

Review

Not peer-reviewed version

Photocatalytic Ozonation for Remediation of Contaminants in Aquaculture Effluent: A Review

Nurul Najiha Datu Masjidin , [COLLIN G JOSEPH](#) ^{*} , [Siow Hwa Teo](#) , [Jualang Azlan Gansau](#) , [Rosalam Sarbatly](#) , [Sivakumar Ramakrishnan](#) , [Mika Sillanpää](#)

Posted Date: 7 August 2024

doi: 10.20944/preprints202408.0521.v1

Keywords: Advanced Oxidation Processes; Aquaculture Wastewater; Contaminants of Emerging Concern; Photocatalysis; Ozonation



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Review

Photocatalytic Ozonation for Remediation of Contaminants in Aquaculture Effluent: A Review

Nurul Najiha Datu Masjidin ^{1,2}, Collin G. Joseph ^{1,2,*}, Siow Hwa Teo ^{1, 2}, Jualang Azlan Gansau ³, Rosalam Sarbatly ⁴, Sivakumar Ramakrishnan ⁵ and Mika Sillanpää ⁶

- ¹ Sonophotochemistry Research Group, Faculty of Science and Natural Resources, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
 - ² Industrial Chemistry Programme, Faculty of Science and Natural Resources, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
 - ³ Biotechnology Programme, Faculty of Science and Natural Resources, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
 - ⁴ Chemical Engineering Programme, Faculty of Engineering, Universiti Malaysia Sabah, 88400 Kota Kinabalu, Sabah, Malaysia
 - ⁵ School of Materials & Mineral Resources Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Malaysia
 - ⁶ School of Mining, Metallurgy and Chemical Engineering, University of Johannesburg, 2028 Doornfontein, South Africa; affiliation 1; e-mail@e-mail.com
- * Correspondence: collin@ums.edu.my; Tel: +6-088-320000 ext. 101017 Fax: +6-088-435324; ORCID: 0000-0002-0199-4735

Abstract: The growing global population and limitations in fish catch production have led to a surge in the demand for aquaculture. Contaminants of emerging concern (CEC) are frequently being detected at low levels in surface water. These CECs, which include previously unidentified or unregulated pollutants, pose potential risks to health and the environment, though their impacts are not yet fully understood. Extensive research studies have been proposed and undertaken to address the issue of aquaculture wastewater, aiming to minimize its impact and implement effective treatment methods. This review provides an analysis of various technologies used for treating aquaculture wastewater using advanced oxidation processes (AOPs) focusing on photocatalysis and ozonation. It examines their advantages and disadvantages, as well as their respective treatment efficacies and discusses their potential applications in sustainable aquaculture practices complying with the Sustainable Development Goals of 1,2 and 6 and the Environmental Social and Governance (ESG) framework.

Keywords: Advanced Oxidation Processes; Aquaculture Wastewater; Contaminants of Emerging Concern; Photocatalysis; Ozonation

1. Introduction

Natural water regularly gets contaminated from anthropogenic sources. These materials originate from various sources, such as domestic, storm, urban runoff, agricultural and aquaculture runoff, as well as industrial discharge. They can exist as a mixture within sewer inflow or infiltration. The contaminants found in natural water are referred to as dissolved organic matters (DOM) and dissolved particulate matters (DPM), which are commonly used as indicators for monitoring wastewater quality [1].

Several research groups worldwide have studied the effectiveness of using a combination of photolysis, ozone, oxygen, and hydrogen peroxide, as well as various homogeneous and heterogeneous catalysts and photocatalysts in both light and dark conditions, to treat contaminated water and wastewater. These techniques were investigated to evaluate their capacity to decompose pollutants and assess the treatment efficiency. This study aims to provide an analysis of various technologies used for treating aquaculture wastewater using advanced oxidation processes (AOPs)

focusing on photocatalysis and ozonation. It examines their advantages and disadvantages, as well as their respective treatment efficacies. Several findings for the disintegration of new pollutants including antibiotics that may be found in water are reviewed as well.

