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Review

Microalgae-Based Solutions for Sustainable Swine Wastewater Management: Challenges, Opportunities, and Future Directions

[Soluciones basadas en Microalgas para la Gestión Sostenible de las Aguas Residuales Porcinas: Desafíos, Oportunidades y Direcciones Futuras]

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Abstract

Swine wastewater poses significant environmental challenges, needing comprehensive management strategies. In addressing these challenges, integrated wastewater treatment systems utilizing microalgae emerge as promising solutions. These systems integrate biological, chemical, and physical processes to efficiently remove pollutants while producing valuable biomass. Considering this, the present review aimed to analyze the challenges and opportunities of microalgae-based swine wastewater treatment systems, assessing their efficiency in pollutant removal, biomass productivity, and resource utilization. Various cultivation methods, such as raceway ponds and photobioreactors, offer versatile approaches for treating swine wastewater. Moreover, advanced technologies can complement microalgal-based processes, further enhancing treatment efficiencies. Hybrid systems, which combine multiple technologies, play an important role in optimizing resource utilization and enhancing treatment performance. By leveraging these integrated approaches, it becomes possible to maximize the reuse potential of treated wastewater post-treatment. Evaluating the effectiveness and economic feasibility of microalgae-based treatment processes involves quantifying pollutant removal efficiency, biomass productivity, and resource utilization rates. Despite the promising potential, several challenges remain, including wastewater variability, high initial capital costs, and scalability issues, which hinder widespread adoption. To overcome these challenges, future research activities should concentrate on enhancing our understanding of microalgal physiology, exploring innovative cultivation strategies, and development interdisciplinary collaborations to advance swine wastewater management practices. Through concentrated efforts and innovative solutions, microalgae-based treatment systems can play a fundamental role in sustainable swine wastewater management, contributing to both environmental conservation and resource optimization.

Keywords: *Swine wastewater, nutrient removal, biochemical composition, microalgae-based treatment systems*.

Resumen

Las aguas residuales porcinas plantean desafíos ambientales significativos que requieren estrategias de gestión integrales. Al abordar estos desafíos, los sistemas integrados de tratamiento de aguas residuales que utilizan microalgas emergen como soluciones prometedoras. Estos sistemas integran procesos biológicos, químicos y físicos para eliminar eficientemente los contaminantes mientras producen biomasa valiosa. Considerando esto, la presente revisión tuvo como objetivo analizar los desafíos y oportunidades de los sistemas de tratamiento de aguas residuales porcinas basados en microalgas, evaluando su eficiencia en la eliminación de contaminantes, la productividad de la biomasa y la utilización de recursos. Varios métodos de cultivo, como estanques de circuito y fotobiorreactores, ofrecen enfoques versátiles para el tratamiento de aguas residuales porcinas. Además, las tecnologías avanzadas pueden complementar los procesos basados en microalgas, mejorando aún más la eficiencia del tratamiento. Los sistemas híbridos, que combinan múltiples tecnologías, desempeñan un papel importante en la optimización de la utilización de recursos y en el mejoramiento del rendimiento del tratamiento. Al aprovechar estos enfoques integrados, se vuelve posible maximizar el potencial de reutilización de las aguas residuales tratadas posterior al tratamiento. La evaluación de la efectividad y la viabilidad económica de los procesos de tratamiento basados en microalgas implica cuantificar la eficiencia de eliminación de contaminantes, la productividad de biomasa y las tasas de utilización de recursos. A pesar del potencial prometedor, persisten varios desafíos, incluida la variabilidad de las aguas residuales, los altos costos de capital inicial y los problemas de escalabilidad, que obstaculizan la adopción generalizada. Para superar estos desafíos, las actividades de investigación futuras deben concentrarse en mejorar nuestra comprensión de la fisiología de las microalgas, explorar estrategias de cultivo innovadoras y desarrollar colaboraciones interdisciplinarias para avanzar en las prácticas de gestión de aguas residuales porcinas. A través de esfuerzos concentrados y soluciones innovadoras, los sistemas de tratamiento basados en microalgas pueden desempeñar un papel fundamental en la gestión sostenible de aguas residuales porcinas, contribuyendo tanto a la conservación del medio ambiente como a la optimización de recursos.

