripping and coagulation-flocculation can reduce ammonium and color and improve light conditions and nutrient utilization during subsequent microalgal cultivation [28]. Ozonation pretreatment can reduce the color of digested swine manure and increase photosynthetic oxygen production rates, indicating that oxidative pretreatment can alleviate the limitations imposed by dark-colored digestate on microalgal photosynthesis [29]. Pretreatment strategies should be selected based on wastewater pollution load, ammonia nitrogen concentration, turbidity, and resource recovery objectives; their core purpose is not simply to reduce pollutant concentrations but to create suitable light, nutrient, and microecological conditions for algal-bacterial synergistic metabolism [92].

6. Conclusions and Perspectives

6.1. Conclusions

Algal-bacterial symbiotic systems provide a biological treatment pathway for livestock wastewater that integrates pollutant reduction, nutrient recovery, and biomass valorization. Livestock wastewater is typically characterized by high organic loads, high ammonia nitrogen, high phosphorus, and composite contamination involving antibiotics, heavy metals, and antibiotic resistance genes. Algal-bacterial systems can achieve synergistic removal of multiple pollutants through microalgal photosynthesis, bacterial heterotrophic degradation, nitrogen and phosphorus assimilation and transformation, and EPS-mediated adsorption and flocculation. Compared with conventional aerobic biological treatment, oxygen released by microalgae can support bacterial organic matter degradation and nitrogen transformation, while CO_2 and small-molecule nutrients released by bacteria can promote microalgal growth, forming a close metabolic complementarity.

From the perspective of pollutant removal, algal-bacterial systems show good potential for reducing conventional pollutants such as COD, ammonia nitrogen, total nitrogen, and total phosphorus in livestock wastewater. Organic matter is mainly removed through bacterial hydrolysis, oxidation, and mineralization, with microalgae indirectly promoting this process through photosynthetic oxygen supply. Nitrogen removal involves multiple pathways, including microalgal assimilation, bacterial nitrification-denitrification, and algal-bacterial biomass harvesting. Phosphorus removal mainly depends on microalgal uptake, chemical precipitation, and EPS-mediated adsorption and immobilization. For antibiotics, antibiotic resistance genes, heavy metals, persistent organic pollutants, and microplastics, algal-bacterial systems can contribute to reduction through adsorption, complexation, biotransformation, photodegradation, and phase transfer, but their environmental fate and potential risks still require further clarification.

The treatment performance of algal-bacterial systems is jointly affected by algal species and bacterial community composition, inoculation ratio, light conditions, pH, temperature, dissolved oxygen, wastewater pretreatment, and pollutant loading. Among these factors, algal species and bacterial communities determine the basic metabolic capacity of the system; light and dissolved oxygen influence photosynthetic oxygen production and nitrogen transformation; pH and temperature regulate pollutant speciation and microbial activity; and pretreatment and load matching determine the adaptability of real wastewater entering algal-bacterial systems. Therefore, algal-bacterial treatment of livestock wastewater is not a single biological reaction process but a complex ecological process jointly governed by wastewater characteristics, algal-bacterial interactions, pollutant transformation, and biomass utilization.

6.2. Perspectives

Future research should be further oriented toward real wastewater conditions and promote the transition of algal-bacterial systems from experimental verification to continuous operation and practical application assessment. Many existing studies still focus on synthetic wastewater, diluted wastewater, or short-term cultivation, whereas real livestock wastewater is characterized by large fluctuations in water quality, high suspended solids and color, high ammonia loading, and complex pollutant composition. Therefore, long-term studies using real piggery wastewater, dairy wastewater, poultry wastewater, and anaerobic digestate should be strengthened, with particular attention to treatment performance under different seasons, loading rates, and pretreatment conditions.

Construction and regulation of algal-bacterial communities remain key directions for improving treatment performance. Future research should strengthen the screening of algal strains tolerant to ammonia, salinity, antibiotics, and heavy metals, while integrating indigenous bacterial acclimation, algal growth-promoting bacteria screening, and functional bacterial enrichment to construct algal-bacterial systems suitable for complex livestock wastewater environments. Rather than focusing solely on high removal efficiencies, future studies should pay more attention to functional differentiation, interaction relationships, and succession patterns within algal-bacterial communities, and identify the microbial groups that play key roles in organic matter degradation, nitrogen transformation, phosphorus immobilization, antibiotic transformation, and heavy metal adsorption.