1.1. Aquaculture Effluent

Aquaculture is directly affected by numerous laws such as land, water environmental and even trade laws. Some laws may be specific to certain region or countries. All these laws are there to safeguard public domain, thus preventing the waste created by aquaculture farms from becoming a public burden [2]. Fish cultivation is one of the aquaculture frameworks with the significance of financial matters. Because of fish discharge and feed extras, this causes excess of phosphorus and nitrogen in the water which can corrupt neighboring water bodies especially during high tide, seepage and flooding. However, the repercussions are low when compared to those from industrial and household wastewater [3]. Therefore, aquaculture wastewater treatment is essential to avert more damage to the aquatic and adjacent terrestrial environment.

Omofunmi et al., [4] investigating the effect of aquaculture effluent produced from catfish farming (*Clarias gariepinus*), noted that chemical, physical, and biological criteria were important aspects in water quality analysis. Physicochemical parameters, such as alkalinity (CaCO₃), ammoniacal nitrogen (NH₃), biological oxygen demand (BOD), chemical oxygen demand (COD), pH, temperature, total solids (TS), total nitrogen (TN), total phosphorus (TP), and suspended solids (SS), are the common measurements noted in water quality index (WQI) (DOE, 2020) in order to evaluate the quality of the given water sample. The water quality index, introduced in 1965, was adapted by Asian, African, and European countries and fitted to the requirements according to national and international organizations, with several improvements and modifications to suit the individual countries [5].

However, the specific values assigned to each surface water category can differ based on the type and suitability within a particular region, mainly due to the lack of generally recognized composite indicator for water quality. In Malaysia, for example, the water quality analysis focuses on six parameters, namely BOD, COD, SS, NH₃, and pH. These parameters are utilized to assess and monitor water quality in the country. Table 1.0 shows some examples of this indexing.

Table 1. Water quality classification according to different Water Quality Index (WQI) methods.

CCME WQI [7]		OWQI [8]		MMWQI [9]	
91-100	Excellent	95-100	Excellent	90-100	Excellent
71-90	Good	80-94	Good	85-89	Good
51-70	Medium	60-79	Fair	80-84	Fair
26-50	Bad	45-59	Marginal	60-79	Poor
0-25	Very Bad	0-44	Poor	0-59	Very Poor

¹NSFWQI–National Sanitation Foundation Water Quality Index; CCME WQI–Canadian Council of Ministers of the Environment Water Quality Index; OWQI–Oregon Water Quality Index; MMWQI–Malaysian Marine Water Quality Index; DOE–Department of Environment.

River water used for fish farming will contain high nitrogen and phosphorus concentrations leading to eutrophication. When eutrophication occurs, the water usually contains higher concentrations of BOD, SS, TN, and TP [10].

Antibiotics, feed-derived waste, and hormones are other compounds that are commonly detected in aquaculture wastewater. Feed-derived waste compromises phosphorus and nitrogen-based nutrients, which forms part of the suspended solid. These solids typically include 7%–32% of the TN and 30%–84% of TP in wastewater. The remainder are released in the dissolved fraction from

the farm [11]. An innovative treatment method is certainly needed to address the shortcomings of conventional methods.

1.2. *Aquaculture Effluent Sources and Components*

According to Turcios and Papenbrock [12], solid waste comprises a huge proportion of total waste which typically originates through feed spillage alongside fish feces varying between 5 and 50mg/l inside flow-through farms. The main sources of solid waste are unattached feed and feces, as well as dead fish, from cultivated fish processing. Furthermore, solid waste is usually name as suspended solids alongside other solid components. Suspended solids are the most challenging to eradicate from culture systems as they consist mainly of fine particles suspended in the water. The larger solids can be separated from the culture column in a short time because of their larger sizes. Aerobic bacterial activities acting on solid waste present inside the aquaculture system will cause a higher demand for COD and BOD in the culture column. Only 30 per cent of the feed would be solid waste if aquafeeds were properly processed, efficiently fed, and used in the right sizes. By comparisons, the recirculated aquaculture systems can be more efficient in removing waste than flow-through systems [13].