Palabras clave: *Aguas residuales porcinas, eliminación de nutrientes, composición bioquímica, sistemas de tratamiento basados en microalgas.*

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1. Introduction

Untreated or inadequately treated swine wastewater can result in significant water pollution, soil contamination, and air quality degradation, posing risks to ecosystems and human health (Al-Hazmi *et al*., 2023). This wastewater contains a complex mixture of pollutants, including nutrients such as nitrogen (591 mg L^{-1}) and phosphorus (67 mg L^{-1}) (Yu *et al*., 2024). These nutrients can trigger eutrophication in water bodies (Chen *et al*., 2020). Additionally, organic matter in the wastewater contributes to biochemical oxygen demand, adversely affecting aquatic life and water quality. Swine feces harbor pathogens (*Salmonella, Escherichia coli,* Circovirus type 2, Rotavirus) (Michelon *et al*., 2023; Souza *et al*., 2020; Viancelli *et al*., 2013), and residues from supplements containing heavy metals and antibiotics further contribute to environmental contamination (Chen *et al*., 2020).

Addressing the environmental impacts of swine wastewater necessitates comprehensive management strategies. These include advanced waste treatment technologies, rigorous regulations, and best management practices to mitigate pollution and safeguard environmental and public health (Varma *et al*., 2021).

Wastewater treatment typically involves four stages: preliminary treatment to retain granular solids, primary treatment mainly consisting of physical processes, secondary treatment employing biological processes mainly for organic matter removal mediated by a mixed population of heterotrophic bacteria, and tertiary treatment that can be used to remove nutrients, as phycoremediation process (Silva, 2023).

Phycoremediation employing microalgae has traditionally been used as tertiary treatment or final polishing (Tiron *et al*., 2021). According to Chai *et al*. (2021) biotreatment with microalgae becomes attractive due to their ability to incorporate nutrients such as nitrogen and phosphorus. The commercial use of microalgae cultures in effluent treatment and biomass production dates back approximately 75 years, being applied in wastewater treatment and the production of biomass from various genera of microalgae and cyanobacteria such as *Chlorella*, *Dunaliella* and *Spirulina* (Abdel-Raouf *et al*., 2012; Arashiro *et al*., 2022; Spain *et al*., 2021).

In this sense, several studies have reported the use of wastewater from different sources as a nutrient for microalgae cultivation, including swine wastewater (Liu *et al*., 2022; Michelon *et al*., 2016), cattle wastewater (Lv *et al*., 2018; Viegas *et al*., 2021), agro-industrial effluents (Carvalho *et al*., 2022; Castro *et al*., 2021; Magalhães *et al*., 2022; Posadas *et al*., 2014), domestic sewage (Moondra *et al*., 2020), dairy effluent (Choi, 2016; Khalaji *et al*., 2023), slaughterhouse (Terán Hilares *et al*., 2021), and aquaculture (Tejido-Nuñez *et al*., 2019).

Microalgae are microorganisms that provide nutrient recycling by incorporating them into their cells. The nitrogen ratio present in swine wastewater makes this substrate ideal for microalgae cultivation (Chen *et al*., 2020; Ciardi *et al*., 2022; González-Fernández *et al*., 2013).

Kumar *et al*. (2018) reported the cultivation of mixed microalgal biomass using swine manure at a concentration of 5 g L^{-1} of culture. The initial concentrations of total nitrogen and phosphorus in the manure ranged from 566 to 1363 mg L^{-1} and 120 to 528 mg L^{-1}, respectively. The optimal biomass growth achieved in this study was 2.57 g L^{-1}. The use of microalgae in the tertiary treatment of stabilized wastewater from swine farming is promising because they can grow in different dilutions of swine waste and even undiluted, with the ability to tolerate high concentrations of ammonia, up to 1300 mg L^{-1} (Cañizares and Domínguez, 1993; Dinnebier *et al*., 2021).

The effective integration of microalgae into wastewater treatment processes not only enhances nutrient removal but also contributes to the production of valuable biomass to be used on production of biofuels, animal feed, fertilizers, pharmaceuticals, and nutraceuticals. Consequently, the application of microalgae-based treatments represents a sustainable and efficient approach to managing the environmental impacts of swine wastewater. This review aims to comprehensively evaluate the potential and challenges of using microalgae for nutrient removal in swine wastewater treatment, providing insights into the latest advancements and research trends. This review seeks to justify the importance of further research and development in this area, ultimately contributing to the optimization of wastewater management practices and the promotion of environmental sustainability.

2. Swine manure characteristics

The intensive production of swine has grown significantly in recent decades, driven by the increased demand for pork (Tzanidakis *et al*., 2021). This growth, however, is directly related to the increase in the volume of waste generated. Swine at different stages of the life cycle produce varying volumes of waste (including urine and feces), ranging from 2.3 liters per animal per day for piglets to 4.5 liters per animal per day in finishing pigs (Barros *et al*., 2019). China, the world's largest producer of swine, has a herd of 434 million heads in 2024, followed by the European Union with 133.6 million, the United States with 75.8 million, and Brazil with 33.1 million (Ritchie *et al*., 2023). This vast volume of liquid waste requires effective treatment to remove pollutants before it can be applied to crops as fertilizer.

