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REVIEW PAPER

Aquaculture from inland fish cultivation to wastewater treatment: a review

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Abstract The aquaculture industry is rapidly developing, generating a high amount of wastewater. Inland aquaculture effluents contain nutrients and other substances that can cause eutrophication and the emergence of resistive organisms if released into the environment. Hence, aquaculture wastewater should be treated appropriately for reuse in different applications or safely released into the environment, promoting a sustainable industry and a circular economy. The current review provides insight into aquaculture wastewater generation, constituents, and treatment through various technologies. This study's treatment technologies could be classified as physical, chemical, and biological. SWOT analysis was conducted on each technology to provide an in-depth understanding of the advantages and drawbacks. Suggestions were also stated to shed light on the importance of a sustainable aquaculture industry and the means to transition toward a circular economy.

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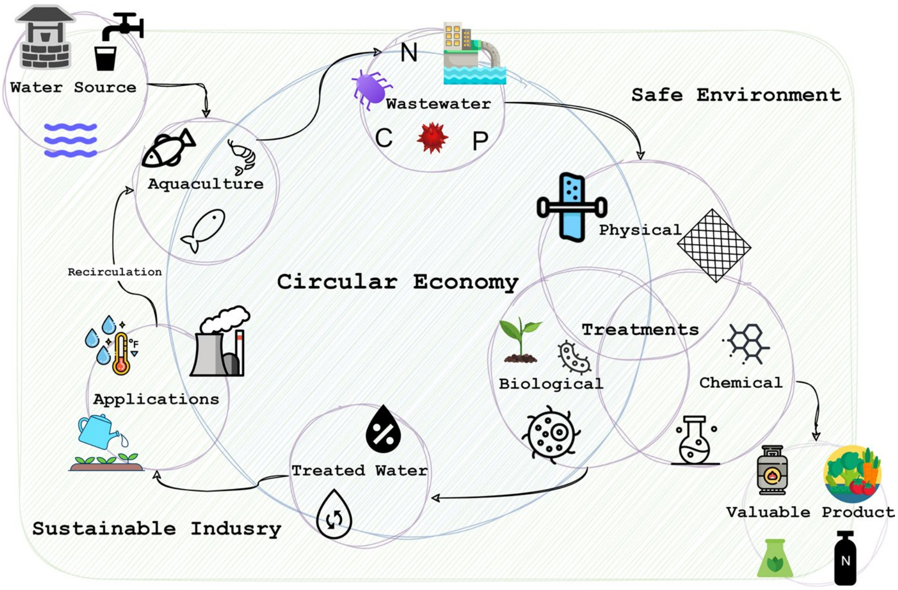
Graphical abstract



Keywords Aquaculture · Wastewater · Treatment · SWOT analysis · Sustainability · Circular economy

1 Introduction

Fish is considered an important ingredient in most meals for human consumption. It contains all the essential amino acids that promote healthy growth and a better overall diet. In addition, fish consumption prevents the development of various diseases such as strokes, heartbreaks, depression, etc. (Ryu et al. 2021). Due to economic and population growth, the consumption of seafood rapidly increased (Naylor et al. 2021). Understandably, there is a continuous increase in fish demand, a common trend between communities and continents worldwide, which makes aquaculture the fastest-growing food production sector (Tran et al. 2019). In fact, in 2020, the aquaculture industry produced up to 50% of the world's food (Hawrot-Paw et al. 2020). The aquaculture industry is dominating the traditional fishery method in production by 18.32 million tonnes, with an estimated US $250 billion (Tacon 2020). The fast development and the increase in fish production by the aquaculture industry forced the captured fisheries to reach a plateau in terms of fish production since 1995 (FAO 2023), as can be clearly illustrated in Fig. 1. Over 190 countries are contributing to producing aquatic species, including fish, crustaceans, mollusks, and aquatic plants (Iber et al. 2021). Asia is responsible for almost 91% of global aquaculture production, with an estimated 102.9 million tonnes in 2017, while 95% of aquaculture production is established in developing countries, with a 6.13% annual production increase (Tacon 2020). By weight, the constituent of fish, aquatic plants, mollusks, and crustaceans, are 47.7%, 28.4%, 15.4%, and 7.5%, respectively, while the remaining 1% includes other species (Tacon 2020). The aquaculture industry has an essential role in providing employment opportunities and developing the economy. Globally, the industry provides either directly or indirectly 23 million full-time jobs (Nasr-Allah et al. 2020). Ghana, for example, developed a program to produce 91,000 tonnes of fish over 3 years (2018–2020), employing 86,177 people and enhancing its economic status (Ragasa et al. 2022).

The cultivated fish in the aquaculture industry could be classified as brackish water, freshwater, and seawater species, and the global contribution of each

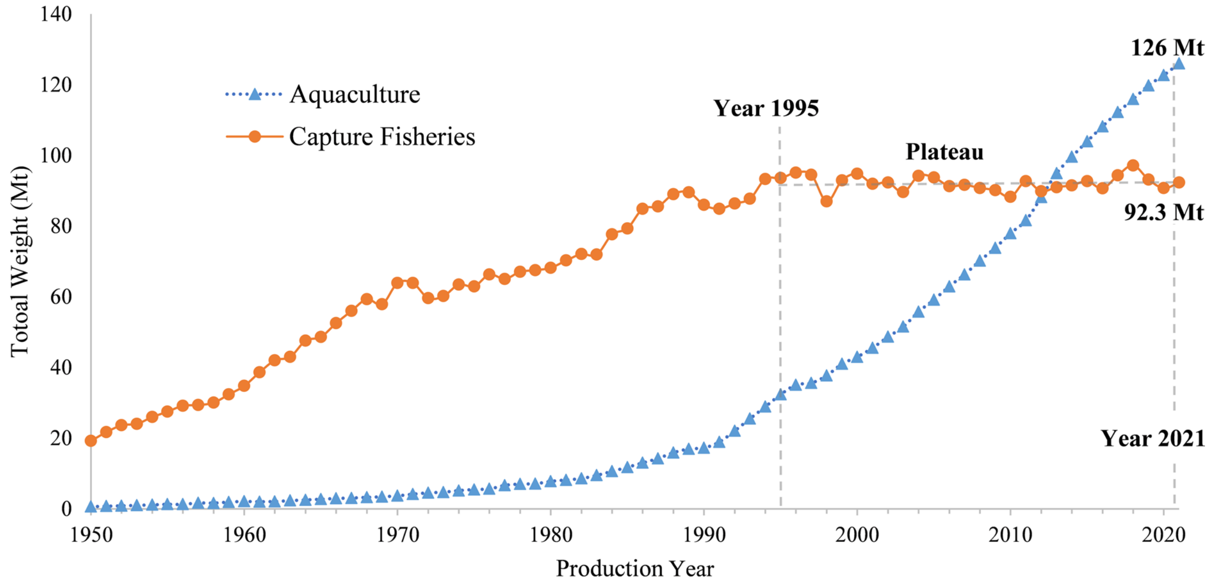


Fig. 1 Aquaculture and capture fisheries production (Million tonnes) per year. The capture fisheries fish production has reached a plateau since 1995 (FAO 2023)

species in terms of production is 9.06%, 43.22%, and 47.72%, respectively (Boyd et al. 2020). When tracing the production of the top commonly cultivated fish species, it is apparent that Asian countries lead with more than 90% of the total global output, and the production volumes are predicted to be doubled by 2050 (Stentiford et al. 2020).

Also, due to the high demand for fish supply in China, the wastewater discharged from the aquaculture facilities exceeded the land sewage waste (Lang et al. 2020; Zhang et al. 2023a). According to the study (Xu et al. 2020), in China, the municipal wastewater discharge in 2015 was 53.5×10^9 m^3, while the agricultural water usage was 39.22×10^{10} m^3 in 2013, which is approximately more than 7 times the municipal wastewater discharge. Furthermore, another study stated that in 2018, 35.86×10^{10} m^3 of water supply was used by the aquaculture industry alone in China (Liu et al. 2021). Hence, the rapid development of the aquaculture industry and the continuously increasing production have their drawbacks as challenges emerge, hindering future sustainability. Land subsidence (due to groundwater extraction, land use, and land reclamation), excessive use of water resources, and pollution of the surrounding water bodies are a few of the challenges that are expected to escalate further by 2050 (Ahmed et al. 2019; Hung et al. 2023; Liu et al. 2023).

According to a study, fish meal and fish oil are the most utilized nutritious and digestible feed materials for fish cultivation; however, the overuse of these two materials could result in economic risks, forcing the production of lower-quality fish (Zhang et al. 2020). Furthermore, with the rampant growth of the aquaculture industry, the overuse of traditional feeding has a noticeable contribution to harmful gas emissions, such as greenhouse gasses or GHGs, and huge loss of water resources (MacLeod et al. 2020; Kurniawan et al. 2021a; Li et al. 2021). These negative aspects result in environmental impacts such as global warming, waste of energy, waste of water resources, and the release of valuable nutrients (Pulido-Rodriguez et al. 2021). In addition, the aquaculture industry discharges an abundant amount of wastewater, containing organic and inorganic materials, pharmaceutical substances, and a high amount of nutrients; if dealt with properly, the wastewater can be treated, or the resources can be recovered through various methods (Kurniawan et al. 2021a). The aquaculture wastewater (AWW) contains nitrogenous and phosphorous compounds, along with high chemical oxygen demand (COD) and other nutrients, which will result in eutrophication if discharged untreated to waterbodies (Ahmad et al. 2021). Furthermore, the discharge of AWW without treatment will induce the growth of toxic algal blooms unfavorable to aquatic life (Liu et al. 2019). In addition, antibiotics are periodically added to maintain the health of the cultivated fish. Even though the concentration of the antibiotics is relatively low, it promotes the development of bacteria with resistive characteristics (Chen et al. 2020b); these emerging bacteria will have an adverse effect on humans, animals, and generally the natural ecosystem (Huang et al. 2019). Consequently, the remediation of AWW should receive more attention due to the related adverse environmental impacts.

Multiple approaches were developed to treat the aquaculture effluent and minimize the harmful effects of the wastewater on the environment. Generally, the methods could be classified as biological, physical, and chemical treatments, and sometimes a treatment can be classified as a combination of two methods, like the physiochemical treatment. The biological treatment utilizes living organisms such as algae (Al-Jabri et al. 2020) and plants in aquaponics (Yanes et al. 2020) to consume the nutrients in the wastewater. Physical treatment processes separate contaminants in their original forms through physical processes. For example, coagulation/flocculation is a physiochemical treatment process that neutralizes the charge of colloidal or suspended contaminants, creating flocs that precipitate with time and can be easily removed (Zhao et al. 2021). Adsorption is another example of a physiochemical treatment where the soluble contaminants or absorbates attach to the surface of the solid adsorbent (Rashid et al. 2021). Chemical treatment is the process of degrading the existing contaminants in the wastewater and converting them to byproducts that are less harmful to the environment. Chemical treatments usually revolve around the advanced oxidation process of free radicals or reactive oxygen to degrade wastewater contaminants, producing oxidized intermediates, carbon dioxide, water, and inorganic acids (Kanakaraju et al. 2018). For more effective remediation, an integration of multiple treatment types could be utilized, resulting in safer effluents to be discharged.

The rapid development of the aquaculture industry and the continuous generation of AWW captured the attention of researchers due to the consequential harmful effect on the environment. The research in the field of AWW is in increasing trend (Fig. 2), highlighting the importance of the matter and the necessity for more efficient, economical, and environmentally friendly treatment methods, leading to a more sustainable aquaculture industry.