Ongoing aquaculture methods normally impose strict limits upon the usage of chemicals in fish farms but some chemicals such as medicinal products, disinfectants, and antiviral products are commonly used. Drugs, including antibiotics, are utilized as prophylaxis and for curative objectives. Other medication such as anesthetics, ectoparasiticides and vaccines are used for the prevention and control of parasites and microbial infections. Lime is used for acidity treatment during the preparation of the tank, and similarly used are other substances deemed safe for fish. While said substances are vital for the cultivation of fish, they can still have possible adverse environmental effects as pond water is released and flows into natural water bodies as effluents [14].

The release of pathogens from aquaculture and wastewater discharges are another problem that can have negative effects on natural water sources. These discharges can introduce additional pathogenic loads to the environment, potentially causing stress and mortality. In semi-intensive, open flow pond settings commonly found in aquaculture, the effluent from aquaculture ponds is a characteristic feature. Furthermore, the use of organic fertilizers within aquaculture systems, which is practiced in many countries, may contribute to increased pathogen levels. For example, in certain regions, the utilization of four specific organic fertilizers—bovine blood, goats, swine, and poultry manure—has been associated with higher concentrations of fecal streptococci [15].

1.3. *Environmental Impacts of Aquaculture*

The global demand for cheap and sustainable protein sources has resulted in aquaculture is gaining worldwide prominence [16]. According to Muir and Young (1998), the worldwide dispersion of the aquaculture industry is impacted by numerous sectors such as geography, market requirements, structure availability, human capital, technical proficiency as well as institutional framework.

Despite its positive impacts on food security and economic growth, the ecological effects of aquaculture should not be disregarded. This due to the fact that farming of aquatic species necessitates the introduction of exogenous substances into culture water and the utilization of land for fish cultivation. These deliberately introduced elements serve various purposes, primarily to maintain fish health. Nonetheless, they are usually incompletely assimilated and remain as contaminants in the water. Additionally, the metabolic waste products of fish lead to the generation of waste in aquaculture water [13]. Table 1.6 below shows the possible environmental impacts of aquaculture.

Table 1.1 Possible environmental Impacts of aquaculture.

Culture Method	Common species cultivated	Impact upon the environment
----------------	---------------------------	-----------------------------

Seaweed culture		Extensive May colonize formerly pristine reefs, suffer bad weather losses.
Coastal bivalve culture	Mussels, oyster, clams, cockles	Public health hazards and consumer resistance Rough weather losses. Seed limitations; The demolishment of ecosystems, especially mangroves.
Coastal fishponds	Mullets, milkfish, shrimps, tilapia	Increasingly non-competitive with more intensive systems. Unsustainable with excessive population growth; Exclusion of traditional fishermen.
Pen and cage cultivation in eutrophic waters and/or dense benthos	carps, catfish, milkfish tilapias	Navigational risk. Management challenges. Wood demand. Semi-Intensive
Fresh- and brackishwater pond	shrimps and prawns, carps, catfish, milkfish, mullets, tilapias	Freshwater: health hazards for farm workers from infections transmitted through water. Brackishwater: soil and aquifers acidification, salinization. Market rivalry particularly for export output produce, availability and cost of feed and fertilizer. Health hazards for farm workers from infections transmitted through water.
Integrated agriculture-aquaculture	rice-fish; livestock/poultry-fish; vegetables - fish and all combinations of these	Potential consumer resistance to excreta-fed produce. Competing from other consumers of inputs such as livestock excreta and cereal brans. Hazardous compounds and pesticides in livestock feeds may accumulate in pond sediments and fish. Health hazards for farm workers and consumers. Exclusion of traditional fishermen.
Sewage-fish culture		Navigational risk. Management challenges. Wood demand.
Cage and pen culture, especially in eutrophic waters or on rich benthos	carps, catfish, milkfish, tilapia	Intensive
Freshwater, brackishwater and marine ponds	shrimps; fish, especially carnivores, catfish, snakeheads, groupers, sea bass finfish, especially carnivores - groupers, sea bass, etc. - but also some omnivores such as common carp	Effluents/drainage with high BOD and suspended solids levels. Market competition particularly for export products.
Freshwater, brackishwater and marine cage and pen culture		Anoxic sediments accumulate underneath cages due to fecal and waste feed build-up; Market competition particularly for export products. Wood demand and other supplies.
Other	raceways, silos, tanks	Effluents/drainage high in BOD and suspended solids. Numerous location-specific issues.