Swine manure is a complex mixture of feces, urine, water, and feed residues, the quantity of which is proportional to the number of animals raised and their nutritional management (Qi *et al*., 2023). With the intensification of swine farming, managing this waste has become an environmental and public health challenge due to the high concentration of components present in manure that can be harmful to the environment. Among these, nutrients such as nitrogen and phosphorus stand out, which can lead to the eutrophication of water bodies, promoting excessive algal growth and the subsequent reduction of dissolved oxygen, harming aquatic life (Qi *et al*., 2023). In addition to nutrients, swine manure can contain pathogens such as *Salmonella, Escherichia coli*, and other zoonotic pathogens that pose risks to human and animal health (Viancelli *et al*., 2013). Antibiotic residues are also often found in the waste, resulting from the prophylactic and therapeutic use of these drugs in pig farming, which can contribute to the spread of antibiotic-resistant bacteria (Zhou *et al*., 2020).

The composition of pig manure can vary significantly depending on the age of the animal and the diet to which it is subjected (Trabue *et al*., 2021; Verschuren *et al*., 2018). Younger pigs, such as those in nursery or grower phases, typically produce waste with different nutrient profiles compared to older finishing pigs or breeding sows (Wilson *et al*., 2020). Additionally, the type of feed and its nutrient content, including protein levels and the presence of additives, can influence the concentration of nitrogen, phosphorus, and other elements in the manure (Fuentes *et al*., 2006; Trabue *et al*., 2021). These variations are important to consider when managing waste treatment and nutrient recycling in agricultural systems.

In a general way, a study conducted by Sheppard (2019) evaluates the concentrations of total nitrogen and ammonium in swine manure from 1998 to 2002 and observed that the nutrients composition did not change significantly over time. Phosphorus concentrations presented a reduction of 22% in finishing swine's and 36% reduction in sow and nursery. These results indicate an improvement in nutrient management in swine production, with positive implications for environmental sustainability and agricultural production efficiency (Sheppard, 2019).

The direct discharge of these effluents into soils without treatment can contaminate water resources, degrade soil quality, and release greenhouse gases such as methane and nitrous oxide, contributing to climate change (Sakadevan and Nguyen, 2017). To mitigate these impacts, it is essential to implement effective waste treatment and management strategies. In this sense, the microalgae treatment is a promising alternative, promoting nutrient recovery and the production of biogas, a renewable energy source.

3. Removal of nutrients by microalgae

Table 1 shows the application of different species of microalgae in the treatment of swine wastewater, and the nutrients removal percentages. The removal process involves the utilization of nitrogen and phosphorus compounds as essential nutrients for growth and metabolism, resulting in microalgae biomass. Through mechanisms like active transport and diffusion, microalgae absorb dissolved inorganic nitrogen species (e.g., ammonium, nitrate, nitrite) and orthophosphate from the water column (Al-Jabri *et al*., 2020).

In addition to nutrient removal, microalgae employ diverse mechanisms for removing pollutants from swine wastewater, including adsorption, bioaccumulation, biodegradation, and precipitation (Bhatt *et al*., 2022). Microalgae can adsorb pollutants heavy metals (Cd, Pb, Cu and Cr) (Mustafa *et al*., 2021) onto their cell surfaces or extracellular matrices, serving in their removal from the water phase through electrostatic interactions, hydrogen bonding, and Van der Waals forces. They can also bioaccumulate pollutants (chemicals, dyes, pesticides, and pharmaceuticals) (Kabra *et al*., 2014; Li *et al*., 2009; Premaratne *et al*., 2021; Xiong *et al*., 2017) within their cells via active uptake or passive diffusion mechanisms. Furthermore, microalgae possess enzymatic systems capable of degrading organic pollutants into simpler, less toxic compounds through metabolic processes like oxidation, hydrolysis, and conjugation (Sutherland and Ralph, 2019). Additionally, microalgae can facilitate the precipitation of insoluble pollutants like phosphate minerals, removing them from the water column and decreasing their bioavailability and environmental impact (Al-Jabri *et al*., 2020). These mechanisms work synergistically to enhance pollutant removal efficiency and promote water quality improvement.

Additionally, microalgae serve as valuable bioindicators of quality in swine wastewater treatment systems, providing insights into ecosystem health and pollutant levels (Miranda and Krishnakumar, 2015). By monitoring the composition, abundance, and

Table 1. Efficiency of microalgae in removing nitrogen and phosphorus from various types of swine wastewater.