This review covers various processes of aquaculture, including fish production, AWW generation, and various treatment methodologies. Multiple recent treatment studies were summarized, and a SWOT analysis was conducted for each treatment category, emphasizing the opportunities, challenges, and fit-to-purpose applications. Suggestions and

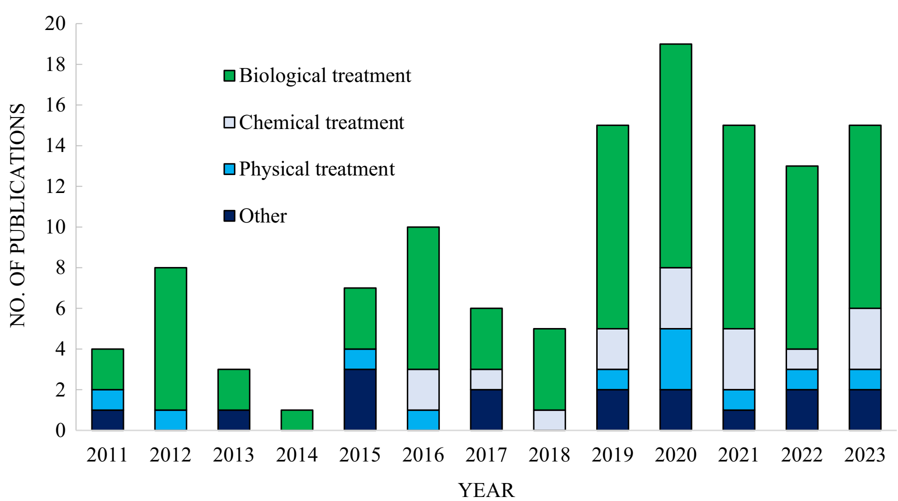


Fig. 2 Publication history using the keyword "Aquaculture wastewater treatment" in SCOPUS, limited to the publication title. Other: includes case studies, descriptive research, identifications, monitoring, and reviews

recommendations were included to promote a more sustainable industry by adopting a circular economy approach.

2 Land-based fish cultivation

Land-based fish cultivation is an intensive fish farming system done on land. When talking about wastewater generation and treatment, the focus is more on the systems where the accumulation of waste occurs, unlike fish rearing on river streams and offshore areas with the continuous renewal of water. Depending on the availability of technology and initial capital cost, intensive fish cultivation systems can generally be either by using tanks and ponds or through a Recirculation aquaculture system (RAS). More details about the two cultivation methods can be found in the supplementary.

2.1 Tanks and ponds or traditional cultivation

The traditional fish cultivation using tanks and ponds is a more economical approach that requires less energy and skilled labor. Traditional aquaculture is valued at US$ 2000 per tonne (Waite et al. 2014), and the cultivated fish are confined in a specific volume of water that is often not regularly changed. The general size of the ponds ranges from 100 to 100,000 m^2, and the depth ranges between 1.2 and 1.5 m (Ngo et al. 2017). In intensive cultivation, water usage could be as high as 45 m^3/kg of fish (Tal et al. 2009; Verdegem et al. 2006). Additionally, under intensive cultivation, the accumulation of fish waste (feces), unutilized fish feed, and sometimes antibiotics will increase the nutrient contents, forcing the growth of undesired microbes and pathogens. Traditional aquaculture requires large land and a high volume of water (Lin and Wu 1996; Thomas et al. 2021). Also, ammonia accumulation could be a major concern as it can increase fish mortality, even at low concentrations of 0.05–0.5 mg/L (Bernardi et al. 2018).

2.2 Recirculation aquaculture system (RAS) or modern cultivation

RAS is the modern method to cultivate fish, but the annual production cost using the RAS system is expensive and ranges between US$ 2250 to US$ 8800 per tonne (Waite et al. 2014). The typical energy consumption in RAS is in the range of 15–30 kWh/kg production of fish (Ayer and Tyedmers 2009; Badiola et al. 2017; d'Orbcastel et al. 2009; Martins et al. 2010). The main idea behind RAS is the simultaneous cultivation of fish and treating the wastewater, then recirculating the treated to the fish tanks. Water usage in RAS could be as low as 0.016 m^3/kg marine fish (Tal et al. 2009; Verdegem et al. 2006). The typical stocking density in RAS is in the range of 70–120 kg/m^3 with a feed conservation ratio of 0.8–1.1, and the production rate could be up to 400–500 tonnes/year (Ahmed and Turchini 2021). RAS is extremely efficient in water conservation; the water recirculation rate could be in the range of 90–99% (Dalsgaard et al. 2013). The production rate could be up to 400–500 tonnes/year (Ahmed and Turchini 2021).

Table 1 Aquaculture wastewater generated, treated, and reused in different regions around the world (Sato et al. 2013; Kurniawan et al. 2021b)

Aquaculture wastewater (km^3/year)	Generation	Treatment	Reuse
Asia	133.12	42.17	14.4
North America	85	61.12	2.35
Latin America	29.75	5.31	0.55
Europe	52.44	34.86	1.38
The Soviet Union	27.84	20.16	0.99
Middle East and North Africa	22.64	11.9	3.69
Sub-Saharan Africa	3.71	3.3	0.06
Total	356.59	181.15	23.768

3 Aquaculture wastewater generation

3.1 Statistics on aquaculture wastewater

Generally, a huge amount of fresh water is used to cultivate fish. For instance, almost 50 m^3 of fresh water is needed to produce 1 kg of tilapia (Cardoso et al. 2021). According to the studies (Sato et al. 2013; Kurniawan et al. 2021b), Asia is considered the highest in terms of AWW generation, as it generates almost 133,120 m^3/year, which contributes to 37.3% of the total AWW generation (Table 1). In contrast, the region with the least wastewater generation is Sub-Saharan Africa, which is understandable as the region already suffers from a lack of water resources (Hughes 2019). Considering the latter probable cause, almost 90% of the wastewater is treated with little reuse, indicating the efforts exerted to protect the environment and receiving water bodies against wastewater-related problems in Sub-Saharan Africa. Most of the treated water is used for irrigation or released into the environment. The wastewater generated from aquaculture in the US, Europe, The Soviet Union, and the Middle East ranges from 22,640 to 85,000 m^3/year.

3.2 Characteristics of aquaculture wastewater

Several substances exist in the cultivation ponds in the aquaculture industry. Fish feed, medicine, and fish excreta are some of the constituents that accumulate in the cultivating water, then released as a part of the wastewater discharge. The wastewater can be later characterized by determining multiple parameters. The concentration of COD, Total Ammonia Nitrogen (TAN), and Total nitrogen (TN) could reach as high as 1201, 101, and 359 mg/L, respectively (Chen et al. 2020a). Table 2 lists the characteristics of AWW depending on the type of cultivated fish. Generally, effluents from shrimp farms are considered the richest in terms of nutrients when compared to other species, as the concentration of TN and total phosphorus (TP) of shrimp effluents could be as high as 210 and 176.43 mg/L, respectively. Meanwhile, the concentration of TN and TP in the effluent of other species are in the range of 1.09–51.51 mg/L and 0.07–85 mg/L, respectively.

3.3 The impact of wastewater release on the environment

Aquaculture indeed has an essential role in providing food resources and covering food demand while improving the economy at the same time. However, the effect of the industry on the environment should be taken into consideration. Rearing fish requires the addition of various substances, whether for feed or to preserve the overall health of the fish, the added constituents will not be completely absorbed and will remain as contaminants in the water. It is reported that about 8.6–52.2% of fish feed is considered waste in the culturing water (Ballester-Moltó et al. 2017). Additionally, the excreta of the cultivated fish also contributes to the contamination of the cultured water (Dauda et al. 2019). Hence, releasing the contaminated water into the environment will lead to various complications, as illustrated in Fig. 3.

3.3.1 Eutrophication

Eutrophication can occur in different types of water bodies due to its pervasive attribute, forcing the degradation of the water quality (Le Moal et al. 2019). Eutrophication is primarily caused by the overgrowth of organic matter and microorganisms due to the accumulation of contaminants, mainly nitrogen and phosphorus (Ferreira et al. 2011; Le Moal et al. 2019). In general, almost 52–95% of nitrogen and 85% of phosphorus of the added feed in the fish rearing pond are lost as excess or unconsumed feed, fish excretion, and fish faces (Zhou et al. 2006). Multiple complications can be developed due to eutrophication like the reduction in oxygen content in water bodies, which leads to the fatality of aquatic life, the propagation of undesired algal blooms, and contributes to the emission of greenhouse gasses (Wurtsbaugh et al. 2019; Li et al. 2021). A conservative projection suggests that the yearly expenses caused by eutrophication are approximately \$2.4 billion for streams and lakes in the United States, \$1 billion and \$ 100 million for coastal waters in Europe and the United States, where 37% of the latter cost caused by losses related to commercial fisheries (Wurtsbaugh et al. 2019). The contaminants in the wastewater could induce the rapid growth of aquatic microorganisms

Table 2 Characteristics of aquaculture wastewater

Fish type	pH	NO_3^-–N (mg/L)	NO_2^-–N (mg/L)	NH_4^+–N (mg/L)	PO_4^{3-}–P (mg/L)	TN (mg/L)	TP (mg/L)	DO (mg/L)	COD (mg/L)	Turbidity (NTU)	Salinity (PPT)	References
Tilapia	6.5–8.27	0.389–40.67	5.52	1.06–5.3	8.82	10.8–51.51	0.909–8.82	4.17	65–96	8.7	0.26–6	Bhuyar et al. (2021), Ansari et al. (2017) and Kashem et al. (2023)
Southern flounder	7.7–8.1	–	0.03–0.04	0.2–0.4	–	–	–	6.5–8.2	2.1–4.1	1.2–1.6	–	Chen et al. (2015)
Pike perch	7.05–7.5	–	–	7.4–9.6	3.3–5.0	24.1–34.1	3.5–6.1	–	153–273	–	–	Tossavainen et al. (2019)
Catfish	6.68–7.5	2.5–11.9	–	0.08–24.5	0.07–4.8	23.7–29.2	3.6–5.7	4.17–6.3	12.6–256	307	–	Tossavainen et al. (2019), Omotade et al. (2019) and Kurniawan et al. (2023a, b)
Salmon	7.98–8.54	–	–	–	–	31.83	1.1	–	–	–	10	Hawrot-Paw et al. (2020)
Shrimp	7–8.2	0.499	0.108	0.14–0.28	–	210	85–176.4	5.3	18.3–1730	29.4	22–23	Ge et al. (2008), Vijayaraghavan et al. (2008) and Ramos et al. (2009)
Eel	6.3–7.8	17	0.05–0.21	1.6–4.62	3.6–5.4	12.4	3.64–5.4	–	48–155	0.41–44.5		Chung (2006), Han et al. (2019) and Bennett et al. (2018)
Crucian carp	–	–	–	72	–	47.6	–	–	368	–	–	Han et al. (2019)

Table 2 (continued)

Fish type	pH	NO_3^-–N (mg/L)	NO_2^-–N (mg/L)	NH_4^+–N (mg/L)	PO_4^{3-}–P (mg/L)	TN (mg/L)	TP (mg/L)	DO (mg/L)	COD (mg/L)	Turbidity (NTU)	Salinity (PPT)	References
Rainbow trout	7–7.6	0.38–14	0.3	0.27–2.06	0.54–5.45	1.18	0.19–7.6	–	17.6–74	–	–	Schulz et al. (2004), Heiderscheidt et al. (2020) and Gorzelnik et al. (2023)
Yellow catfish	–	0.51	0.134	2.35	–	3.6	0.23	2.45	66.6	–	–	Huang et al. (2019)
Mixed culture	6.72–8.04	0.38–30.17	0.17–30	0.63–9.7	0.93–34	1.09	0.07–32.5	3.82–3.84	204–206	67.2–76.2	44	Akinbile and Yusoff (2012), Villar-Navarro et al. (2019) and Hesni et al. (2020)
Whitefish	7.39–7.49	96.87–97.03	0.03–0.05	0.03–0.05	3.76–3.83	–	–	–	–	1.33–5.27	–	Calderini et al. (2021)