Source: Modified from [18].

2. Antibiotics

The government has fostered the growth of the aquaculture industry in Malaysia by providing diverse and extensive assistance and intensives, to farmers in this industry, indicating the growing interest of this industry in the country and in neighboring countries. However, the increasing of production has a correlation to the increased chances of epizootic infections. These widespread infections have been a staid hindrance in the growth of aquaculture, specifically in the shrimp and marine fish farming. Fish infections in the Malaysian aquaculture have been recorded since the mid of 1980s [19]. While several parasitic, bacterial, viral, and fungal pathogens are commonly found in the Malaysian aquaculture sector have been identified by Shariff et al. [20].

Antimicrobials are also utilized in livestock and aquaculture sectors. Their application can be classified as therapeutic, prophylactic, or metaphylactic. Therapeutic usage is the to the treatment of existing infections. Metaphylactic refers to a group-medication practice that aims to treat sick animals and at the same time treating others to prevent sickness. Prophylaxis is the use of antimicrobials in individuals or groups to avoid the occurrence of infections [21]. In aquaculture, antibiotics at therapeutic doses are oftentimes administered for short period orally to groups of fish that share tanks or cages. All permissible medications used in aquaculture must be licensed by the government authority. These regulatory authorities may define guidelines for antibiotic usage, including authorized modes of distribution, routes of delivery, dose forms, withdrawal periods, tolerances, and use by species, including dose rates and restrictions [21].

Fish disease is commonly caused by the existence of pathogens and unfavorable environmental circumstances which induce infection to animals. Many diseases in aquaculture are caused by inadequate sanitation and water quality. Farmers prefers to find a fast-problem-solving solution for the illness concern that they deal with. Both criteria have promoted the use of chemotherapeutics in managing illness. The term chemotherapeutant refers to any medication, drug or chemical utilized in preventing or treating diseases. This terms addresses chemical used to enhance the raising environment. However, it excludes dietary supplements such as vitamins and immunological boosters which undoubtedly played a significant role in disease management.

The 4 major categories of chemotherapeutants are topical disinfectants, antibiotics, probiotics, and anesthetics. Topical disinfectants have a broad spectrum which are commonly used to eradicate external bacteria, fungus, and protozoans. The third category consists of probiotics or bacterial concentrates which are utilized to increase microbial breakdown of organic accretions in the pond, hence lowering the biochemical oxygen demand and the potential of anaerobiosis. The last group, anesthetics, contains chemicals used to sedate fish during shipping and handling. The uncontrolled use of these chemotherapeutants might cause major difficulties.

2.1. Type of Antibiotics in Aquaculture

Parameters such as the type, quantity of antibiotics and frequency of usage used in aquaculture are determined by the type of species farmed, the farming environment, the production technology used, farming practices, expert support from veterinarian/fish health specialist, and food safety regulations applicable in target markets. A wide range of antibiotics are used to treat fish and shrimp infections. However, many of these cannot be used on a big scale due to legal constraints. Almost all antibiotics being use are generics sourced from China and Thailand. Commercial preparations (non-generics) from Japan, Europe, and North America are often labelled adequately, including composition information and application precautions. The subsequent subsections will discuss about selected antibiotics commonly used in aquaculture in Malaysia.