Microalgae	**Swine wastewater type and/or culture conditions**	**Removal (%)**		**Reference**
		Nitrogen	**Phosphorus**	
Coelastrella sp. QY01	Anaerobically and aerobically	100 *	100 †	Luo *et al*., (2016)
Chodatella sp.	Filtrated and sterilized	99.7 *	75.9 †	Li *et al*., (2014)
Neochloris aquatica CL-M1	Autoclaved and undiluted	96.2 *	100 ††	Wang *et al*., (2017)
Chlorella vulgaris JSC-6	Centrifuged, filtered and diluted for 20-, 10-, and fivefold, then autoclaved	40–90 *	-	Wang *et al*., (2015)
Chlamydomonas mexicana	Anaerobic/oxic and filtrated	62	28	Abou-Shanab *et al*., (2013)
Chlorella vulgaris	Undiluted and outdoor raceway	89.5 **	85.3 †	Wang *et al*., (2016)
Chlorella zofingiensis	Autoclave and diluted (at a level of 2500, 1900, 1300, 800 and 400 mg L^{-1} COD)	70-85 **	80-100 †	Zhu *et al*., (2013)
Chlorella vulgaris	Filtrated and autoclaved	90.5 **	91.5 †	Wen *et al*., (2017)
Chlorella spp.	Non-sterile digested and diluted (6% v/v)	100 *	100 ††	Michelon *et al*., (2016)
Chlorella sorokiniana	Digestate undiluted and diluted	70 *	90 ††	Dinnebier *et al*., (2021)
Tribonema sp. and *Synechocystis* sp.	Anaerobic digestion, diluted threefold and autoclaved	75-90 *	62 †	Cheng *et al*., (2020)
Parachlorella kessleri	Real swine wastewater	95 *	100 †	Qu *et al*., (2019)
Nannocholropsis oculata	Anaerobically and aerobically	83-100 *	100 ††	Wu *et al*., (2013)
Coelastrella sp.	Sedimentated, filtrated and autoclaved	62.3 * [presence of 0.50 mg L^{-1} Zn (II)]	77.6 † [presence of 8.0 mg L^{-1} Zn (II)]	Li *et al*., (2020)

Table 1. Efficiency of microalgae in removing nitrogen and phosphorus from various types of swine wastewater.

Microalgae	Swine wastewater type and/or culture conditions	Removal (%)		Reference
		Nitrogen	Phosphorus	
Spirulina sp.	Pretreatment using different aeration periods (i.e. from 3 to 7 days)	67-99.8 [*]	47.1-90.8 [††]	Doan *et al*., (2020)

[*] NH_3-N, [**] TN, [†] TP and [††] PO_4-P.

physiological status of microalgal communities, such as changes in species composition, dominance patterns, and diversity indices, can reflect variations in nutrient availability, water chemistry, and environmental conditions. For example, excessive nutrient inputs, specially nitrogen and phosphorus (about 20 µg L^{-1}), can stimulate algal blooms dominated by fast-growing species (Fenton and Ó hUallacháin, 2012; Miranda and Krishnakumar, 2015) that are potentially toxic and harmful. When the N:P ratio is high and water temperatures increase, ammonium (NH_4^+) predominates, promoting the proliferation of flagellates, cyanobacteria, and chlorophytes. In this condition, the *Prorocentrum minimum* has been found associated with harmful bloom events (Pei *et al*., 2022). Conversely, a lower N: P ratio and cooler temperatures favor nitrate (NO_3^-) and diatoms proliferation (Glibert and Burkholder, 2018), such as those from the genus *Pseudo-nitzschia* capable of producing the neurotoxin domoic acid (Ajani *et al*., 2020; Bates *et al*., 2018).

Furthermore, microalgae can respond rapidly to changes in water quality parameters such as nutrient concentrations, pH, temperature, and dissolved oxygen levels, making them sensitive indicators of environmental stress and pollution events (Essa *et al*., 2024). Monitoring microalgal biomass and photosynthetic activity can provide real-time assessments of water quality dynamics and guide management decisions in swine wastewater treatment, offering a cost-effective and ecologically relevant approach (Essa *et al*., 2024).

4. Microalgae biochemical composition

Microalgae possess the capacity to augment the nutritional profile of conventional foods, thereby exerting a positive influence on the health of both humans and animals. This attribute stems from their inherent chemical composition (Spolaore *et al*., 2006). Table 2 presents a comparative analysis of the overall compositions of food sources utilized for human consumption, contrasting them with various species of microalgae.