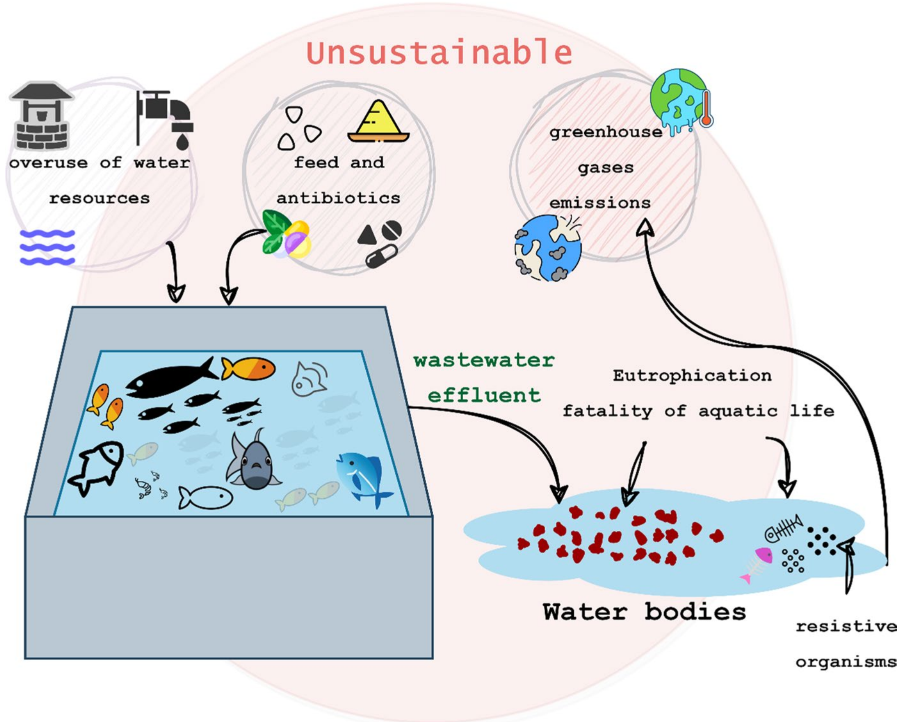


Fig. 3 The effect of aquaculture wastewater release into the environment

such as microalgae, cyanobacteria, dinoflagellates, etc. (Jing et al. 2021). Among these microorganisms, several cyanobacteria and dinoflagellates could produce several toxic substances, further contaminating the eutrophic waters (Carmichael 1992; Jia et al. 2014); these toxic substances could also enter the aquatic food ecosystem (Wurtsbaugh et al. 2019). The overgrowth of undesired algal blooms and cyanobacteria, especially on the surface of water bodies, will obstruct the light from penetrating the water, causing harm to the aquatic life and increasing the acidity of the water due to the accumulation of dead algae and plants—affecting the ecosystem (Cai et al. 2011; Zhu et al. 2013; Jiang et al. 2017).

3.3.2 The emergence of resistive organisms

In the aquaculture industry, the use of synthetic antibiotics is common, where these compounds can kill pathogenic microorganisms and play an important role in treating infectious diseases (Shao et al. 2021). Antibiotics can be administered orally, sprinkled on ponds, or by direct injection to prevent the disease from spreading while promoting fish growth (Chen et al. 2020b). It is reported that China uses up to 105 thousand tonnes of antibiotics for animal consumption, equivalent to almost 50% of the amount of antibiotics produced in China (Chen et al. 2020b). The global consumption of antibiotics by the aquaculture industry is estimated to be 10,259 tonnes in 2017, 57% of the antibiotic consumption is attributed to the aquaculture industries in China, and it is predicted that the global consumption of antibiotics will increase by 33% (13,600 tonnes) in 2030 (Schar et al. 2020). In a typical aquaculture industry in China, commonly known residual antibiotics could be detected within the range of 13.6 and 102.8 ng/L, and due to the lack of discharge standards, the majority of these residual antibiotics end up being discharged in nearby rivers (Zhang et al. 2023c). The accumulation of antibiotics also contributes to the degradation of water quality. On some occasions, several antibiotics, such as norfloxacin, sulfadiazine, and many others, were reported to exist at concentrations up to 7722 ng/L in fish ponds (Zou et al. 2011). Analysis of water bodies where the AWW is released revealed that they contain over-the-counter (OTC) antibiotic-resistive bacteria, enforcing the fact that OTC antibiotics are present in AWW in

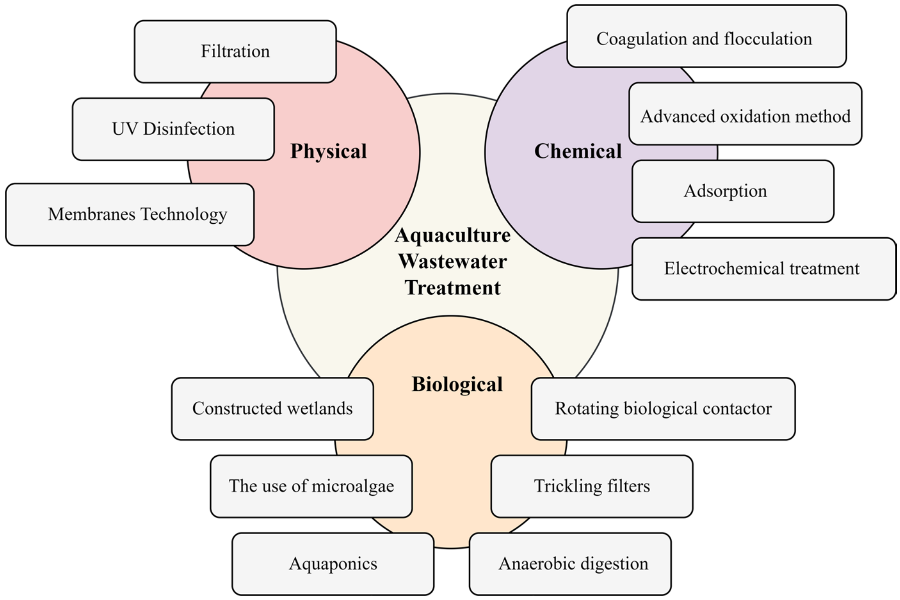


Fig. 4 Aquaculture wastewater treatment classification

most cases (Tendencia and de la Peña 2001). A study confirmed that resistive bacteria were detected in an environment with residual antibiotics in concentrations as low as 0.1 µg/mL, implying that the accumulation of antibiotics will increase the emergence of resistive microorganisms (Le et al. 2005). If resistive organisms, such as bacteria, are transferred to the animal or human body, it will lead to some health issues, such as the development of various infections (Junaid et al. 2022). According to a study, more than 700 thousand deaths occur each year due to drug-resistant diseases caused by resistive organisms, and the lack of mitigation plans will increase the mortality to 10 million deaths per year (Shao et al. 2021).

4 Aquaculture wastewater treatments

The aquaculture wastewater treatment method could be generally classified as physical, chemical, and biological treatment (Fig. 4). The classification is based on the methodology in which the contaminants are separated, either by pure separation in their original form, by assimilation, or by degradation and conversion to other substances. Different studies were summarized in Tables 3, 4, and 5, and SWOT analyses were conducted for these treatment methods in Tables 6, 7, and 8, accentuating the suitability of the treatment methods depending on the desired outcomes. The SWOT analysis also includes the typical energy requirement, giving a perspective on the economic state of each treatment method.

4.1 Physical treatments

4.1.1 Filtration and membrane technology

One of the conventional ways of treating wastewater is the use of filters. The same concept is applied to AWW, as the effluent goes through the small pores of the filters, it leaves behind a supernatant free of any contaminants larger than the pore size (Nora'aini et al. 2005; Chen et al. 2015; Xu et al. 2021). However, filtration alone cannot remove the dissolved contaminants, or at least not entirely. For that reason, filtration processes, most of the time, are coupled with other systems before or after the filtration to achieve effective remediation. Catalytic Ozonation is one of the Advanced Oxidation Processes, which can remove 52.1% of organic matter, 75% of total ammonia nitrogen, and 95.8% recovery of water (Chen et al. 2015). In electrocoagulation, an electric field is developed that releases metal cations and flocculates the pollutants while simultaneously degrading microorganisms and removing color (Xu et al. 2021). Sand filtration could also be used as a pretreatment of the wastewater so that it can be suitable to be treated using filters (Nora'aini et al. 2005). However, the

Table 3 Summary of various physical treatments of AWW

Treatment method	Material/strain	Wastewater source	Optimum conditions	Treatment efficiency	Recommendation	References
Filtration system	Electrocoagulation + filtration system	White leg shrimp (*Litopenaeus vannamei*) aquaculture wastewater	Current density: 19.22 A/m^2, Anode: 3AL + Fe, HRT: 4.5 min, Pore size: 45 µm	COD: 48.99%, TAN: 57.06%, NO_2^-–N: 34.09%, NO_3^-–N: 18.47%, TN: 55.26%	To explore the coupling of low energy-consuming treatment with the filtration system	Xu et al. (2021)
Filtration system	Catalytic ozonation + filtration in two forms: (TiO_2/Al_2O_3) and (Ti-$MnTiO_2/Al_2O_3$)	Aquaculture farm cultivates fish (*Paralichthys lethostigma*). China	Pressure: 2.22–2.3 bar, Velocity: 1.04 m/s, Ozone dosage: 52 mg O_3/min Gas flow: 4000 L/h Temp: 17–19 °C	Water recovery: 95.8%, SS: 100%, COD: 35.7–52.1%, TAN: 60%, NO_2^-–N: 93%	The energy requirement for the treatment process should be determined	Chen et al. (2015)
Filtration system	Filtration system + biological remediation using microalgae	Aquaculture farm cultivating whitefish (*Coregonus lavaretus*), Finland (LUKE) Laukaa fish farm	Filter pore size: 45 µm, Microalgae: *Haematococcus pluvialis, Monoraphidium griffithii,* and *Selenastrum* sp.	PO_4^{3-}–P: 75–99%, NO_3^-–N: 40%	The filtration did affect the biological treatment process	Calderini et al. (2021)
Ultraviolet treatment	flow-through ultraviolet/electro-chlorine (EO + UV) process	Marine aquaculture wastewater, seafood breeding factory, Tianjin	10 mA (1.4 mA/cm^2), flow rate 15 mL/min, pH of 8	Sulfamethazine: 100%, NH_4^+–N: 77–97%	An economic analysis should be conducted regarding this study	Lang et al. (2022)
Ultraviolet treatment	ultraviolet/peroxysulfate (UV/PS) process	Synthetic wastewater	Volume: 200 mL, 30 mg/L persulfate, 30 min of UV irradiation	The inactivation of tetracycline-resistant bacteria within 5 min	The removal of other contaminants should be explored	Zhang et al. (2022)
Membrane technology (MBR)	Membrane PBR + microalgae (*Chlorella vulgaris*)	The supernatant of white leg shrimp (*Penaeus vannamei* Boone) wastewater, salinity: 2.8%, China	T:25 °C: pH: 6.8–7.2, HRT: 1 day	TN: 86.1%, TP: 82.7%	An economic evaluation of large-scale treatment using the studied treatment technology could be explored	Gao et al. (2016)
Membrane technology(MBR)	Membrane distillation, polyvinylidene fluoride templated membrane	n.s	Feed temp: 60 °C, permeate temp: 20 °C, Q: 0.5 L/min	NH_4^+-N: 93.8%, TP: 99.6%, Ca: 98.9%, Na: 97.6%, Mg: 100%, TOC: 96.3%	The energy requirement of the treatment process and the fouling of the membrane should be investigated	Chin et al. (2020)

Table 3 (continued)

Treatment method	Material/strain	Wastewater source	Optimum conditions	Treatment efficiency	Recommendation	References
Membrane technology(MBR)	Dead and permeation cell, polysulfone nano-filtration membrane	The wastewater obtained from the hatchery pond of the Department of Fisheries, catfish, University Malaysia Terengganu	Pressure: 6 bar, pH: 6	PO_4^{3-}–P: 95%, NH_4^+–N: 85%	The energy requirement of the treatment process and the fouling of the membrane should be investigated	Ali et al. (2011)
Membrane technology—direct contact membrane distillation	Templated membrane and intermediate physical flushing	Synthetic seawater fish farm wastewater	Permeate temp: 20 °C, feed temp: 60 °C. Effective are: 9.45 cm^2	Up to almost 100% removal of all reported contaminants	The feasibility of large-scale treatment should be explored	Teoh et al. (2023)

filtration process has some major disadvantages that revolve around the fouling of the membrane and the high energy demand. Even though there are studies to enhance the efficiency of the filters by reducing fouling to a certain extent (Chen et al. 2015), membrane fouling is almost inevitable, and the requirement of backwashing cannot be avoided. Furthermore, filtration processes are always considered energy-intensive regardless of the added enhancements.