2.1.1. Tetracyclines

Tetracyclines, a class of antibiotics discovered in the 1940s and are a family of antibiotics that inhibit protein synthesis by inhibiting the attachment of aminoacyl-tRNA to the ribosomal acceptor

(A) site. The use of tetracycline in Malaysia is very common because it belongs to a group of broad-spectrum which makes it more potent against a broad spectrum of Gram-negative and Gram-positive bacteria and because of their minimal expense compared to other antibiotics. There are almost 20 types of tetracycline antibiotics available but chlortetracycline, oxytetracycline and doxycycline are among the commonly used in veterinary medication [22].

Notwithstanding remedial purposes, in numerous different nations, antibiotic medications are regularly added into animal feed at subtherapeutic portions as development advertisers for swine, poultry and aquaculture. For a period of time, the utilization of antibiotics as development advertisers have been connected with advantageous perspectives (particularly expansion in the effectiveness of supplement take-up and commercial income for ranchers), however, there is research information that aligns the way this activity causes bacterial resistance, hypersensitivity responses in people and animals, some alteration in natural microflora and bacterial population amid some other negative impacts [23,24].

Tetracycline has a few therapeutic signs in managing disease problems in food-producing animals and pets. Therapeutic signs in animals include dermal, respiratory diseases, soft tissue diseases, peritonitis, metritis, and other intestinal diseases just as the treatment infection for bees and aquatic species. To treat and prevent diseases in food-producing animals, antibiotics were given through drinking water or food for easier administration [25]. Even though tetracycline brings a huge concern related to the increases in bacterial resistance [26] but the use of tetracycline is still allowed in many countries as a growth promoter except for European countries and the USA [27]. Tetracycline is effective in against Mycoplasma, Chlamydia, Pasteurella, Clostridium, Ornithobacterium rhinotracheale, and a few protozoans. Table 2.0 shows the applications of tetracycline for different species of food-producing animals [28].

Table 2. Applications of tetracycline.

Species		Indications for use
Chlortetracycline Chemical name: (7-Chlortetracycline) Trade name: (Aureomycin)	Swine	Help in gaining weight Reduction of jowl abscesses Control of leptospirosis
		Control of proliferative enteropathies
		Prevent bacterial pneumonia disease caused by <i>Pasteurella sp.</i>
	Cattle	Control infection caused by <i>Anaplasma Marginale</i>
		Help in gaining weight
	Calves	Treatment of bacterial enteritis caused by <i>Escherichia coli.</i>
		Treatment of bacterial pneumonia caused by <i>P. multocida.</i>
	Poultry & Aquaculture	Help in gaining weight (growth promoter) Control of synovitis caused by <i>Mycoplasma synoviae</i> Control of avian cholera caused by <i>Pasteurella multocida.</i>
		Control chronic respiratory disease of the air sacs caused by <i>Mycoplasma gallisepticum</i> and <i>Escherichia coli.</i>
		Reduce fatality caused by <i>Escherichia coli.</i>
Oxytetracycline Chemical name: (5-Hydroxytetracycline)	Swine	Help in gaining weight (growth promoter) Treatment of bacterial pneumonia and bacterial enteritis
		Control of leptospirosis in sows
	Cattle	Help in gaining weight (growth promoter) Reducing the incidence and severity of liver abscesses

Trade name: (Terramycin)	Calves	For the treatment of various bacterial infections Prophylaxis and treatment of the early stages of shipping fever complex Help in gaining weight (growth promoter) For the treatment of various bacterial infections Help in gaining weight (growth promoter) Control of synovitis caused by <i>Mycoplasma synoviae</i> Control of avian cholera caused by <i>Pasteurella multocida</i> .
		Control chronic respiratory disease of the air sacs caused by <i>Mycoplasma gallisepticum</i> and <i>Escherichia coli</i> . Reduce mortality due to air sacs infection caused by <i>Escherichia coli</i> .
	Poultry & Aquaculture	
Doxycycline		For dogs, Treat bacterial illness and infections caused by <i>Rickettsia</i> , Canine ehrlichiosis (anaplasmosis), <i>Toxoplasma</i> , <i>Borrelia burgdorferi</i> (Lyme disease), leptospirosis, and <i>Neorickettsia helminthoeca</i> (Salmon poisoning). For cats, Treat bacterial infections and
Chemical name: (6-Deoxy-5-hydroxytetracycline)	Pet (companionship animal)	infections caused by some other organisms. including <i>Bartonella</i> , <i>Hemoplasma</i> , <i>Chlamydia felis</i> , <i>Ehrlichia</i> , <i>Anaplasma</i> , and <i>Toxoplasma</i> .
Trade name: (Vibramycin)		