The fate of pollutants and ecological risk assessment require further investigation. For antibiotics, antibiotic resistance genes, heavy metals, POPs, and microplastics, a decrease in aqueous concentration does not necessarily mean complete removal or detoxification. Future studies should combine LC-MS, metagenomics, transcriptomics, metabolomics, stable isotope tracing, and toxicity assessment to clarify pollutant distribution among the aqueous phase, algal-bacterial biomass, and sediments, identify major transformation products and residual toxicity, and prevent pollutants from re-entering the environment through biomass valorization.

Safe utilization of algal-bacterial biomass is a prerequisite for resource-oriented livestock wastewater treatment. Algal-bacterial systems can convert nitrogen, phosphorus, and organic carbon in wastewater into biomass, but this biomass may also accumulate heavy metals, antibiotic residues, microplastics, or antibiotic resistance genes. Therefore, future studies should select differentiated utilization pathways according to pollutant enrichment levels in biomass, such as anaerobic digestion for biogas production, composting, fertilizer production, biochar preparation, or biobased material development, and establish corresponding safety evaluation and pollutant control standards.

In addition, comprehensive benefit assessment of algal-bacterial systems should be strengthened. Future studies should not evaluate performance solely based on COD, nitrogen, and phosphorus removal efficiencies, but should also incorporate energy consumption, greenhouse gas emissions, carbon fixation capacity, nutrient recovery efficiency, biomass productivity, operating cost, and environmental risk into a unified assessment framework. Life cycle assessment, carbon footprint analysis, and techno-economic analysis can provide a more comprehensive evaluation of the practical value of algal-bacterial systems in low-carbon livestock wastewater treatment and circular agriculture.

CRediT Authorship Contribution Statement

Kaiwei Xu: Writing – original draft, Conceptualization, Resources, Funding acquisition

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] Silva-Gálvez, A. L., López-Sánchez, A., Camargo-Valero, M. A., et al. (2024). Strategies for livestock wastewater treatment and optimised nutrient recovery using microalgal-based technologies. Journal of Environmental Management, 354, 120258. https://doi.org/10.1016/j.jenvman.2024.120258

[2] Wang, Y., Ma, J., Chu, H., et al. (2024). Advances in microalgae-based livestock wastewater treatment: Mechanisms of pollutants removal, effects of inhibitory components and enhancement strategies. Chemical Engineering Journal, 483, 149222. https://doi.org/10.1016/j.cej.2024.149222

[3] Sacristán de Alva, M., Oceguera-Vargas, I., Lamas-Cosío, E., et al. (2024). Removal of nitrogen, phosphorus, organic matter, and heavy metals from pig-farming wastewater using a microalgae-bacteria consortium. Bulletin of Environmental Contamination and Toxicology, 113(5), 58. https://doi.org/10.1007/s00128-024-03922-6

[4] Kundu, P., Dutta, N., & Bhattacharya, S. (2024). Application of microalgae in wastewater treatment with special reference to emerging contaminants: A step towards sustainability. Frontiers in Analytical Science, 4, 1513153. https://doi.org/10.3389/frans.2024.1513153

[5] Satiro, J., dos Santos Neto, A. G., Marinho, T., et al. (2024). The role of the microalgae–bacteria consortium in biomass formation and its application in wastewater treatment systems: A comprehensive review. Applied Sciences, 14(14), 6083. https://doi.org/10.3390/app14146083

[6] Wang, Z., Hu, G., & Hong, Y. (2024). Strong alliance of microalgae and bacteria: The state-of-the-art review and future prospects of utilizing microalgae-bacteria consortia for comprehensive treatment of swine wastewater. Current Pollution Reports, 10(4), 744–764. https://doi.org/10.1007/s40726-024-00436-8