The use of membrane technology or membrane bioreactor (MBR), which is a combination of physical filtration and biological degradation, in treating wastewater from aquaculture is becoming more popular due to promising results in both laboratory and on-site experiments. Membrane technology has proven to be highly effective in removing small contaminants such as organic compounds, viruses, and harmful bacteria present in aquaculture wastewater (Teoh et al. 2021). The operation mechanism of membranes can differ depending on their types and configurations. Generally, membranes function as separation device that removes unwanted substances from water. They act as a selective barrier, allowing certain molecules to pass through while blocking others, while the biological treatment assimilates dissolved contaminants. This results in the separation and degradation of contaminants from wastewater. However, membrane technology often faces fouling issues, where the membrane pores become clogged over time due to the accumulation of unwanted substances on the membrane surface, leading to a decline in flux (Zhou et al. 2021). Sharrer et al. (2007) examined how MBR can treat wastewater from rainbow trout that is raised in an RAS. The study found that MBR can eliminate up to 99.98% of total suspended solids and 99.99% of total volatile solids in wastewater. Additionally, it achieved outstanding removal rates of up to 95.5% and 96.1% for total nitrogen and phosphorus in the wastewater, respectively. Another study showed that while treating wastewater, the average removal of Biological Oxygen Demand (BOD), COD, TN, and TP using MBMBR can reach up to 94%, 92%, 74%, and 73% (Saidulu et al. 2021).

4.1.2 UV disinfection

The accumulation of fish feed and fish waste in the rearing tanks increases the organic and inorganic compounds, creating a favorable habitat for the

Table 4 Summary of various chemical treatments of AWW

Treatment method	Material/strain	Wastewater source	Optimum conditions	Treatment efficiency	Application of treated water	Recommendation/ comment	Reference
Coagulation and flocculation	Chemical-based coagulation (alum) and biological-based coagulation (neem leaves/*azadirachta indica*)	Aquaculture wastewater cultivating catfish, Malaysia	Alum: 0.4 mg/L, Neem: 0.3 mg/L	For alum: TSS: 99.7%, Turbidity: 98.8%, Color: 97.3%, For neem: TSS: 81%, Turbidity: 82%, Color: 84%	The study proposed that the treated water can be used to cultivate daphnids or microalgae	The study concluded that the treatment is not economical The specifically proposed application of the treated water is due to the inability of the treatment method to remove dissolved nutrients	Kurniawan et al. (2023a)
Coagulation and flocculation	Bio-coagulation using chitosan from carapace of Giant Freshwater Prawn (*Macrobrachium rosenbergii*)	Intensive shrimp culture facility, Malaysia	For turbidity removal: Dosage: 20 mg/L, pH: 6.25, settling time: 30 min, for salinity removal: Dosage: 5 mg/L, pH: 7.5, settling time: 30 min	Turbidity: 87.67%, Salinity: 21.43%	n.s	The economic feasibility of the treatment method should be explored	Iber et al. (2023)
Coagulation and flocculation	In organic Poly aluminum chloride (PAC)	RAS aquaculture facility that cultivates rainbow trout (*Oncorhynchus mykiss*), Finland	Dosage: 32 mg/L, Rapid mix: 200 rpm 30 s. Slow mix: 40 rpm 5 min, Settling time: 30 min	Turbidity: > 98%, TSS: > 97%, PO_4^{3-}–P: 98.2%	The study suggests that the treated water can be recirculated back to the fish tanks	The economic feasibility of the treatment method should be explored	Heiderscheidt et al. (2020)
Coagulation flocculation	plant-based coagulant extracted from *Leucaena leucocephala* seeds	Aquaculture wastewater from freshwater fish farm, Malaysia	Dosage of 240 mg/L. Mixing speed of 150 rpm. Settling time of 40 min	Turbidity: 96.32%, TSS: 92.85%, Color: 86%	n.s	The treatment was able to remove the solid contaminants but increased the dissolved contaminants such as NO_3, PO_4, and COD	Alnawajha et al. (2023)

Table 4 (continued)

Treatment method	Material/strain	Wastewater source	Optimum conditions	Treatment efficiency	Application of treated water	Recommendation/comment	Reference
Advanced oxidation process	Ultrasonic cavitation coupling with H_2O_2 and Fenton reagent	Tilapia fish farm	H_2O_2: 500 ppm, Ultrasound: 50% (1000 W), Time: 30 min	TAN:100%	n.s	The feasibility of large-scale treatment should be explored	Tan et al. (2021)
Advanced oxidation process	Fenton process coupled with coagulation	Nile Tilapia farm	Batch reactor: 60 L, H_2O_2: 10 mmol/L, Fe^{2+}: 0.1, 0.3, 0.5 mmol/L	COD, Turbidity, PO_4^{3-}–P, and NO_2^-–N: > 99%, BOD: 88%	The treated water can be discharged to receiving bodies	According to the study, the results were not satisfactory The economic status of the treatment method should be explored	Gomes et al. (2020)
Advanced oxidation process	Electrochemical oxidation	Seafood breeding factory	Current: 30 mA, Flow rate: 5 mL/min, pH: 5–9, Cl^-: 9 g/L	NH_4^+-N: 98%, NO_2^-–N: 96%, TP: 72%, COD: 48%	n.s	–	Lang et al. (2020)
Adsorption	The use of smectite clays with different chemical composition	Two types of wastewater: Synthetic (20 mg/L TAN), Aquaculture wastewater (Oreochromis *niloticus* and Rhamdia *quelen*), Brazil	For synthetic: 7.5% (w/w) clay, pH: 7.5, for aquaculture: 0.5% (w/w)	For synthetic: NH_4^+–N: 97.48%, For aquaculture: NH_4^+–N: 93%	n.s	The economic feasibility of the treatment method should be explored	Zadinelo et al. (2015)
Adsorption	The use of chitosan	Synthetic (7.35 mg/L TAN) and collection of aquaculture wastewater (0.14, 0.27, 0.5 mg/L TAN)	For synthetic: 10% (mm^{-1}), For aquaculture: Dosage: 1% (mm^{-1})	For synthetic: NH_4^+–N: 94.33%, For aquaculture: NH_4^+–N: 100%	n.s	The economic feasibility of the treatment method should be explored	Bernardi et al. (2018)
Adsorption	The use of aluminum pillared bentonite	shrimp farm, fish larval ponds, and others	pH: 4–10, dosage: 0.05–2 g, temp: 25–45 °C	PO_4^{3-}–P: 85.3–99.6%	n.s	The treatment of other contaminants should be explored	Kumararaja et al. (2019)

Table 4 (continued)

Treatment method	Material/strain	Wastewater source	Optimum conditions	Treatment efficiency	Application of treated water	Recommendation/ comment	Reference
Adsorption	Activated carbon + (*Bacillus cereus*)	Eel aquaculture wastewater, China	Temp: 28 °C, AC dosage: 2–8 g, Mixing: 120 rpm, HRT: 2–4 days	TP: 96.1%, COD: 98%, NH_4^+–N: 100%, TN: 97.4%	n.s	The energy requirement of the treatment process should be explored	Huang et al. (2023)
Adsorption	Zr-modified-bentonite filled polyvinyl chloride membrane	Sea cucumber aquaculture wastewater	The use of a cross-flow system Membrane area of 70 cm^2 Temp: 25 °C	TP: 91.5%, PO_4^{3-}–P: 95.9%	The application of the treated water is not specified. However, the phosphate captured by the membrane was used to cultivate microalgae	The energy requirement of the treatment method should be explored The treatment of other contaminants should be explored	Zhang et al. (2023a)
Electrochemical oxidation	Iron single-atom electrode (Fe–Sas/N–C)	Synthetic wastewater: 20 mg/L TAN, Aquaculture wastewater: 15 mg/L	for both wastewater: current (0.75 mA/cm^2) and the time is 2 h	For synthetic: NH_4^+–N: > 99%, For aquaculture: NH_4^+–N: 96.7%	The treated water meets the discharge limits	The economic feasibility of the treatment process should be explored	Quan et al. (2023)
Electrochemical oxidation	Electrochemical filter (RuO_2-IrO_2-TiO_2/Ti) mesh anode	Recirculating aquaculture wastewater	Current density: 2 mA/cm^2, Solution volume: 300 mL, Reaction time: 1.5 h	TN: > 94%	n.s	The removal of other contaminants should be explored	Kang et al. (2023)
Electrochemical oxidation	Electrochemical treatment using a Ti/RuO_2-IrO_2 anode	RAS system that cultivates tilapia fish	1.7 g/L sodium chloride, Electrolysis time: 1 h	TAN: 78%, NO_2^-–N: 95%	n.s	The feasibility of large-scale treatment should be evaluated	Ruan et al. (2016)

Table 4 (continued)

Treatment method	Material/strain	Wastewater source	Optimum conditions	Treatment efficiency	Application of treated water	Recommendation/comment	Reference
Electrochemical treatment	The combination of electrocoagulation and electrooxidation processes. Iron or aluminum for the anode, and stainless steel for the cathode	Shrimp aquaculture wastewater Purdue University Aquaculture Laboratory, USA	Changes depending on the contaminant to be removed	More than 87% for inorganic N, TDN, and PO_4^{3-}–P, 76.2% for sCOD	To be safely released to the environment	The economic feasibility and the scaling up of the treatment process should be explored	Bhatt et al. (2023)

n.s. not specified

growth of microbes and pathogens (Liu et al. 2018). The use of Ultraviolet (UV) irradiation can be introduced as a disinfectant method, preventing microbial growth and immobilizing the growth of harmful bacteria (Dahle et al. 2022), thereby preventing hindered fish cultivation process through pathogenic diseases. The common spectral bands of the UV are divided into UVA, UVB, and UVC. Each one of the bands has a specific wavelength of 400–315 nm, 315–280 nm, and 280–100 nm, respectively (Braslavsky 2007). Traditional UV lamps contain mercury which is a toxic material. Hence, the UV LED emerged as an alternative with additional advantages. Being mercury-free, flexible in terms of size and irradiation strength, and having a longer service life contributed substantially to eliminating the use of UV mercury-vapor lamps (Chen et al. 2017). When treating AWW, it was revealed that using membrane filtration as a complementary treatment to UV can remove bacterial communities by almost 99%. Furthermore, membrane filtration can remove 96% of the suspended solids, allowing better transmittance of UV irradiation. However, the use of membrane filtration requires frequent backflushing, and the cost of operation is considerably high compared to the UV disinfection process (Huyben et al. 2018). Another study developed a combination of electro-chlorine/ultraviolet processes to treat saline aquaculture wastewater. Under the optimum conditions of 10 mA, pH of 8, and flow rate of 0.9 L/h, the study concluded that this process was capable of degrading the antibiotics by 100%, removing ammonia nitrogen by 77%, and inactivating bacterial growth by 100% (Lang et al. 2022).