2.1.2. Sulfonamides

Sulfonamides are synthetic antibiotics which have been frequently used to treat bacterial and protozoan infections in people, domestic animals, and aquaculture species since their introduction to clinical practice in 1935 [29,30]. Sulfonamides are a class of antimicrobial medicines that inhibit the folic acid pathways of susceptible microorganisms. Sulfonamides are now widely pushed by regulatory agencies worldwide, owing to their progressively dwindling usage in human medicine [31]. There are many types of sulfonamides such as sulfamethazine, sulfamerazine and sulfathiazole. Other than that, sulfonamides such as Romet-30 and Tribessen, were both permitted by the US FDA to be used in fish farming. Table 2.1 shows the application of sulfonamides in fish farming [20].

Table 2.1 Application of Sulfonamides in fish farming.			
Trade Name	Pharmacologically active substances	Indications for use (Advantages)	Disadvantages
Sulfonamides			
Dimeton	sulfamonomethoxine & sulfadimethoxine	Control bacterial infections including <i>Vibrio sp.</i> Cure fin rot in seabass and grouper bred in floated cages	Limited Efficiency High Cost They create resistance in target infections and are unable to be utilized for lengthy periods of time.
Potentiated Sulfonamides			
Romet-30	Sulfadimethoxine potentiated with ormetoprim	Control bacterial infections including <i>Vibrio sp.</i> Cure fin rot in seabass and grouper bred in floated cages	-
Tribessen	sulfadiazine potentiated with		

trimethoprim	More effective Less amenable to inducing resistance
--------------	---

2.1.3. Nitrofurans

Nitrofurans are synthetic chemotherapeutic drugs with a vast antibacterial spectrum. They are effective against both gram-positive and gram-negative bacteria, including Salmonella and Giardia spp, trichomonads, amebae, and several coccidial species. Meanwhile, when contrasted to different antibiotics, their efficacy is nothing worth mentioning. Nitrofurans tends to disrupt numerous microbial enzyme systems, especially those involved in carbohydrate metabolism, also hindered the initiation of translation. Their primary action is bacteriostatic, but at high doses, they are also bactericidal. They are significantly more active in acidic conditions. Resistant mutations are uncommon, and clinical resistance develops at a slower pace. Nitrofurans are completely cross-resistance among themselves, but not with any other antibacterial agents [32]

Nitrofurans, such as furoxone, nitrofurazone (Furazolidone) and nifurpirinol (Furanace) were formerly considered to be promising for aquaculture. Furanace has subsequently been completely prohibited due to its carcinogenic potential, while the usage of the other two has been severely restricted. In Malaysia, all the three antibiotics are still available for use by the aquaculture sector, although they are not widely employed. Nitrofurans were frequently utilized as feed additives for growth stimulation, and mainly used for livestock such as poultry, swine, and cattle, aquaculture and bee colonies in the prophylactic and therapeutic treatment of bacterial and protozoan infections such as gastrointestinal enteritis caused by Escherichia coli and Salmonella spp. fowl cholera and coccidiosis black heads [33].