[7] Xu, K., Zou, X., Xue, Y., et al. (2021). The impact of seasonal variations about temperature and photoperiod on the treatment of municipal wastewater by algae-bacteria system in lab-scale. Algal Research, 54, 102175. https://doi.org/10.1016/j.algal.2021.102175

[8] Li, X., Li, S., Xie, P., et al. (2024). Advanced wastewater treatment with microalgae-indigenous bacterial interactions. Environmental Science and Ecotechnology, 20, 100374. https://doi.org/10.1016/j.ese.2024.100374

[9] Xiao, Z., Meng, H., Li, S., et al. (2024). Insights into the removal of antibiotics from livestock and aquaculture wastewater by algae-bacteria symbiosis systems. Environmental Research, 257, 119326. https://doi.org/10.1016/j.envres.2024.119326

[10] Zambrano, J., García-Encina, P. A., Jiménez, J. J., et al. (2023). Removal of veterinary antibiotics in swine manure wastewater using microalgae–bacteria consortia in a pilot scale photobioreactor. Environmental Technology & Innovation, 31, 103190. https://doi.org/10.1016/j.eti.2023.103190

[11] Chaudry, S., Alavianghavanini, A., Darvehei, P., et al. (2024). Feasibility of nutrient removal and recovery from abattoir wastewater using microalgae. Energies, 17(2), 308. https://doi.org/10.3390/en17020308

[12] Bedane, D. T., & Asfaw, S. L. (2023). Microalgae and co-culture for polishing pollutants of anaerobically treated agro-processing industry wastewater: The case of slaughterhouse. Bioresources and Bioprocessing, 10(1), 81. https://doi.org/10.1186/s40643-023-00696-4

[13] Chang, Y.-C., Pan, Y.-J., Huang, T.-H., et al. (2023). Cultivation of brackish water microalgae for pig manure liquid digestate recycling. Sustainability, 15(23), 16278. https://doi.org/10.3390/su152316278

[14] Luzzi, S. C., Gardner, R. G., & Heins, B. J. (2024). The use of Chlorella species to remove nutrients from dairy wastewater to produce livestock feed. Sustainability, 16(4), 1382. https://doi.org/10.3390/su16041382

[15] de Sousa Oliveira, A. P., Assemany, P., Covell, L., et al. (2023). Microalgae-based wastewater treatment for micropollutant removal in swine effluent: High-rate algal ponds performance under different zinc concentrations. Algal Research, 69, 102930. https://doi.org/10.1016/j.algal.2023.102930

[16] Nguyen, M. T., Nguyen, T. P., Pham, T. H., et al. (2022). Removal of nutrients and COD in wastewater from Vietnamese piggery farm by the culture of Chlorella vulgaris in a pilot-scaled membrane photobioreactor. Water, 14(22), 3645. https://doi.org/10.3390/w14223645

[17] Jia, H., & Yuan, Q. (2016). Removal of nitrogen from wastewater using microalgae and microalgae–bacteria consortia. Cogent Environmental Science, 2(1), 1275089. https://doi.org/10.1080/23311843.2016.1275089

[18] Kang, D., & Kim, K. (2021). Real wastewater treatment using a moving bed and wastewater-borne algal–bacterial consortia with a short hydraulic retention time. Processes, 9(1), 116. https://doi.org/10.3390/pr9010116

[19] Kong, W., Kong, J., Feng, S., et al. (2024). Cultivation of microalgae–bacteria consortium by waste gas–waste water to achieve CO_2 fixation, wastewater purification and bioproducts production. Biotechnology for Biofuels and Bioproducts, 17(1), 26. https://doi.org/10.1186/s13068-024-02468-1

[20] Lee, S.-A., Kim, M., & Kim, H.-S. (2022). Extra benefit of microalgae in raw piggery wastewater treatment: Pathogen reduction. Microbiome, 10(1), 142. https://doi.org/10.1186/s40168-022-01332-7

[21] Rossi, S., Pizzera, A., Bellucci, M., et al. (2022). Piggery wastewater treatment with algae-bacteria consortia: Pilot-scale validation and techno-economic evaluation at farm level. Bioresource Technology, 351, 127051. https://doi.org/10.1016/j.biortech.2022.127051