The cellular biochemical composition of microalgae can vary due to changes in pH (Andeden *et al*., 2021), light (Gonçalves *et al*., 2019), temperature (Arena *et al*., 2021), different concentrations of N and P (Chu *et al*., 2014), saline conditions (Venckus *et al*., 2021), metallic ions concentration (Zhou *et al*., 2018), and autotrophic-heterotrophic cultivation regimes (Chavoshi and Shariati, 2019).

To obtain a high lipid content, the ideal approach is to produce a large amount of

Table 2. General composition of different human food sources and algae (% dry matter) (Becker, 2013b, 2013a, 2007; Bruton *et al*., 2009; Illman *et al*., 2000; Zhang *et al*., 2014).

Product/Microalgae	Carbohydrate	Lipid	Protein
Meat	1	34	43
Milk	38	34	26
Rice	77	2	8
Soy	30	20	30
Anabaena cylindrica	25-30	4-7	43-56
Aphanizomenon flos-aquae	23	3	62
Arthrospira maxima	13-16	6-7	60-71
Chlamydomonas rheinhardii	17	21	48
Chlorella vulgaris	12-17	14-22	51-58
Chlorella pyrenoidosa	20-70	13-15	20-60
Chlorella minutissima	14-42	31-57	9-24
Chlorella emersonii	11-41	29-63	28-32
Dunaliella salina	32	6	57
Euglena gracilis	14-18	6	39-61
Nannochloropsis sp.	5-17	9-62	23-59
Porphyridium cruentum	40-57	9-14	28-39
Protothecoides auxenochlorella	41-52	11-23	36-38
Scenedesmus obliquus	10-17	12-14	13-16
Spirogyra sp.	33-64	11-21	6-20
Spirulina maxima	13-16	6-7	60-71
Spirulina platensis	8-14	4-9	43-63
Synechococcus sp.	15	11	63

biomass and then deprive it of nutrients. This nutrient deprivation promotes lipid accumulation in the algal cells (Michelon *et al*., 2016, 2022). If a high growth rate and a high lipid content are achieved simultaneously, microalgae could emerge as a promising feedstock for biofuel production, particularly in the field of biodiesel (Chen *et al*., 2015). Lipid accumulation in microalgae, especially triacylglycerols (TAGs), under stress conditions is considered an adaptive mechanism since these compounds can serve as energy/carbon compounds, as well as important electron acceptors (Liu *et al*., 2012).

The lipid composition mainly consists of saturated, monounsaturated, and polyunsaturated fatty acids composed of 12-22 carbon atoms (Tvrzicka *et al*., 2011), with saturated fatty acids being preferable for biodiesel production (Atadashi *et al*., 2012). When subjected to nutrient deprivation, microalgae alter their cellular composition; for example, nitrogen deprivation may lead to a decrease in protein content, decrease in growth rate and photosynthetic efficiency, and a relative increase in carbohydrates and/or lipid storage (Cointet *et al*., 2019).

Carbohydrates are stored in plastids as reserve materials, primarily in the form of starch, and constitute the primary components of the cell wall, including cellulose, pectin, and sulfated polysaccharides (Pierre *et al*., 2019). However, the composition and metabolism of carbohydrates (starch and cellulose) in microalgae can differ significantly from species to species (Chen *et al*., 2013).

The metabolic pathways of carbohydrate- and lipid-rich molecules (energy) are closely linked. Some studies have shown that there is competition between lipid and starch synthesis because the main precursor of triacylglycerols (TAGs) is the synthesis of glycerol-3-phosphate, which is produced through glucose catabolism (glycolysis) (Tan and Lee, 2016). Thus, it is important to understand and manipulate related metabolisms to achieve microalgal carbohydrate accumulation through strategies such as increased polysaccharide storage (Costa *et al*., 2021).

5. Biomass application

Due to microalgae accumulating large quantities of energy-rich compounds (lipids and carbohydrates) under favorable conditions, these compounds can be converted into biodiesel (lipids) and bioethanol (carbohydrates).

Advanced biofuels, particularly those derived from microalgae, are highly sought-after to renewable energy integration objectives and serve for the transportation sector. This approach helps overcome challenges related to land use associated with biofuel production (Moshood *et al*., 2021). Biofuels, which are produced from biomass, are currently seen as one of the most viable energy alternatives to reduce our dependence on fossil fuels, presenting several advantages over them, including sustainability, non-toxicity, biodegradability, and extremely low CO_2 emissions (Jeswani *et al*., 2020).

Biodiesel is a potential substitute for conventional diesel fuel. Biodiesel can be obtained from various feedstocks through a process called transesterification or esterification. The transesterification reaction can be performed using enzymatic processes, acid-catalyzed, or alkali-catalyzed (Kalita *et al*., 2022).