2.1.4. Chloramphenicol

Chloramphenicol (CAP) is a broad-spectrum antibiotic commonly utilized in animal farming and aquaculture sector. Chloramphenicol (CAP) derived naturally from Streptomyces venezuelae Ehrlich or produced synthetically, has a solubility of 2.5 g L⁻¹ and a pKa of 9.5[34,35]. Despite being banned in various nations throughout the world, it is still being used in several underdeveloped countries because of its efficacy in human medicine even though it brings harmful effects on the surrounding aquatic environment [36]. Nonetheless, the unauthorized use of restricted antimicrobial drugs like chloramphenicol in aquaculture has become a serious problem in terms of consumer safety and the development of drug-resistant strains in bacteria. Furthermore, even at low doses, chloramphenicol can induce permanent aplastic anaemia in humans, providing a risk to workers who handle the items. Regardless, it is still accessible in Malaysia [20].

2.1.5. Oxolinic Acid

Oxalinic acid is a synthetic antimicrobial drug that is identical in structure to the naturally occurring nalidixic acid but is more active against both Gram-negative and Gram-positive bacteria. Oxalinic acid also has demonstrated action against a wide range of Gram-negative microbes, being highly active against proteus species but less active, or inactive, against pseudomonas [37]. This antimicrobial drug is an older member of a category of synthetic antibacterial drugs often known as quinolones. Despite the fact that the latest additions to the quinolones drug family out-perform oxalinic acid in terms of both bactericidal activity and bioavailability, its relatively low cost, low mammalian and fish contamination, and satisfactory performance render it a useful and widely used drug, especially in the aquaculture industry. [38].

Oxolinic acid is also utilized in veterinary medicine to treat problems arising from Gram-negative infections. Subsequently, the drug’s primary application is in the aquaculture industry, where, in addition to its Gram-negative action, its broad spectrum of activity against fungi, protozoans, and helminths has resulted in its beneficial application in fish farming in lots of nations,

both as a prophylactic and chemotherapeutic agent. The price of the oxolinic acid is higher than other antibiotics currently accessible in the market [20]

2.2. Effect of Antibiotic Residue towards Environment

The most frequent method for administering antibiotics to aquatic animals is to combine them with specially prepared formulated feed. Fish and aquatic animals do not adequately metabolize antibiotics and will excrete them completely wasted into the environment. It is believed that 75% of the antibiotics provided to fish are eliminated and dissolves in water [39]. Unregulated use of antibiotics in the aquaculture industry to produce seafoods such as farm-raised fish and shrimps could potentially cause human health hazards and food safety risks that are mainly disregarded in most developing nations throughout world. The use of antibiotics in food-producing animals leads to the accumulation of drug residues in the edible tissues of the treated animal. Antibiotics administered according to label guidelines should not leave residues at slaughter.

Antibiotic residues in aquaculture products may cause bacterial resistance and toxicity to consumers, resulting in illness or death. For instance, chloramphenicol residues increase the chance of developing cancer. It can induce aplastic anemia, a disorder in which the bone marrow stops producing red and white blood cells which can be irreversible and deadly even at extremely low quantities. Other hazardous consequences include immunopathological and carcinogenicity effects by sulfamethazine, oxytetracycline, and furazolidone; mutagenicity and nephropathy from gentamicin; and allergy by penicillin. The prevalence of antibiotic residues in domestic animal products and their associated consumer health hazards have been reported, with minimal emphasis focused on the aquaculture sector. [21].

Regardless of the method or purpose of administration, accumulation of antibiotics as residues in tissues before being entirely metabolized or eliminated from the body. The residues in fish or other animal tissues are most found when animals are taken for human food while still undergoing treatment or immediately after medication before the withdrawal period expires [40]. The intake of such goods may cause several health concerns in people [30,41].

Chloramphenicol, dimetridazole, ipronidazole, nitroimidazoles, furazolidone, nitrofurazone, and fluoroquinolones are restricted for usage off-label in food-producing animals [43]. International standards established by the FAO/WHO Codex Alimentarius Commission mandate food safety activities and monitoring. Maximum residual limits (MRLs) of authorized veterinary medications in food consumption are established with permissible levels of parent pharmaceuticals and/or metabolites in food products of treated animals that are safe for people (National Council regulation EEC/2377/90). Despite attempts to unify maximum residue limits globally under the supervision of the World Trade Organization (WTO) and the Codex Alimentarius, MRLs remains differ from one nation to another. Furthermore, MRLs in a certain animal product may vary from one nation to another based on the local food safety regulatory bodies and medication consumption trends, and most emerging countries have yet to define their own MRLs. Drug manufacturers establish withdrawal periods during which treated animal products are not permitted to enter the food system. When veterinarians authorize extra-label use of antibiotics, the withdrawal period is expected to be changed correctly, with most times being expanded to decrease the possibilities of residue buildup in animal tissues [44].