[22] Kisielewska, M., Dębowski, M., Zieliński, M., et al. (2022). Effects of liquid digestate treatment on sustainable microalgae biomass production. Bioenergy Research, 15(1), 357–370. https://doi.org/10.1007/s12155-021-09334-8

[23] Wang, Y., Guo, W., Yen, H.-W., et al. (2015). Cultivation of Chlorella vulgaris JSC-6 with swine wastewater for simultaneous nutrient/COD removal and carbohydrate production. Bioresource Technology, 198, 619–625. https://doi.org/10.1016/j.biortech.2015.09.067

[24] Goh, P. S., Ahmad, N. A., Lim, J. W., et al. (2022). Microalgae-enabled wastewater remediation and nutrient recovery through membrane photobioreactors: Recent achievements and future perspective. Membranes, 12(11), 1094. https://doi.org/10.3390/membranes12111094

[25] Ayre, J. M., Moheimani, N. R., & Borowitzka, M. A. (2017). Growth of microalgae on undiluted anaerobic digestate of piggery effluent with high ammonium concentrations. Algal Research, 24, 218–226. https://doi.org/10.1016/j.algal.2017.04.015

[26] Lee, S.-A., Lee, N., Oh, H.-M., et al. (2021). Stepwise treatment of undiluted raw piggery wastewater, using three microalgal species adapted to high ammonia. Chemosphere, 263, 127934. https://doi.org/10.1016/j.chemosphere.2020.127934

[27] Ferreira, A., Figueiredo, D., Cardeiras, R., et al. (2022). Exploring different pretreatment methodologies for allowing microalgae growth in undiluted piggery wastewater. Agronomy, 12(3), 580. https://doi.org/10.3390/agronomy12030580

[28] Qian, J., Xu, C., Song, H., et al. (2023). Enhancing algal growth and nutrient recovery from anaerobic digestion piggery effluent by an integrated pretreatment strategy of ammonia stripping and flocculation. Frontiers in Bioengineering and Biotechnology, 11, 1219103. https://doi.org/10.3389/fbioe.2023.1219103

[29] Palomar, C. R., Álvaro, A. G., Hermosilla, D., et al. (2024). Ozonation as pretreatment of digested swine manure prior to microalgae culture. Water, 16(12), 1740. https://doi.org/10.3390/w16121740

[30] López-Patiño, A. M., Cárdenas-Orrego, A., Torres, A. F., et al. (2024). Native microalgal-bacterial consortia from the

Ecuadorian Amazon region: An alternative to domestic wastewater treatment. Frontiers in Bioengineering and Biotechnology, 12, 1338547. https://doi.org/10.3389/fbioe.2024.1338547

[31] Collao, J., García-Encina, P. A., Blanco, S., et al. (2022). Current concentrations of Zn, Cu, and As in piggery wastewater compromise nutrient removals in microalgae–bacteria photobioreactors due to altered microbial communities. Biology, 11(8), 1176. https://doi.org/10.3390/biology11081176

[32] Wang, C., Wang, H., Zheng, R., et al. (2025). Piggery wastewater treatment by microalgae: Mechanisms and technologies. Algal Research, 104205. https://doi.org/10.1016/j.algal.2025.104205

[33] Khoo, K. S., Chia, W. Y., Chew, K. W., et al. (2021). Microalgal-bacterial consortia as future prospect in wastewater bioremediation, environmental management and bioenergy production. Indian Journal of Microbiology, 61(3), 262–269. https://doi.org/10.1007/s12088-021-00958-8

[34] Zheng, X., Liu, R., Li, K., et al. (2025). Microalgae-bacteria symbiosis enhanced nitrogen removal from wastewater in an inversed fluidized bed bioreactor: Performance and microflora. Frontiers in Microbiology, 16, 1591974. https://doi.org/10.3389/fmicb.2025.1591974

[35] Oon, Y.-S., Oon, Y.-L., Ayaz, M., et al. (2025). Microalgae-bacteria synergy in photosynthetic bio-electrochemical systems supports nitrogen transformation, microbial dynamics and greenhouse gas mitigation. Communications Earth & Environment, 6(1), 884. https://doi.org/10.1038/s43247-025-01523-9