4.2 Chemical treatment

4.2.1 Coagulation and flocculation

Coagulation and flocculation is a treatment method where chemicals (i.e., coagulant) are added to capture the contaminants, such as organic solids or suspended solids and color, producing sludge as an end product (Kurniawan et al. 2020; Zhao et al. 2021). The coagulants can be classified under different categories: synthetic chemicals such as organic (polyacrylamide) and inorganic (aluminum sulfate), and natural or bioflocculant like chitosan (Mohd Nasir et al. 2019). Bioflocculants are preferred as environmentally friendly alternatives to

Table 5 Summary of various biological treatments of aquaculture wastewater

Treatment method	Material/Strain	Wastewater source	Optimum Conditions	Treatment Efficiency	Application of Treated water	Recommendation	References
Constructed wetland	Sedimentation + Charcoal based constructed wetland + Macrophytes (*Sacciolepsis africana* and *Commelina cyanae*)	Catfish Research Farm, Nigeria	Sedimentation pretreatment, CW surface area of 0.97 m^2, depth of 0.62 m, layers of gravel, fine gravel, charcoal, and sand with depths of 20, 9, 15, and 7 cm. flow rate of 24.02 m^3/day, HRT of 5 days	TSS: 50%, NO_3^-–N: 100%, NH_4^+-N: 100%, PO_4^{3-}–P: 100%, COD: 88%, BOD_5: 93%	Proposed to be used for irrigation, recreational purposes, aquaculture, industrial application, and recharging for groundwater	The implementation of constructed wetlands by itself could be sufficient in treating aquaculture wastewater The treated water could be used for irrigation or could be recirculated back to the fishpond	Omotade et al. (2019)
Constructed wetland	*Canna indica, Typha latifolia, Acrorus calamus*, and *Agrave sisalana*	RAS system, Channel catfish, Blunt snout bream, silver carp, and Black carp	A medium-scale vertical flow gravel constructed wetland. HRT: 0.58–144 days	BOD_5: 70.5%, Chl a: 91.9%, PO_4^{3-}–P: 20%, NH_4^+–N: 61.5%, TSS: 81.9%, TN: 54.6%, TP: 20%	The recirculation of treated water in the RAS	The feasibility of implementation on a larger scale should be studied Testing other types of fish cultivation	Liang et al. (2017)
Constructed wetland	Sedimentation tank + aeration pond + constructed wetland. Plants included *Thalia dealbata, Iris germanica,* and *Canna indica*	The fish farm that cultivates largemouth bass (*Micropterus salmoides*), China	Sedimentation (250 m^2), aeration (250 m^2), three layers (cobblestone 30 cm bottom, pellet 50 cm top). of CW (2400 m^2). HRT: 0.83 days	TN: 25–24%, TP: 62–72%, NH_4^+-N: 56–69%, NO_3^-–N: 57–65%, NO_2^-–N: 56–64%, COD: 28–43%	It is proposed that the treated water will be recirculated back to the fishpond	It is valuable to know the rate of water recirculation, water loss, and water reservation A techno-economic assessment of the treatment should be explored	Li et al. (2022)
Labe scale investigation on microphytes in constructed wetlands	Real microphytes using *Vallisneria natans* (*V. natans*) and artificial microphytes	Aquaculture pond (31° 4′ 25″ N, 121° 2′ 59″ E)	Temp: 25 °C, Cylinders contain a sand layer of 30 mm, A sequence of 12 h of light and dark with a light density of 90 µmol/m^2/s	TOC: 58.8%, TN 74.5%, TP: 77.33%, Antibiotics: 79.92%	n.s	The study mentions that there is a risk of the propagation of antibiotic-resistant genes even though the treatment is good in water purification	Ge et al. (2023)

Table 5 (continued)

Treatment method	Material/Strain	Wastewater source	Optimum Conditions	Treatment Efficiency	Application of Treated water	Recommendation	References
Microalgae treatment	Screening of different strains in an indoor condition using 1 L photobioreactor. The outdoor treatment of 200 L AWW using raceway tanks and three strains (*Monoraphidium* sp., *Haematococcus* sp., and *Neochloris* sp.)	Local tilapia fish farm that uses brackish groundwater, Qatar	200 L (1 m^2) raceway tanks, an inoculum of 10 L of each strain, 180 L of AWW, depth of 20 cm, HRT: 10 days	TN: > 70.5%, TP: > 93.5%	It is proposed that the treated water is safe to be recirculated back to the fish tanks. Otherwise, it could be released into the sea	The treatment duration or the HRT is long, further research should be conducted for a continuous or semi-continuous process	Kashem et al. (2023)
Microalgae treatment	The use of three strains (*Chlorella vulgaris, Scenedesmus dimorphus,* and *Haematococcus pluvialis*) to treat 1 L of AWW using glass PBR. Then the cultivation process using *Daphnia magna*	The AWW is collected from RAS and cultivates rainbow trout (*Oncorhynchus mykiss*)	1 L glass PBR with 20 L/h aeration, PBRs were in chemostat condition, light intensity: 600–10000 µmol/m^2/s HRT: 3 and 5 days, (N:P) ratio: 7.75	TP: 100%, TN: 50–70%	n.s	The uptake of toxic elements by the algae should be explored, as well as testing the treated water for toxic elements such as heavy metals The energy requirement and economic feasibility should be addressed	Gorzelnik et al. (2023)

Table 5 (continued)

Treatment method	Material/Strain	Wastewater source	Optimum Conditions	Treatment Efficiency	Application of Treated water	Recommendation	References
Microalgae treatment	600 mL of AWW is treated using column PBR and *Chlorella sorokiniana* strain, different light intensities and colors were used	High-density aquaculture, Institute of Hydrobiology, Wuhan, China	Column PBR, light intensity: 100 µmol/m^2/s, Temp: 23–37 °C, CO_2: 1.5–2% (v/v), HRT: 8 days	TOC: 82.27%, TN: 86.42%, NH_4^+–N: 93.25%	n.s	It would be interesting to know how the large-scale treatment will be addressed, whether it will be indoor or outdoor, and how the ambient light will affect the treatment process	He et al. (2023)
Aquaponics	Phytoremediation using five aquatic plants (*Centella asiatica, Ipomoea aquatica, Salvinia molesta, Eichhornia crassipes,* and *Pistia stratiotes*)	Aquaculture wastewater, temp: 27.7 °C, pH: 8.29. DO, TSS, BOD, NH_3^+–N, TP, are 4.63, 45.67, 1.06, 4.2, 0.35, mg/L	Rectangular tanks, 5 L of AWW and 5 g of each plant, the use fluorescent light, HTR: 14 days	NH_3-N: 63.9–98%, TSS: 73–98%, TP: 64–98%	n.s	Developing a way to reduce hydraulic retention time should be explored To investigate the treatment efficiency by using multiple plants in the same treatment	Mohd Nizam et al. (2020)
Aquaponics	Phytoremediation using *Azolla Pinnata*	Aquaculture wastewater	–	NH_3-N: 78%, TP: 79%	n.s	–	Farah et al. (2019)
Aquaponics	Phytoremediation using Morning Glory (*Ipomea asarifolia*)	Aquaculture wastewater, Catfish, Niger Delta University Fish Farm, Nigeria	Tanks with 100 g of the used plants, aeration is supplied, HRT: 30 days	NH_3-N: 85%, TSS: 73%, TP: 53%	The treated water is safe for reuse, with no specific application	The investigation of a suitable application of the used plants	Kiridi and Ogunlela (2020)

Table 5 (continued)

Treatment method	Material/Strain	Wastewater source	Optimum Conditions	Treatment Efficiency	Application of Treated water	Recommendation	References
Hydroponics	Growing sea peat in a glass greenhouse	Wastewater generated from RAS that cultivates Gilthead Sea bream (*Spaurus aurata*)	Temp: 25 °C, 50 L plastic tanks, Growth periods: 28 and 43 days. Water depth of 25 cm. crop density of 96 plan per m^2. DO level kept above 6 mg/L	Not specified. However, the plant was able to grow and absorb the nutrients from the wastewater	The study mentioned that the water can be used for irrigation purposes	The efficiency of the treatment should be reported The economic feasibility of the process should be explored	Puccinelli et al. (2023)
Anaerobic digestion	Anaerobic sequencing batch reactor (ASBR), the inoculum is from a digested sewage plant	The fish sludge was collected from a RAS system that cultivates Scortum bacoo, China	Temp: 35 °C, rector: 4 L ASBR, inoculum: 300 mL, HRT: 20 days, operating in the dark	COD: 97%, TSS: 96%, VSS: 91%	n.s	The inhibition of anaerobic digestion by salts and ammonia should be investigated	Luo et al. (2013)
Anaerobic digestion	Anaerobic digestion using bottles, the inoculum is from the effluent of aerobic digestion on a dairy farm	The fish sludge was collected from a gravity-thickening settler, AWW, salmon (*Salmo salar*), and trout (*Oncorhynchus mykiss*)	Three TS concentrations (1.5, 2.5, and 3.5%), inoculum to substrate ratio of 2:1, 300 mL glass serum bottles, purged with nitrogen and sealed, Temp: 35 °C. HRT:39 days	TS: 42–50%, VS: 27–30%, COD: 57–69%	n.s	The techno-economic assessment of applying this treatment process should be explored	Choudhury et al. (2023)
Anaerobic digestion	Anaerobic digestion using raw fishery byproducts, rice bran, and tap water AD was conducted in a 10 L circular sequencing batch system reactor	n.s	Adding 10% water, 150 rpm, 35 °C, HRT: 30 days	COD: 30.4–83.8%, VS: 39.2–87.6%, TS: 25.3–77.9%	n.s	There is no report of any inhibition	Choi (2021)

Table 5 (continued)

Treatment method	Material/Strain	Wastewater source	Optimum Conditions	Treatment Efficiency	Application of Treated water	Recommendation	References
Trickling filters	Pilot scale six 330 L tanks with six different tricking filters. The water is recirculated continuously via a pump. The trickling filter is cylindrical and filled with plastic filter media. Valencia	In synthetic aquaculture wastewater, the salinity of 37 ppt using sea salt, ammonia was added in the form of ammonium chloride (1.5 g)	330 L of water, flowrate of 1.08 m^3/h, varying temperature(16–27 °C), hydraulic loading (4–11 m^3/ m^2/h, and total ammonia nitrogen (3–9 gTAN /m^3/day)	Removal of TAN by varying temperature (37.4–51%), Hydraulic loading (27.7–53.6), and TAN (34–62.7%)	n.s	No real aquaculture wastewater was used	Godoy-Olmos et al. (2019)
Trickling filters	Six fiberglass tanks filled with 250 L of seawater, plastic cube filled with Bactoballs as biofilter added to each tank. Different fish diets and feeding methods were used	Gilthead sea bream (Sparus aurata) was added to each tank as the cultivated fish and source of aquaculture wastewater	Temp: 22 °C, 30 fish in each tank (avg weight of 7.9 g)	Ammonia removal rates: depending on diets (0.05–0.11 gTAN /m^2/day) Depending on the feeding method (0.05–0.1 11 gTAN /m^2/day)	In this study, the water is in continuous recirculation	The effect of cultivating other types of fish could be explored	Godoy-Olmos et al. (2022)
Trickling filters	Trickling filters using different packing media (woodchips, maize cobs, and sugarcane bagasse), biofilter height (14, 18, 22 cm), and hydraulic retention time (12, 24, 48 h)	Raw aquaculture wastewater	Temp:22 °C, The use of wood chips, filter height of 18–22 cm, and HRT of 48–60 h	Treatment efficiency of 94% of all nutrients	n.s	the valorization of the microbial matt generated in the filter should be explored The possibility of filter clogging and mitigation approaches should be investigated	Ng'erechi et al. (2020)
Rotating biological contactor	3 compartments. Surface area of 4880 m^2 for 1 and 2. 3660 m^2 for 3	Tilapia aquaculture wastewater	HRT: 0.267 h, Rpm: 1, Hydraulic load: 407 m^3/m^2	TAN: ~ 40%	n.s	The treated water could be recirculated back to the fish bond	Brazil (2006)
Rotating biological contactor	Combined with a floating bead filter with a surface area of 178 m^2	Tilapia aquaculture wastewater	Flow rate: 146.8 L/min	Nitrite: 51.7%, TAN: 30.7%	n.s	The treated water could be recirculated back to fish tanks	Aurelio Jr and Lawson (1996) and Suriasni et al. (2023)

Table 5 (continued)