The utilization of carbohydrate-producing microalgae presents an alternative biomass reservoir for ethanol production. The process of ethanol production from biomass through carbohydrate fermentation involves two main steps: saccharification and fermentation. Saccharification necessitates the use of enzymes to hydrolyze carbohydrates prior to fermentation (Silva and Bertucco, 2019).

As microalgal cells possess the capability to synthesize both essential and non-essential amino acids, their amino acid profile closely resembles the standard profile for human nutrition suggested by the World Health Organization and Food Agricultural Organization. This resemblance establishes the nutritional quality of protein, which is fundamentally governed by the amino acid composition (Safi *et al*., 2014, 2013).

Numerous microalgae find diverse applications in aquaculture, with their primary uses revolving around nutrition. They are employed either as a separate component or as a dietary supplement to provide essential nutrients, owing to their high protein, vitamin, and antioxidant content (Mapelli-Brahm *et al*., 2023). As a result, they serve as an important food source in the cultivation of various stages of marine bivalve mollusks, as well as the larval stages of certain marine gastropods, fish species, marine shrimp, and zooplankton (Becker, 2013a).

In addition to its importance in aquaculture, research has shown that their use can replace up to 50% of protein diets in existing animal feed (Spolaore *et al*., 2006). Ginzberg *et al*. (2000) studied the role of microalgae as a dietary supplement in chicken metabolism and found that egg yolk cholesterol was reduced by 10%.

The use of microalgae for human and animal nutrition purposes has been widely reported. Due to their antioxidant activity, they help control body weight, reduce symptoms in subjects with mild to moderate hypertension, reduce lipid absorption, prevent hyperlipidemia and atherosclerosis, and possess antiviral, anticancer, and anti-ulcer properties (Chen *et al*., 2011; Coulombier *et al*., 2021; Deng and Chow, 2010; Kamath *et al*., 2008; Lauritano *et al*., 2016; Michelon *et al*., 2022; Ramos-Romero *et al*., 2021).

6. Applications of integrated wastewater treatment systems

Integrated wastewater treatment systems utilizing microalgae offer promising solutions for managing swine wastewater while mitigating environmental impacts. These systems combine biological, chemical, and physical processes to efficiently remove pollutants and produce valuable biomass for various applications (Nagarajan *et al*., 2019).

The most recommended microalgae-based treatment systems include closed photobioreactors, high-rate algal ponds (HRAPs), and raceway ponds (Nagarajan *et al*., 2023). Closed photobioreactors are transparent, controlled structures that optimize the growth conditions of microalgae, such as light, temperature, and carbon dioxide. These systems are highly efficient in nutrient removal and biomass production; however, they have high operational costs due to the need for stringent control of internal conditions (Koller, 2015).

High-rate algal ponds are a more economical alternative and have been widely used due to their simplicity and efficiency (Young *et al*., 2017). These ponds utilize sunlight and continuous mixing to promote microalgae growth. They are particularly effective in nutrient removal and pathogen reduction. Additionally, HRAPs can be integrated into existing wastewater treatment systems, enhancing their economic and operational viability (Young *et al*., 2017).

Raceway ponds are another popular option for wastewater treatment with microalgae (Rayen *et al*., 2019). These systems consist of open channels where microalgae are cultivated in circulating water. Raceway ponds are known for their ease of operation and low cost, making them ideal for large volumes of wastewater. However, they can be susceptible to contamination and climatic variations. The choice of the ideal system depends on the specific characteristics of the wastewater to be treated and the resources available for the implementation and maintenance of the system (Rayen *et al*., 2019).

One application of integrated wastewater treatment systems is the use of constructed wetlands or algae ponds, where swine wastewater is treated through natural processes involving microalgae, macrophytes, and microbial communities. In these systems, microalgae play an essential role in nutrient removal, carbon fixation, and oxygen production, contributing to water purification (Figure 1) (Abdel-Raouf *et al*., 2012; Bang *et al*., 2024).