[36] Yu, T., Wang, S., Yang, H., et al. (2024). Carbon capture and resource utilization by algal–bacterial consortium in wastewater treatment: A mini-review. Water, 16(15), 2197. https://doi.org/10.3390/w16152197

[37] Abate, R., Oon, Y.-S., Oon, Y.-L., et al. (2024). Microalgae-bacteria nexus for environmental remediation and renewable energy resources: Advances, mechanisms and biotechnological applications. Heliyon, 10(10). https://doi.org/10.1016/j.heliyon.2024.e29125

[38] Yao, S., Lyu, S., An, Y., et al. (2019). Microalgae–bacteria symbiosis in microalgal growth and biofuel production: A review. Journal of Applied Microbiology, 126(2), 359–368. https://doi.org/10.1111/jam.14127

[39] Solomon, W., Mutum, L., Janda, T., et al. (2023). Potential benefit of microalgae and their interaction with bacteria to sustainable crop production. Plant Growth Regulation, 101(1), 53–65. https://doi.org/10.1007/s10725-023-00930-1

[40] Fuentes, J. L., Garbayo, I., Cuaresma, M., et al. (2016). Impact of microalgae-bacteria interactions on the production of algal biomass and associated compounds. Marine Drugs, 14(5), 100. https://doi.org/10.3390/md14050100

[41] Tandon, P., & Jin, Q. (2017). Microalgae culture enhancement through key microbial approaches. Renewable and Sustainable Energy Reviews, 80, 1089–1099. https://doi.org/10.1016/j.rser.2017.05.208

[42] Anand, U., Dey, S., Parial, D., et al. (2023). Algae and bacteria consortia for wastewater decontamination and transformation into biodiesel, bioethanol, biohydrogen, biofertilizers and animal feed: A review. Environmental Chemistry Letters, 21(3), 1585–1609. https://doi.org/10.1007/s10311-023-01597-1

[43] Xu, S., Li, Z., Yu, S., et al. (2024). Microalgal–bacteria biofilm in wastewater treatment: Advantages, principles, and establishment. Water, 16(18), 2561. https://doi.org/10.3390/w16182561

[44] Wang, X., Wen, X., Li, Y., et al. (2025). The response of extracellular polymeric substances (EPS) in Spirulina platensis to environmental stresses: Salt, light and heavy metal. Environmental Research, 122513. https://doi.org/10.1016/j.envres.2025.122513

[45] Naveed, S., Li, C., Lu, X., et al. (2019). Microalgal extracellular polymeric substances and their interactions with metal (loid)s: A review. Critical Reviews in Environmental Science and Technology, 49(19), 1769–1802. https://doi.org/10.1080/10643389.2019.1619642

[46] Wang, Y., Gong, X., Huang, D., et al. (2022). The binding effect and photooxidation on oxytetracycline with algal extracellular polymeric substances and natural organic matter. Chemosphere, 307, 135826. https://doi.org/10.1016/j.chemosphere.2022.135826

[47] Li, S., Bai, Y., Li, Z., et al. (2025). Overlooked role of extracellular polymeric substances in antibiotic-resistance gene transfer within microalgae-bacteria system. Journal of Hazardous Materials, 488, 137206. https://doi.org/10.1016/j.jhazmat.2025.137206

[48] Klawonn, I., Bonaglia, S., Brüchert, V., et al. (2015). Aerobic and anaerobic nitrogen transformation processes in N_2-fixing cyanobacterial aggregates. The ISME Journal, 9(6), 1456–1466. https://doi.org/10.1038/ismej.2014.230

[49] Zhang, X., Chen, D., Hou, X., et al. (2023). Nitrification-denitrification co-metabolism in an algal-bacterial aggregates system for simultaneous pyridine and nitrogen removal. Journal of Hazardous Materials, 460, 132390. https://doi.org/10.1016/j.jhazmat.2023.132390