Treatment method	Material/Strain	Wastewater source	Optimum Conditions	Treatment Efficiency	Application of Treated water	Recommendation	References
granular sludge (AGS) and algal–bacterial granular sludge (ABGS) systems	sequencing batch reactors R1 (ABGS) and R0 (AGS)	synthetic aquaculture wastewater. The synthetic wastewater based on a concentrated wastewater sample taken from the bottom of a commercial tilapia pond in Qinghai, China	Reactors with 6 and 110 cm of inner diameter and height. Volum of 2 L. 50% volume exchange ratio. HRT of 8 h. R0 in the dark. LED (15W) with luminance of 62.9 μmol/m^2/s added to R1, 20 cm away, 12 h of light and dark sequence. Temp: 25 °C	In AGS, COD:96.7%, TP:75.7%, TIN:73.2% In ABGS, COD:96.8%, TP:82.5%, TIN:76.7%	The application of the treated water is not specified. However, the produced biomass is proposed to be used as a feed additive	It is recommended that the study be conducted using raw aquaculture wastewater and whether its competition, including other contaminants and species like zooplankton, could hinder the treatment process The scale-up and energy requirement of the process should be explored	Zhang et al. (2023b)

n.s. not specified

Table 6 SWOT analysis of various physical wastewater treatments

Physical treatments	
Filtration	*TER: 5 MJ/m^3* (Kashem et al. 2023)
Strength	Weaknesses
High-efficiency treatment	Fouling of the filters
Low retention time	High energy treatment process
	Does not remove dissolved contaminants
Opportunities	Threats
to be coupled with other treatments for cleaner treated water	Increasing the capital cost of aquaculture industries
The easy separation of grown biomass from wastewater	The production of additional waste due to the accumulation of used filters
The production of high-quality treated water	
UV disinfection	*TER: 3.6–360 MJ/m^3* (Miklos et al. 2018)
Strength	Weaknesses
Producing high-quality treated water	UV transmittance can be easily obstructed
The prevention of byproduct formation	There are some safety concerns
Small size equipment, the requirement of small space	Might be high in terms of energy
Lack of producing additional waste	Might be high in terms of cost
Opportunities	Threats
The opportunity of coupling additional treatment methods for higher quality production of treated water	The worrying thought of using irradiation
The higher quality treated can increase its application range	The existence of other treatment methods that do not pose safety problems
Membrane technology (MBR)	*TER: 0.12–28.2 W/m^3* (Yuan and He 2015)
Strength	Weaknesses
Ability to remove a wide range of contaminants	Fouling of the membrane requires constant backflushing
Byproducts are not produced	Energy-intensive treatment method
The ability to control removing specific contaminants	The membranes may be damaged
Opportunities	Threats
The opportunity to synthesize a specific type of membrane with selective permeation	Regulatory issues on the disposal of brine
The opportunity to commercialize the treatment process as there is an increasing trend of membrane usage in water treatment plants	The competition with other cheaper treatment methods

TER typical energy requirement

chemical coagulants (Ahmad et al. 2022a). Some coagulants could be produced from bacteria such as *Serratia marcescens*, but research on this type of flocculant is still limited (Kurniawan et al. 2023b). The factors that affect the coagulation/flocculation process are pH, the dosage of coagulants/flocculants used, the intensity and duration of mixing, temperature, and settling duration (Ang et al. 2020). A study was conducted to treat aquaculture wastewater using bioflocculant, where the treatment managed to decrease the turbidity by 84% and remove suspended solids by 79% (Kurniawan et al. 2022). Another study was conducted using a natural flocculant (chitosan) and was able to remove the turbidity by 87.7% (Iber et al. 2023), which falls in the same range as the bioflocculant used in the previous study. However, when using organic poly aluminum chloride, a chemical coagulant, the removal efficiency of turbidity, TSS, and phosphorus was over 97% (Heiderscheidt et al. 2020). The removal efficiency can be increased when utilizing a suitable coagulant in each specific circumstance. For example, plant-based coagulants can remove up to 99% of turbidity and TSS from aquaculture wastewater (Alnawajha et al. 2022). Also, suspended solids can be removed from other wastewater water sources,

Table 7 SWOT analysis of various chemical wastewater treatments

Chemical treatments	
Coagulation and flocculation	*TER: 23.44–36.828 MJ/m³* (Rizvi et al. 2022)
Strength	Weaknesses
Simple in terms of operation	Cannot remove or degrade dissolved contaminants like nitrogen and phosphorus
High efficiency in removing suspended solids and color	
Low requirement of energy and cost	Mostly, the coagulants cannot be reclaimed after usage
A good harvesting method	Will be incorporated with the produced sludge
Opportunities	Threats
To be incorporated with biological treatment as an efficient harvesting method that requires low energy	The toxicity of some coagulants
The utilization of waste materials as coagulants	The residual coagulants can have negative impacts
A pretreatment step that removes solids and suspended materials	The production of waste sludge, adds to the operational cost
Advanced oxidation	*TER: 12.96–540 MJ/m³* (Lin et al. 2021)
Strength	Weaknesses
The ability to degrade a wide range of contaminants with high efficiency	The possibility of producing harmful byproducts
Fast reaction rate, lower retention time	The use of chemical oxidants could be expensive and pose safety risks
The requirement of a small footprint	The need for constant monitoring
Opportunities	Threats
The opportunity to degrade emerging contaminants and microplastics	Challenges of using chemicals or the production of toxic materials
Can be coupled with other treatment methods for higher treatment quality	May not be economically justified as an AWW treatment method
	The competition with other treatment methods that are cheaper and more efficient
Adsorption	*TER: N/A*
Strength	Weaknesses
High treatment efficiency	Adsorption alone is not enough for the treatment of wastewater
No issues with treating ammonia	
Cheap and easy to operate	Some adsorbents may require preparation or enhancement before usage
Low energy requirement	
Opportunities	Threats
The opportunity to reduce the cost of the wastewater treatment process	The reuse of adsorbent depends on the characteristics of the wastewater
The opportunity to create a marketable adsorbent product	The wastewater characteristics may not be suitable for adsorption, requiring chemicals to adjust the wastewater
Electrodes	*TER: 29.99 MJ/m³* (Gerek et al. 2019)
Strength	Weaknesses
High efficiency in terms of treatment	Difficult to implement on a large scale
Simple setup that can be controlled	The corrosion of the equipment
The production of nitrogen	The production of ammonia
Opportunities	Threats
The cooperation of aquaculture with other facilities that require nitrogen sources	The cost of the treatment may not be justified
Taking advantage of the salinity of the AWW	The possibility of incorporating rust in the treated water, which is unacceptable
	The exitance of a danger factor, as the treatment is highly dependent on electricity

TER typical energy requirement, *N/A* not available

Table 8 SWOT analysis of various biological wastewater treatments

Biological treatments	
Constructed wetland	*TER: 0.36 MJ/m^3* (Brix 1999)
Strength	Weaknesses
Low energy consumption	The requirement of a large area
Moderate operation and maintenance costs	May be affected by climate conditions
Sustainable, environmentally friendly, high-efficiency treatment	longer treatment durations
The provision of aesthetic values, and regeneration of natural habitat	Treatment depth is limited to the depth of the roots
Opportunities	Threats
The opportunity to construct on-site, near the aquaculture facility	The propagation of undesired organisms such as mosquitoes
The opportunity to grow specifically desired plants or to provide a natural habitat to a certain organism	The overaccumulation of waste and the generation of unpleasant odors
Microalgae technology	*TER: 0.64–5.68 MJ/m^3* (Kashem et al. 2023)
Strength	Weaknesses
The requirement of sunlight for algal growth, which is available for free, especially in the Gulf region	Can be contaminated by other organisms
	Affected by environmental conditions
	High retention time
The salinity of the wastewater is not an obstacle, as algae can grow in fresh, brackish, and saline water	Depending on the algae strain, it could be difficult to implement on a large scale
The ability to absorb carbon from the atmosphere, causing a negative carbon footprint	The energy requirement for algae harvesting is very high and may not be economically justified
The assimilation of valuable nutrients that are supposed to be wasted	
Opportunities	Threats
The possibility of valorizing the produced biomass to different types of products	The general unacceptance of society or being untrusted as a capable treatment method
Since the algae are capable of capturing carbon dioxide, it is possible to utilize carbon emissions such as flue gas in the treatment instead of being released to the environment	The growth and accumulation of undesired organisms during the treatment, like zooplankton and harmful bacteria
The opportunity to standardize the treatment method and commercialize the produced biomass	
Aquaponics	*TER: N/A*
Strength	Weaknesses
The production of high-value products	Can be affected by the environment such as the temperature
Source of revenue as most of the products have market demand	The possibility of being contaminated by pests
High in terms of production and quality, less utilization of water	High in terms of cost
Can be incorporated with fish cultivation	Requirement of highly skilled personnel
Opportunities	Threats
The availability of advanced technologies such as greenhouses and automated devices	The instability of the market demand and the emergence of cheaper alternatives
The opportunity to keep the nutrients in balance while cultivating the fish	The rejection of society to consume produce that was grown using contaminated water
To create a process that provides a path to a circular economy	
Anaerobic digestion	*TER: 2.16 MJ/m^3* (Chen et al. 2020a)
Strength	Weaknesses
Simple technology and easy to implement	The produced methane is mixed with carbon dioxide
Requires a small area	
The Production of methane gas	Can be inhibited by the existence of ammonia

Table 8 (continued)

Biological treatments	
Low operation and maintenance costs	Requires high organic material, a lacking feature in aquaculture
Opportunities	Threats
Self-sustenance via bioenergy	Foaming occurrence
Residual solids can be used for soil enhancement	Over-acidification during the treatment
Trickling filters	*TER: 0.99 MJ/m^3* (Arous et al. 2022)
Strength	Weaknesses
Can be operated in different ranges of organic and hydraulic loading	The requirement of continuous electrical energy and water flow
The requirement of a relatively small area with high-efficiency treatment	High in terms of cost The requirement of skilled personnel for maintenance proposes
Opportunities	Threats
The opportunity to utilize waste aggregates	The unacceptance by society as it is an open treatment method. The production of odor, attraction, and propagation of undesired insects is highly possible
The opportunity to use the treated water for other purposes like irrigation	
Rotating biological contactor	*TER: 0.65 MJ/m^3* (Waqas et al. 2021b)
Strength	Weaknesses
Requires a relatively small land for operation	Difficult to expand to a large scale
Relatively easy to construct and expand	Operational failures are common such as structural failure or corrosion
Simple treatment process that can be easily controlled	The wastewater requires sufficient primary treatment, tertiary treatment is also required
Short hydraulic retention time, the production of high amount of biomass	
Opportunities	Threats
The opportunity to treat higher volumes in lower retention time	The energy requirement may not be justified, as many mechanical parts and electricity are involved
The opportunity to utilize waste materials such as plastic waste as a biofilm surface	The wastewater's salinity may hinder the quality of the mechanical parts

TER typical energy requirement, *N/A* not available

such as palm oil mill effluent, by almost 100% when using Moringa as a coagulant (Jethani and Hebbar 2021). Apart from some microalgal strains, several bacteria (e.g., *Serratia marcescens*) (Kurniawan et al. 2022) and fungi (e.g., *Aspergillus niger*) (Mohd Nasir et al. 2019) are capable of producing bioflocculants to treat AWW. Bioflocculation could also be used as a low-cost and low-energy harvesting technique after the biological/microalgal AWW treatment, with harvesting efficiencies of up to 100% (Alam et al. 2016). Furthermore, bioflocculants could offer other post-treatment advantages, such as reduced sludge generation and reusing of the generated sludge (Kurniawan et al. 2020).

4.2.2 Advanced oxidation method

The advanced oxidation process (AOP) utilizes highly reactive oxidants such as hydroxyl radicals to degrade the organic contaminants in aquaculture wastewater (Kasprzyk-Hordern et al. 2003). However, other reactive oxidants can be involved in AOP, like hydroperoxyl, chlorine, ozonide anion, oxide anion, and sulfate (Ribeiro et al. 2019). There are several methods of attaining the radicals, like the use of UV irradiation and Fenton oxidation, some of which can be combined in the treatment process. AOP can be used as a pretreatment step for the bioremediation of wastewater; the pretreatment assists in reducing the toxicity of the wastewater while enhancing the biodegradability of the organics (Barbosa et al. 2016). The use of

AOP as a treatment method attracted the interest of the research community; however, there are limited applications of AOP in full-scale treatments of AWW (Liu et al. 2020; Mousel et al. 2021). Nonetheless, the application of AOP in aquaculture wastewater treatment was explored. The removal of some of the contaminants like ammonia, phosphorus, and total organic carbon reached as high as 100%, $>99\%$, and 97.3%, respectively (Virkutyte and Jegatheesan 2009; Gomes et al. 2020; Tan et al. 2021). In another study, the wastewater collected from a seafood breeding factory was treated using AOP, the removal efficiency of ammonia and nitrite was over 96%, while the removal of total phosphorus and COD was 72% and 48% (Lang et al. 2020). In addition, the use of hormones is common in the aquaculture industry, and residual hormones can remain in the released effluent (Cohen et al. 2017). A study confirmed that up to 64.5% of the estrogen can be degraded using AOP (Bennett et al. 2018). Another recent study explored the degradation of antibiotics using a solar-driven Fe(VI)/oxone process, where the degradation of norfloxacin, which is the highest in terms of concentration in the AWW, could reach up 100% within a short period (Gong et al. 2023).