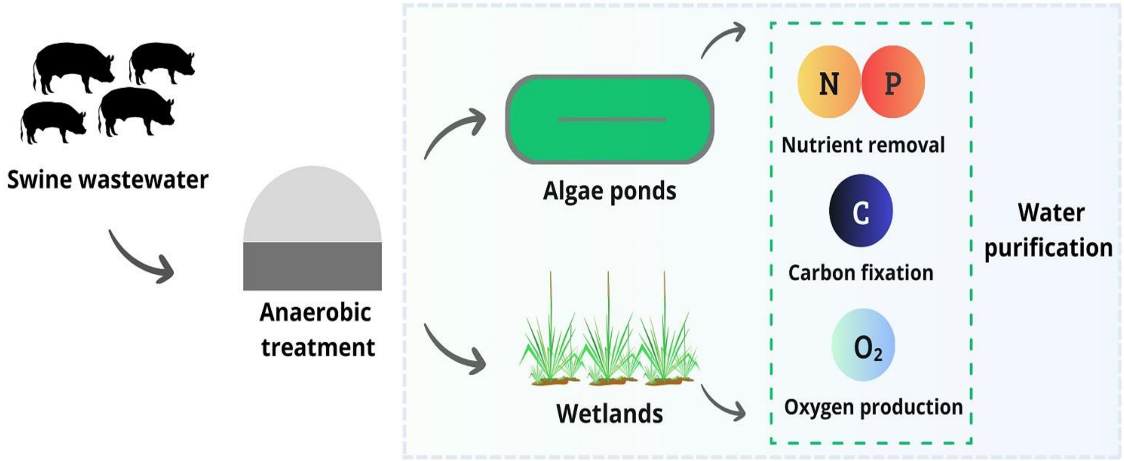

Figure 1. Integrated swine wastewater treatment utilizing hybrid system with anaerobic digestion, algae ponds or/and wetlands with simultaneous nutrient removal, carbon fixation and O_2 production.

Raceway ponds represent another cultivation method, featuring shallow, oval-shaped channels with paddlewheels or circulating pumps to mix and circulate the algal culture. These ponds offer a balance between capital costs and operational efficiency, making them suitable for large-scale microalgae cultivation in wastewater treatment systems (Kumar *et al*., 2015).

Alternatively, flat panel photobioreactors consist of transparent panels or tubes arranged vertically or horizontally to maximize light exposure and biomass productivity. Offering efficient space utilization, uniform illumination, and ease of operation, they are suitable for urban or indoor applications with limited land availability (Chanquia *et al*., 2022).

Another application is the implementation of photobioreactors, closed-loop systems that enable controlled cultivation of microalgae under optimized conditions. These reactors can be integrated into swine wastewater treatment facilities to enhance nutrient uptake, biomass production, and pollutant removal efficiency. Additionally, photobioreactors offer advantages such as high biomass productivity, scalability, and flexibility in operation (Wang *et al*., 2012).

Furthermore, integrated wastewater treatment systems can incorporate advanced technologies such as membrane filtration, adsorption, and chemical precipitation to complement microalgal-based processes and achieve higher treatment efficiencies (Naddeo and Cesaro, 2013). By combining multiple treatment steps, these systems can effectively reduce pollutant concentrations, improve water quality, and meet regulatory standards for discharge or reuse. Overall, the applications of integrated wastewater treatment systems using microalgae, demonstrate their versatility and effectiveness in addressing the environmental challenges associated with swine wastewater, offering sustainable solutions for water management and resource recovery (Li *et al*., 2023).

Selecting the appropriate technology for microalgae cultivation in wastewater treatment systems depends on various factors, including site characteristics, water quality requirements, treatment objectives, and available resources (Dammak *et al*., 2023). By leveraging advanced cultivation technologies, swine wastewater treatment facilities can maximize pollutant removal efficiency, biomass production, and resource recovery, thereby contributing to sustainable water management practices (Sahu *et al*., 2023).

7. Evaluation of efficiency and economic viability

The evaluation of efficiency and economic viability is important for assessing the performance and feasibility of water management strategies employing microalgae in swine wastewater treatment systems. Various key aspects need consideration in this evaluation.

Firstly, the effectiveness of microalgae-based treatment processes in removing nutrients, organic matter, pathogens, and other pollutants from swine wastewater should be quantified (Abdelfattah *et al*., 2023). This involves employing appropriate monitoring and analysis techniques to assess pollutant removal efficiency, enabling optimization of treatment operations and ensuring compliance with regulatory standards for water quality (Abdelfattah *et al*., 2023).

Secondly, the yield, composition, and quality of microalgae biomass harvested from wastewater treatment systems significantly impact the overall economic viability of the process (Srimongkol *et al*., 2022). Evaluating biomass productivity, lipid content, protein content, and other relevant parameters provides insights into the potential for biomass valorization and downstream applications, such as biofuel production, animal feed supplements, and bioremediation (Sundaram *et al*., 2023).

Furthermore, maximizing resource utilization and recovery from swine wastewater, including nutrients, water, and energy, is important for enhancing the sustainability and economic viability of microalgae-based treatment systems. Assessing the efficiency of nutrient uptake, water recycling, and energy generation (e.g., biogas production from anaerobic digestion) allows for optimization of resource use and cost reduction (Perazzoli *et al*., 2016).