[50] Tang, L., Zhang, Y., Gao, M., et al. (2025). Simultaneous nitrification–endogenous denitrification with phosphorus removal sustained by aeration-free filamentous microalgal–bacterial granular sludge for low C/N wastewater treatment. ACS ES&T Engineering, 5(5), 1160–1170. https://doi.org/10.1021/acsestengg.4c00547

[51] Fallahi, A., Rezvani, F., & Asgharnejad, H. (2021). Interactions of microalgae-bacteria consortia for nutrient removal from wastewater: A review. Chemosphere, 272, 129878. https://doi.org/10.1016/j.chemosphere.2021.129878

[52] Jin, Y., Zhan, W., Wu, R., et al. (2023). Insight into the roles of microalgae on simultaneous nitrification and denitrification in microalgal-bacterial sequencing batch reactors: Nitrogen removal, extracellular polymeric substances, and microbial communities. Bioresource Technology, 379, 129038. https://doi.org/10.1016/j.biortech.2023.129038

[53] Li, S., Zhang, S., Bai, Y., et al. (2024). Microalgae shed light on interconnected nitrogen transformation in microalgal-bacterial consortia. ACS ES&T Water, 4(8), 3131–3144. https://doi.org/10.1021/acsestwater.4c00297

[54] Chen, S., Wang, J., Feng, X., et al. (2025). Algal–bacterial symbiotic granular sludge technology in wastewater treatment: A review on advances and future prospects. Water, 17(11), 1647. https://doi.org/10.3390/w17111647

[55] Lu, W., Liu, S., Lin, Z., et al. (2021). Enhanced microalgae growth for biodiesel production and nutrients removal in raw swine wastewater by carbon sources supplementation. Waste and Biomass Valorization, 12(4), 1991–1999. https://doi.org/10.1007/s12649-020-01235-9

[56] Casagli, F., Rossi, S., Steyer, J. P., et al. (2021). Balancing microalgae and nitrifiers for wastewater treatment: Can inorganic carbon limitation cause an environmental threat? Environmental Science & Technology, 55(6), 3940–3955. https://doi.org/10.1021/acs.est.0c07342

[57] Lee, J.-C., Moon, K., Lee, N., et al. (2023). Biodiesel production and simultaneous treatment of domestic and livestock wastewater using indigenous microalgae, Chlorella

sorokiniana JD1-1. Scientific Reports, 13(1), 15190. https://doi.org/10.1038/s41598-023-42328-2

[58] Zheng, Y., Wan, Y., Zhang, Y., et al. (2023). Recovery of phosphorus from wastewater: A review based on current phosphorous removal technologies. Critical Reviews in Environmental Science and Technology, 53(11), 1148–1172. https://doi.org/10.1080/10643389.2022.2161379

[59] Larsdotter, K., Jansen, J. L. C., & Dalhammar, G. (2007). Biologically mediated phosphorus precipitation in wastewater treatment with microalgae. Environmental Technology, 28(9), 953–960. https://doi.org/10.1080/09593332808618873

[60] Hasan, H. A., Rahim, N. F. M., Alias, J., et al. (2024). A review on the roles of extracellular polymeric substances (EPSs) in wastewater treatment: Source, mechanism study, bioproducts, limitations, and future challenges. Water, 16(19), 2812. https://doi.org/10.3390/w16192812

[61] Xu, C., Kong, L., Gao, H., et al. (2022). A review of current bacterial resistance to antibiotics in food animals. Frontiers in Microbiology, 13, 822689. https://doi.org/10.3389/fmicb.2022.822689

[62] Kiki, C., Qin, D., Liu, L., et al. (2023). Unraveling the role of microalgae in mitigating antibiotics and antibiotic resistance genes in photogranules treating antibiotic wastewater. Environmental Science & Technology, 57(44), 16940–16952. https://doi.org/10.1021/acs.est.3c04694

[63] López-Serna, R., García, D., Bolado, S., et al. (2019). Photobioreactors based on microalgae-bacteria and purple phototrophic bacteria consortia: A promising technology to reduce the load of veterinary drugs from piggery wastewater. Science of the Total Environment, 692, 259–266. https://doi.org/10.1016/j.scitotenv.2019.07.272