4.2.3 Adsorption

Adsorption is potentially effective in treating aquaculture wastewater. It involves capturing unwanted substances in the wastewater (known as adsorbate) by using an adsorbent material and effectively separating the contaminants from the wastewater. The adsorbent material typically has a porous surface that allows the adsorbate to accumulate on it. The interaction between the adsorbate and the adsorbent is usually determined by factors like Van der Waals forces, electrostatic attraction, or covalent bonding. Among its benefits, adsorption is relatively inexpensive, easy to manage, and capable of resisting harmful chemicals (Cao et al. 2016). The use of adsorption as a treatment method for aquaculture wastewater was explored; the removal efficiency of ammonium using smectite clays was 93% (Zadinelo et al. 2015). More recent studies reported a 100% removal efficiency of ammonia using chitosan and an 85.3–99.6% removal efficiency of phosphate using aluminum pillared bentonite (Bernardi et al. 2018; Kumararaja et al. 2019). The low-cost adsorbent can be found in abundance in nature, as most of the adsorbent materials are derived from agricultural waste and can remove toxic heavy metals. Pine leaves, for instance, can remove 99% of chromium, and coconut hast can adsorb Copper, Lead, and iron by 92%, 94%, and 94%, respectively (Lim and Aris 2014).

One of the common approaches for adsorption treatment is the use of activated carbon, which is made from carbonaceous material by adding specific chemicals under extreme heat. Some of the characteristics of activated carbon are that it has a large porous surface area with high thermal stability and low reactivity to pH fluctuation (Monsalvo et al. 2011). Due to the advantages of activated carbon, such as endurance against toxic substances, simplicity in terms of design, and highly porous and recyclable, it is one of the suitable adsorbents for wastewater treatment. However, commercial activated carbon is considered an expensive material; recycling it will further increase the cost. Otherwise, it needs to be dumped as waste material in landfills (Mook et al. 2012). Nevertheless, the use of activated carbon in aquaculture was explored, where a study managed to remove 88–100% of four types of therapeutics (Ahmad et al. 2022b). Other studies combined activated carbon with biological treatment to enhance the treatment process. For instance, a study combined activated carbon with bacteria (*Bacillus cereus*) and removed phosphate, magnesium, and ammonium by 90.1%, 95.6, and 95.7%, respectively (Han et al. 2021). Another study that combined activated carbon with bacteria (*Olivibacter jilunii*) was able to remove 96.1% of TP, 98% of COD, 100% of ammonia, and 97.4% of TN from eel aquaculture wastewater (Huang et al. 2023).

4.2.4 Electrochemical treatment: the use of electrodes

The wastewater treatment methods are in continuous development, creating new technologies with advanced features compared to traditional treatments. Electrochemical treatment is an advanced method that takes advantage of electricity to convert nitrogenous compounds into nitrogen gas (Dash and Chaudhari 2005). The setup is simply an anodic and cathodic metal surface that is submerged in the wastewater; then, the nitrogenous compounds are converted to nitrogen gas via electrolysis. Some of the advantages of the electrochemical treatment could be high removal efficiency, minimal sludge production, and the small size of the operating equipment (Li et al. 2009a). The treatment is affected by several factors, such as pH, the electrode material, the electric current, and the concentration of nutrients in the wastewater (Mook et al. 2012). One of the drawbacks of electrochemical treatment is the production of ammonia instead of nitrogen during the treatment process. To prevent ammonia formation, sodium chloride could be added to the AWW; the electrochemical process would then produce hypochlorite ions, which in turn would react with ammonia to produce nitrogen (Li et al. 2009b). The electrochemical process could simultaneously remove other organics from the AWW; the total organic carbon and nitrite removal efficiency from an AWW were 97.3% and 94.8%, respectively (Virkutyte and Jegatheesan 2009). A recent study explored the treatment of synthetic AWW and raw AWW having total ammonia nitrogen as 20 and 15 mg/L, respectively. The electrochemical treatment using an iron single-atom electrode achieved a treatment efficiency of > 99% and 96.7% for synthetic and raw aquaculture wastewater, respectively (Quan et al. 2023). Other studies followed a similar trend of high treatment efficiency, as the total nitrogen and nitrite removal exceeded 94% (Ruan et al. 2016; Kang et al. 2023).

4.3 Biological treatments

4.3.1 Constructed wetlands

Constructed wetlands are artificial lands engineered to allow various forms of wastewater to flow through them while consuming nutrients and capturing suspended solids and organic materials. The wetlands are usually constructed as mitigation steps in areas with a history of urban or industrial development, such as the deconstruction of buildings or the abandonment of mining sites. However, the wetlands can be intentionally constructed for wastewater remediation when it is suitable for specific circumstances, like the availability of land and the need for low-energy treatment (Kadlec et al. 2000). The wastewater flow in constructed wetlands can either be on the surface or the subsurface and depending on the availability of land, the water movement can be vertical or horizontal in the subsurface condition. The main factors affecting the treatment are the vegetation, the soil bed, and the existing microorganisms (Lin et al. 2003). The constructed wetlands combine three treatment mechanisms: physical, chemical, and biological. Generally, the abiotic treatment processes, such as sedimentation and filtration, require short periods, while biotic processes like nitrification and phosphorus removal take longer periods. Nutrients such as nitrogen and phosphorus are assimilated by the vegetation growing on the wetland along with existing microorganisms, making the growing plant a major factor in the treatment process. A previous study on aquaculture wastewater treatment using constructed wetland systems reported nitrogen and phosphorus removals for up to 98% and 71%, respectively, showing the potentiality of constructed wetlands (Lin et al. 2002). Additionally, six subsurface wetlands were used to treat aquaculture wastewater. The wetlands volume and application area were 5 m^3 and 20×1 m^2, while the hydraulic retention time and hydraulic loading rate were 4 days and 0.03 m/day, respectively. The treatment efficiencies for nitrite, COD, BOD_5, and TSS were in the range of 44.1–69.7%, 52.8–91.1%, 68.3–99%, and 96.7–100%, respectively (Naylor et al. 2003). Another study conducted to degrade antibiotics from aquaculture wastewater determined that anaerobic bacteria in the constructed wetland have a major role in the degradation process, where specific antibiotics like trimethoprim, sulfamethoxazole, sulfamonomethoxine, sulfamethazine, and sulfadiazine could be degraded by 89, 61, 20, 20, and 12%, respectively (Deng et al. 2023). Some advantages of constructed wetlands could be the lower construction cost and operation/maintenance requirement compared to other treatment methods (Kadlec et al. 2000).

4.3.2 The use of microalgae

The use of microalgae to treat AWW could offer an efficient, sustainable, and environmentally friendly alternative to other treatment methods. Microalgae bioremediation effectively removes the nutrients, and the resulting biomass can be valorized into useful products such as fish feed or bioenergy.

Nevertheless, two major factors should be considered during the treatment: the quality or characteristics of the wastewater and the microalgae strain to be used (Tejido-Nuñez et al. 2019). For instance, when Tilapia wastewater was treated using raceway tanks and with three different types of microalgae in outdoor conditions, total nitrogen, and total phosphorus treatment efficiency was more than 70.5 and 93.5%, respectively (Kashem et al. 2023). The existence of ammonia is considered toxic, especially for fish; however, it may not obstruct the microalgal treatment process, as studies have proved that microalgae can tolerate and assimilate ammonia nitrogen. *Neochloris* sp., *Heamatococcus* sp., and *Monoraphidium* sp. were able to treat AWW with high ammonia nitrogen with a treatment efficiency of ~100, 99.3, and 99.75%, respectively (Jiang et al. 2016; Ledda et al. 2016; Valev et al. 2020). Several studies explored the use of photobioreactors to treat AWW. The photobioreactors offer more control in the system with a treatment efficiency of TN and ammonia to be 50–70% and 93%, while the removal of TOC and TP was 82.27% and 100%, respectively (Gorzelnik et al. 2023; He et al. 2023). The existence of carbon dioxide (CO_2) is essential for the growth of microalgae. For that reason, in some cases, symbiotic bioremediation by associating bacteria with microalgae is approached. In a symbiotic relationship, bacteria supply CO_2 to microalgae, whereas microalgae supply oxygen to bacteria. This exchange of benefits between the two microorganisms provides more efficient bioremediation, as almost 100% of phosphorous can be removed and develops a more economical wastewater treatment system (Lananan et al. 2014). According to a study, a Life Cycle Assessment was conducted on Pikeperch AWW treatment using microalgal bacterial flocs. The study concluded that the symbiotic bioremediation resulted in improved resource recovery, less effect on the environment by reducing the carbon footprint, and fewer chances of eutrophication occurrences. Furthermore, the generated microalgae-bacteria biomass was explored for two applications: feed for shrimp and bioenergy (biogas). It was concluded that the fish feed was more sustainable, and more studies should be focused on improving the mixing in the treatment system (Sfez et al. 2015). Another study explored the feasibility of the direct application of aquaculture wastewater in rice cultivation by combining microalgae (*Chlorella*) and biochar; the study revealed that the combination managed to treat the wastewater and enhance the physicochemical and biological attributes of the soil, leading to enhanced rice yield (Zhang et al. 2023d).

4.3.3 Aquaponics

The idea of combining agriculture with aquaculture was explored for many decades. The mutual benefit between the two organisms—including some intermediate organisms such as bacteria- helps in developing an efficient and eco-friendly method for treating AWW. The effluent from the fish tank is transferred to the soilless plantation tanks; then, the existing nutrients are assimilated via plant roots. Studies showed that the number of seeds used in each planting unit does not affect the rate of treatment. Instead, the root structure helps in the growth of the necessary bacteria, assimilating the nutrients and achieving more efficient remediation (Enduta et al. 2011). The wastewater effluent can be from freshwater species like tilapia, where fruity vegetables such as cucumbers can be grown. Also, the effluent can be from seawater species such as groupers, and the effluent can be used to grow seaweed. A study was conducted using *Azolla Pinnata* to treat AWW, and the treatment efficiency of ammonia and TP was 78% and 79% (Farah et al. 2019). However, the aquaponics treatment can be further optimized as a study used five aquatic plants to treat AWW, in 5 L tanks with the addition of 5 g of each plant, at 27.7 °C and a pH of 8.29, while the hydraulic retention time was 14 days. The study concluded that the treatment could reach up to 98% removal of ammonia, TSS, and TP (Mohd Nizam et al. 2020). Another study used 100 g of Morning Glory (*Ipomea asarifolia*) with a higher hydraulic retention time of 30 days; the removal of ammonia, TSS, and TP were 85%, 73%, and 53%, respectively (Kiridi and Ogunlela 2020). These results indicate that increasing the retention time and plant use amount does not necessarily enhance the treatment process. While studying different aquaponics systems, the results showed that the husbandry of fish and plants growing together could be more profitable than rearing fish alone (Estim et al. 2019). Furthermore, by taking advantage of additives, for example, biochar, the efficiency of the water remediation can be increased, and the treated water can be recirculated back to the fish pond. Also, the addition of biochar enhances the growth rate of the plant along with the cultivated fish (Su et al. 2020).