Conducting a comprehensive life cycle assessment is also essential to quantify the environmental impacts, energy consumption, and greenhouse gas emissions associated with microalgae-based wastewater treatment systems. Life cycle assessment provides a complete perspective on the sustainability of the process, considering inputs, outputs, and potential trade-offs from cultivation to disposal (Osman *et al*., 2024).

Additionally, assessing the costs and benefits of implementing microalgae-based wastewater treatment systems involves comparing capital investments, operational expenses, and potential revenue streams over the project's lifetime. This cost-benefit analysis helps decision-makers identify opportunities for cost optimization, risk mitigation, and financial viability improvement (Abdelfattah *et al*., 2023; Srimongkol *et al*., 2022).

By evaluating the efficiency and economic viability of water management strategies utilizing microalgae, stakeholders can make informed decisions regarding technology selection, investment prioritization, and implementation planning. Integrating environmental, economic, and social considerations into decision-making processes promotes sustainable development and the long-term resilience of swine wastewater treatment systems (Dwivedi *et al*., 2024).

8. Limitations and challenges

Despite the promising potential of microalgae-based treatment systems for managing swine wastewater, several limitations and challenges exist in their implementation. One significant challenge is the variability in wastewater composition and characteristics, which can affect the performance and efficiency of treatment processes. Swine wastewater contains complex mixtures of pollutants, including nutrients, organic matter, pathogens, and heavy metals, posing challenges for effective removal and treatment (López-Sánchez *et al*., 2022).

Additionally, factors such as seasonal fluctuations, weather conditions, and operational disturbances can further complicate treatment system operation and management. Furthermore, the high capital costs, energy requirements, and maintenance demands associated with advanced treatment technologies, such as photobioreactors and membrane filtration, present economic barriers to widespread adoption, particularly in resource-constrained settings (Sarker and Kaparaju, 2023).

The scalability and applicability potential of microalgae-based treatment systems play a fundamental role in their adoption and integration into swine wastewater management practices. While laboratory-scale studies and pilot-scale demonstrations have shown promising results, scaling up these technologies to commercial or industrial levels presents technical, logistical, and economic challenges (Michelon *et al*., 2022). Achieving scalability requires optimization of cultivation processes, reactor design, nutrient management, and harvesting techniques to maximize biomass productivity and treatment efficiency while minimizing operational costs and environmental footprint (Abdur Razzak *et al*., 2023).

Furthermore, considerations such as land and water availability, and regulatory requirements influence the feasibility and suitability of different treatment approaches in diverse geographic regions and operational contexts (Sarker and Kaparaju, 2023).

Despite significant advancements in microalgae-based treatment technologies for swine wastewater, the need for additional research and future developments remains critical to address emerging challenges and capitalize on untapped opportunities (Wang *et al*., 2024). Research efforts should focus on improving understanding of microalgal physiology, metabolism, and interactions with wastewater constituents to enhance treatment performance and optimize system design. Additionally, exploring innovative cultivation strategies, such as mixed algal consortia, genetically engineered strains, and biofilm reactors, holds promise for overcoming existing limitations and unlocking new potentials in wastewater treatment (Wang *et al*., 2024).

Moreover, interdisciplinary research collaborations involving academia, industry, government, and civil society are essential for integrating diverse perspectives, expertise, and resources to attack complex water management issues effectively. Investing in research and development initiatives, capacity-building programs, and knowledge dissemination platforms can accelerate innovation, substitute technology transfer, and catalyze transformative changes in swine wastewater management practices.

9. Conclusion

Sustainable management of environmental impacts associated with pig manure is important for mitigating water pollution, soil contamination, and air quality degradation. This review has examined emerging strategies for swine effluent treatment, with a particular focus on the use of microalgae. It has been demonstrated that microalgae offer a promising approach for effluent treatment, not only removing nutrients such as nitrogen and phosphorus but also contributing to the production of valuable biomass usable in biofuels, animal feed, fertilizers, and pharmaceuticals.

While microalgae-based technologies show significant potential, challenges remain, including effluent composition variability, operational and maintenance costs, and scalability for industrial implementation. Economic and environmental assessments of these systems are essential to determine their long-term viability and encourage widespread adoption.

Therefore, ongoing investments in research and development are necessary to optimize microalgae-based swine effluent treatment technologies, addressing emerging issues and harnessing new opportunities. By integrating interdisciplinary approaches and development collaborations among academia, industry, and governments, we can advance towards sustainable practices in swine wastewater management, promoting environmental health and human well-being.

10. References

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