[64] Liu, W., Huang, W., Cao, Z., et al. (2022). Microalgae simultaneously promote antibiotic removal and antibiotic resistance genes/bacteria attenuation in algal-bacterial granular sludge system. Journal of Hazardous Materials, 438, 129286. https://doi.org/10.1016/j.jhazmat.2022.129286

[65] Ren, H., Wang, R., Ying, L., et al. (2025). Removal of sulfamethoxazole in an algal-bacterial membrane aerated biofilm reactor: Microbial responses and antibiotic resistance genes. Water Research, 268, 122595. https://doi.org/10.1016/j.watres.2024.122595

[66] Zhao, D., Cheah, W. Y., Lai, S. H., et al. (2023). Symbiosis of microalgae and bacteria consortium for heavy metal remediation in wastewater. Journal of Environmental Chemical Engineering, 11(3), 109943. https://doi.org/10.1016/j.jece.2023.109943

[67] Antolín, B., Torres, A., García, P. A., et al. (2024). Mechanisms of copper and zinc bioremoval by microalgae and bacteria grown in nutrient rich wastewaters. Chemosphere, 355, 141803. https://doi.org/10.1016/j.chemosphere.2024.141803

[68] Vo, T. P., Danaee, S., Chaiwong, C., et al. (2024). Microalgae-bacteria consortia for organic pollutants remediation from wastewater: A critical review. Journal of Environmental Chemical Engineering, 12(6), 114213. https://doi.org/10.1016/j.jece.2024.114213

[69] Guo, W., Ren, H., Jin, Y., et al. (2024). The bioremediation of the typical persistent organic pollutants (POPs) by microalgae-bacteria consortia: A systematic review. Chemosphere, 355, 141852. https://doi.org/10.1016/j.chemosphere.2024.141852

[70] Hoque, M. Z., Alqahtani, A., Sankaran, S., et al. (2023). Enhanced biodegradation of phenanthrene and anthracene using a microalgal-bacterial consortium. Frontiers in Microbiology, 14, 1227210. https://doi.org/10.3389/fmicb.2023.1227210

[71] García, N., Rodríguez, R., Vicente, G., et al. (2024). Comprehensive study on endocrine disruptor removal from wastewater using different microalgae species. Applied Sciences, 15(1), 132. https://doi.org/10.3390/app15010132

[72] Long, B., Li, Q., Hu, C., et al. (2025). Remediation and upcycling of microplastics by algae with wastewater nutrient removal and bioproduction potential. Nature Communications. https://doi.org/10.1038/s41467-025-58923-4

[73] Xu, K., Liu, K., Zou, X., et al. (2026). Environment-driven regulation of EPS secretion and interfacial coupling in microalgae-microplastic hetero-aggregates: Insights from molecular mechanisms to utilization potential. Journal of Hazardous Materials, 141644. https://doi.org/10.1016/j.jhazmat.2026.141644

[74] Kwiatkowska, K., & Ormaniec, P. (2024). Microbial succession on microplastics in wastewater treatment plants: Exploring the complexities of microplastic-microbiome interactions. Microbial Ecology, 87(1), 105. https://doi.org/10.1007/s00248-024-02214-6

[75] Tawfik, A., Eraky, M., Alhajeri, N. S., et al. (2022). Cultivation of microalgae on liquid anaerobic digestate for depollution, biofuels and cosmetics: A review. Environmental Chemistry Letters, 20(6), 3631–3656. https://doi.org/10.1007/s10311-022-01471-9

[76] Flores-Zambrano, K., Tapia, W., & Castillejo, P. (2025). Microalgae strains isolated from piggery wastewater in Ecuador: Effective nitrogen compound removal and growth potential in extremophile conditions. Biotechnology Reports, 45, e00883. https://doi.org/10.1016/j.btre.2025.e00883

[77] Bauer, L., Ranglová, K., & Masojídek, J. (2021). Digestate as sustainable nutrient source for microalgae—Challenges and prospects. Applied Sciences, 11(3), 1056. https://doi.org/10.3390/app11031056