4.3.4 Anaerobic digestion

Anaerobic digestion is the natural degradation of organic matter to biogas (mainly methane) via a group of anaerobic microorganisms in the absence of oxygen, where organic matter undergoes four main stages of degradation (Mirzoyan et al. 2010). The use of anaerobic digestion for the treatment of aquaculture sludge was explored in different studies (Mirzoyan et al. 2008; Zhang et al. 2013, 2014), producing bioenergy in the form of methane and lowering the sludge volume. In a study treated using In a 4 L lab-scale anaerobic sequencing batch reactor, fish sludge was treated at 35 °C with a hydraulic retention time of 20 days, COD, TSS, and VSS removal efficiencies were 97, 96, and 91%, respectively, with an average daily gas production of 0.013–0.022 g/L TCOD (Luo et al. 2013). Another study explored the utilization of rice bran and tap water to degrade raw fishery byproducts using anaerobic digestion. The treatment was conducted at 35 °C, HRT of 30 days, and a mixing rate of 150 rpm, resulting in COD and total solids removal in the range of 30.4–83.8% and 25.3–77.9%, respectively. The methane production was in the range of 0.38–0.57 m^3/kg VS (Choi 2021). In comparison with domestic and industrial sludge, methane production using AWW is low due to the lower amount of solid waste, especially if the waste is derived from traditional fish cultivation methods (Choudhury et al. 2022). Furthermore, anaerobic digestion may be inhibited by the existence of ammonia (Yenigün and Demirel 2013) and long-chain fatty acids (Zonta et al. 2013) derived from fish feed, which is available and sometimes in abundance in AWW (Ebeling et al. 2006). Methane production from the AWW primarily depends on its organic content and type. Depending on the wastewater source, the typical range of methane production could be 50.8–1500 mL/g VS (Li et al. 2019b). A study validated that increasing the sludge organic content from 1.5 to 3.5% will increase the methane production in anaerobic digestion, the highest methane production was 519 mL/g Vs (Choudhury et al. 2023).

4.3.5 Trickling filters

The trickling filter is a secondary biological treatment method that utilizes microorganisms to assimilate the nutrients. The usage of trickling filters in AWW treatment is not new, as one of the first studies was reported in 1974 (Liao and Mayo 1974). The design of a trickling filter is relatively simple. It consists of a containment structure that is usually made from bricks or sometimes steel, a rotary distributor and a rotating arm that distributes the wastewater evenly on top of the containment structure, a porous media that is usually gravel or sometimes plastic that provides sufficient surface area for the microorganisms to grow and consume the nutrient from the wastewater. Atmospheric air penetrates through the porous media, or air is sometimes supplied underneath the reactor using a blower. This is an important step to provide oxygen to the system and for the aerobic degradation process to continue. The wastewater starts to trickle down evenly by the rotary arm over the porous media; the water flows downwards during a pre-determined time, allowing the wastewater to be treated until it reaches a separating filter where the treated water is collected and the produced carbon dioxide is captured. Trickling filters could be advantageous in terms of the simplicity of the design, minimal management, and operational requirements. However, some of the main disadvantages could be the clogging of the media and the relatively low volumetric treatment capacity of the reactor (Eding et al. 2006). A recent study explored the treatment of AWW via a trickling filter by utilizing different media at incremental elevations and varying hydraulic retention times. The study concluded that the best media was large-size woodchips at a height of 22 cm and a retention time of 60 h, resulting in 94% treatment efficiency of all contaminants (Ng'erechi et al. 2020). In another study, media in the form of Leca, Kaldnes, Norton, and Finturf artificial grass were used, resulting in Nitrite removal efficiency of almost 100, 80, 60, and 40%, respectively, indicating that the surface area of the media and the hydraulic retention time has a major role in the efficiency of the treatment (Lekang and Kleppe 2000).

4.3.6 Rotating biological contactor

The rotating biological contactor (RBC) was initially introduced in the 1900s (Mathure and Patwardhan 2005). It is a biological process where several disks are closely attached to a single horizontal shaft. The shaft is in a continuous rotation, allowing the disks to rotate while being fully or partially submerged in wastewater. Biofilms are introduced in rotating disks, allowing the microorganisms to degrade the organic material as well as the dissolved nutrients. The treatment efficiency is highly dependent on the type of wastewater and organic loading, the rotational speed, and the rotating supporting medium. The relatively small usage of the land, simple process and ease of control, low retention time, the provision of high surface area, and the resilience against toxic substrate are some of the advantages of this treatment method (Cortez et al. 2008). However, one of the major disadvantages of the treatment is membrane fouling (Waqas et al. 2021a). For a recirculating aquaculture system cultivating tilapia at 28 °C, an RBC composed of three compartments was coupled to treat the AWW. Compartments 1 and 2 had a similar surface area of 4880 m^2, while compartment 3 had a surface area of 3660 m^2. The study achieved a remediation efficiency of 0.43 g/m^2/day of ammonia nitrogen at a rotating speed of 1 rpm and hydraulic loading of 407 m^3/m^2. Still, the increase of dissolved organics in the wastewater further decreased the ammonia removal efficiency (Brazil 2006). Another study combined the usage of a floating bead filter with a surface area of 178 m^2 and a rotating biological contactor with a surface area of 197 m^2 that rotates at 3 rpm to treat tilapia AWW. The study revealed that the floating bead filter contribution to the treatment was insignificant. However, the process was able to remove on average 30.7% and 51.7% of TAN and nitrite, respectively (Aurelio Jr and Lawson 1996; Suriasni et al. 2023).

5 Towards a sustainable aquaculture industry

As mentioned, the aquaculture industry is witnessing ongoing development, providing the essential need for protein products to a fast-growing population (Stead 2019). This attracted attention to the significance of aquaculture wastewater treatment and how the environment should be protected from the release of harmful effluents. Although there are various ways and methods to treat aquaculture wastewater, as mentioned in Sect. 4, rules and regulations should support, from the beginning, the idea of safer utilization and release of water (Engle and van Senten 2022). To be consistent with the rapid growth of the aquaculture industry, a joint venture of academia, government, and industry should be established for the provision of standards and guidelines, promoting sustainability to the aquaculture industry and superiority to the environment (Stead 2019). For the safe release of aquaculture wastewater, countries should adopt regulations specifically tailored to the aquaculture industry. For example, Taiwan developed parameter standards such as pH being between 6 and 9, and TSS, BOD, and COD should be less than 30, 30, and 100 mg/L, respectively (Lin et al. 2010). Also, in China, the discharge limits for suspended solids, TP, TN, ammonia, BOD_5, and COD, are in the range of 20–30, 0.5–3, 1.5–20, 15–30, 20–30, 50–120 mg/L, respectively (Zhang et al. 2016; Zhou et al. 2018). If specific regulations do not exist, following the standard of other wastewater discharge sources, such as municipal wastewater, is recommended as an adequate alternative.

Reducing water consumption is another alternative for decreasing the impact of AWW on the environment. RAS can achieve the optimized usage and recirculation of water; however, the technology curries various challenges, which, if properly dealt with, will provide a transition toward sustainable aquaculture. The inadequacy and complexity of RAS, in terms of engineering and design, are some of the major challenges (Badiola et al. 2012). Also, sophisticated equipment, measuring sensors, and systems for automatic control are embedded in RAS (O'Shea et al. 2019). These challenges create an economic burden, making it a deterrent to adopting the technology (Murray et al. 2014). Adopting a simple design with limited productivity is suggested to overcome these challenges. Another hindrance is that RAS is an energy-intensive process, where the typical energy consumption can range between 15 and 30 kWh/kg of fish (Ayer and Tyedmers 2009; Martins et al. 2010; Badiola et al. 2017). Consequently, this will increase operational costs while harming the environment (Badiola et al. 2018; O'Shea et al. 2019). Using renewable energy, such as solar panels, could

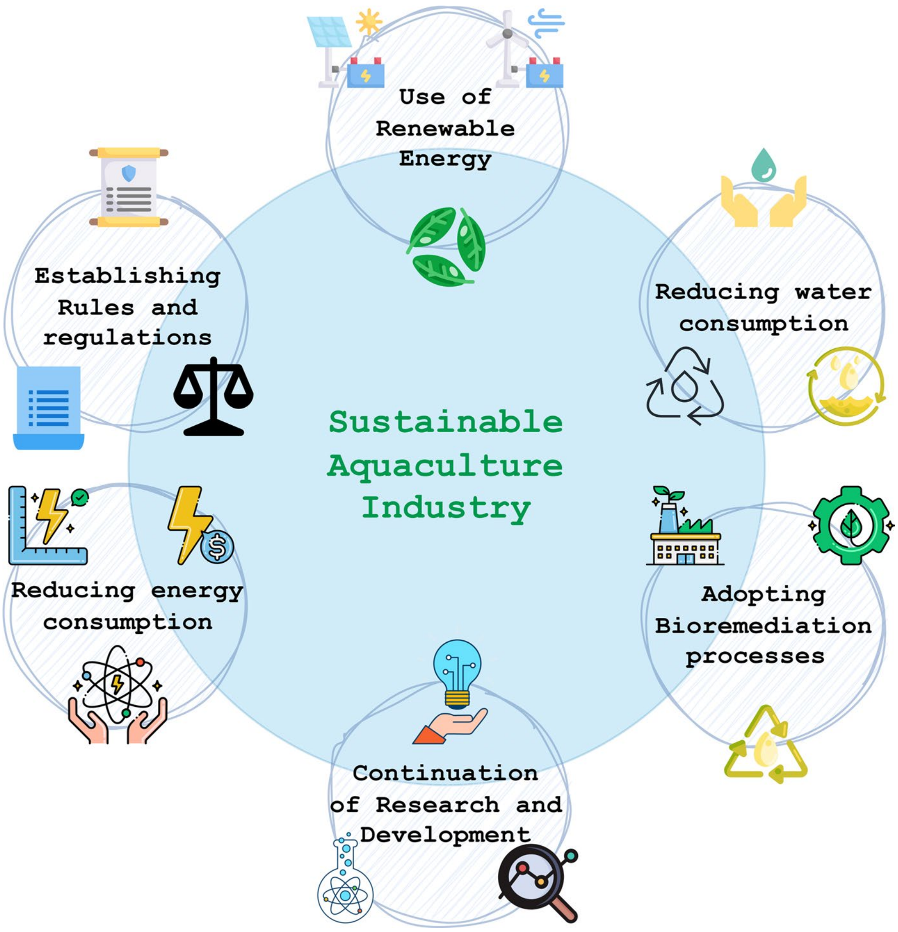


Fig. 5 Some of the main pillars of a sustainable aquaculture industry

overcome this obstacle, reduce energy consumption, and simultaneously make it cost-effective over the long term (Fuller 2007; Badiola et al. 2018; Bergman et al. 2020).

The coupling of bioremediation techniques with RAS has the potential for more efficient resource recovery, less consumption of energy during the treatment process, and the production of various products that can be valorized in different applications. When considering these advantages, it is sensible to adopt bioremediation technology for the transition toward a more sustainable aquaculture industry and circular bioeconomy. Treatment-wise, coupling bioremediation with RAS could achieve a treatment efficiency of more than 96% for most contaminants (Li et al. 2019a). On the other hand, bioremediation is generally considered a sensitive treatment method that could either crash during the process or be susceptible to further contamination by undesired organisms, which requires continuous monitoring of the treatment process. More research should be devoted to coupling bioremediation with RAS to optimize the treatment and overcome challenges, leading to a more sustainable aquaculture industry. Figure 5 depicts some of the main pillars of a sustainable aquaculture industry.

6 Conclusion

The aquaculture industry witnessed rapid development in recent years, surpassing the traditional fishing industry in production to address the high demand for fish protein in the ever-growing population. However, aquaculture imposes an environmental threat due to the increased generation of wastewater and the overuse of resources. This review explains the various techniques for treating aquaculture wastewater and summarizes the outcomes of the latest studies conducted using each technique.

Constraints such as energy requirement, time, and efficiency are highly influential in selecting suitable treatment methods and the desired treatment outcomes. For a more sustainable aquaculture industry, effluent standards and regulations should be established and followed, ensuring the safe release and reuse of treated wastewater. In addition, modernizing fish farming by RAS reduces the environmental impact and water usage. However, the hurdle is to overcome the cost and energy requirements. Hence, further research and development are needed to optimize and develop safer, less time-consuming, energy-efficient, and higher treatment efficiency, ensuring a sustainable industry and a circular economy.

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