[78] Sobolewska, E., Borowski, S., & Nowicka-Krawczyk, P. (2024). Cultivation of microalgae in liquid digestate to remove nutrients and organic contaminants. BioEnergy Research, 17(3), 1843–1855. https://doi.org/10.1007/s12155-024-09993-9

[79] Satiro, J., Cunha, A., Gomes, A. P., et al. (2022). Optimization of microalgae–bacteria consortium in the treatment of paper pulp wastewater. Applied Sciences, 12(12), 5799. https://doi.org/10.3390/app12125799

[80] Laurent, J., Bois, P., & Wanko, A. (2019). Finding optimal algal/bacterial inoculation ratio to improve algal biomass growth with wastewater as nutrient source. Water SA, 45(4), 624–631. https://doi.org/10.4314/wsa.v45i4.12

[81] Oruganti, R. K., Katam, K., Show, P. L., et al. (2022). A comprehensive review on the use of algal-bacterial systems for wastewater treatment with emphasis on nutrient and micropollutant removal. Bioengineered, 13(4), 10412–10453. https://doi.org/10.1080/21655979.2022.2087928

[82] Sun, L., Lei, Y., & Li, H. (2022). Exploring the fundamental factors behind algal-bacterial symbiosis and their impact on ecological interactions. Frontiers in Environmental Science, 10, 893412. https://doi.org/10.3389/fenvs.2022.893412

[83] Abdelfattah, A., Ali, S. S., Ramadan, H., et al. (2023). Microalgae-based wastewater treatment: Mechanisms, challenges, recent advances, and future prospects. Environmental Science and Ecotechnology, 13, 100205. https://doi.org/10.1016/j.ese.2023.100205

[84] Pham, A. L., Luu, K. D., Duong, T. T., et al. (2022). Evaluation of microalgal bacterial dynamics in pig-farming biogas digestate under impacts of light intensity and nutrient using physicochemical parameters. Water, 14(14), 2275. https://doi.org/10.3390/w14142275

[85] Singh, S. P., & Singh, P. (2015). Effect of temperature and light on the growth of algae species: A review. Renewable and Sustainable Energy Reviews, 50, 431–444. https://doi.org/10.1016/j.rser.2015.05.024

[86] Biliani, S. E., & Manariotis, I. D. (2025). Nutrient removal mechanisms of algal-bacteria consortia in secondarily treated wastewater. Environmental Processes, 12(2), 30. https://doi.org/10.1007/s40710-025-00786-1

[87] Wang, H., Hu, Z., Xiao, B., et al. (2013). Ammonium nitrogen removal in batch cultures treating digested piggery wastewater with microalgae Oedogonium sp. Water Science and Technology, 68(2), 269–275. https://doi.org/10.2166/wst.2013.273

[88] Salisu, A., Umar, B. I., Zhong, Z., et al. (2023). Charcoal stabilizes pH and improves nutrients removal of bacteria-microalgae interaction: A potential for improving water quality in aquaculture. Environmental Engineering Research, 28(6). https://doi.org/10.4491/eer.2023.134

[89] Franchino, M., Tigini, V., Varese, G. C., et al. (2016). Microalgae treatment removes nutrients and reduces ecotoxicity of diluted piggery digestate. Science of The Total Environment, 569, 40–45. https://doi.org/10.1016/j.scitotenv.2016.06.094

[90] Sepúlveda-Muñoz, C. A., Hontiyuelo, G., Blanco, S., et al. (2022). Photosynthetic treatment of piggery wastewater in sequential purple phototrophic bacteria and microalgae-bacteria photobioreactors. Journal of Water Process Engineering, 47, 102825. https://doi.org/10.1016/j.jwpe.2022.102825

[91] He, T., Peng, Q., Qian, J., et al. (2025). A comparative study on various pretreatment methods of anaerobic digestion piggery effluent for microalgae cultivation. Processes, 13(9), 2703. https://doi.org/10.3390/pr13092703

[92] Sichel-Crespo, C. M., Ortiz-Montoya, E. Y., & Caicedo-Ortega, N. H. (2022). State of microalgae-based swine manure digestate treatment: An overview. Heliyon, 8(11). https://doi.org/10.1016/j.heliyon.2022.e11629