3. Eliminating Pollutants by Application of AOPs

Advanced oxidation processes (AOPs) have received attention as the technology for the treatment of water and wastewater. AOPs were originally proposed for the treatment of drinking water in the 1980s and they were later employed for the treatment of various kinds of wastewaters [45]. When it comes to the complexes aromatic structure and resistant nature of dyes and compounds, conventional biological and chemical oxidation path are inefficient in degrading these compounds. AOPs are regarded as an extremely attractive technology in terms of water treatments for eliminating organic contaminants that are classified as non-biodegradable and destroying pathogenic

microorganisms that unable to be approached with conventional technology [46]. AOPs are primarily employed to eliminate organic pollutants in water and sewage [45].

Advanced oxidation processes (AOPs) utilize reactive oxygen species (ROS), particularly hydroxyl radicals ($\cdot\text{OH}$), to degrade organic contaminants in wastewater. These hydroxyl radicals have a high oxidation potential and are capable to react with a various organic compound, making them non-selective. The result is the breakdown of the contaminants into harmless by-products such as carbon dioxide and water.

AOPs, or Advanced Oxidation Processes, are oxidation techniques characterized by the generation of reactive oxygen species, particularly hydroxyl radicals, in sufficient quantities to facilitate the production of treated effluents. Hydroxyl radicals are non-selective and have high redox potential (2.8 eV) [47]. Carbon radicals ($\text{R}\cdot$ or $\text{R}-\text{HO}\cdot$), are produced by their reaction with organic pollutants that can be converted to organic peroxy radicals. As a result of their reactivity, the radicals generated in AOPs undergo further reactions, accompanied by the formation of other reactive species. These reactions lead to the chemical breakdown and disintegration of pollutants present in the water and in certain circumstances even complete mineralization of the target water pollutants occurs.

The implementation of advanced oxidation processes (AOPs) became necessary for wastewater treatment whenever a requirement needed to remove micro-pollutants from water sources. Conventional techniques like membrane bioreactors were discovered to be insufficient in this regard, as the continuous use of these bioreactors resulted in the accumulation of particles from previous processes, leading to membrane clogging and hindrance in the separation of micro-pollutants [48].

Although conventional methods have been effective in treating wastewater to a certain extent by removing many pollutants, the increasing water scarcity has created a need for water reuse. This requires more thorough filtration of wastewater to achieve higher standards of water quality ideal for domestic and industrial application. The primary and secondary treatments alone have not been sufficient in raising the standard of reusable water, as they struggle to remove organic contaminants, toxic substances, and nutrients present in low concentrations. As a result, advanced treatment methods have been explored and identified to complement the secondary treatment and effectively remove these residual contaminants [49,50]. When AOP is implemented in tertiary treatment, hydroxyl radicals are generated in situ because of their short lifetime by a range of procedures, including a combination of oxidizing agents, ultrasound or irradiation, and catalysts [51]. Titanium dioxide (TiO_2) is the most commonly used catalyst. An alternative to it, new systems were established which utilize immobilized catalysis [52].

AOPs consist of various combinations of ozone, sonolysis, hydrogen peroxide, fenton, sulfate radicals, UV radiation, and photocatalytic techniques that are efficient in oxidizing various contaminants in water, air, and contaminated soil. One of the advantages of AOPs when contrasted with traditional treatment is that during mineralization the biodegradability of the wastewater accelerates when utilizing AOP as the treatment. Moreover, AOPs detoxify wastewater by degrading and eliminating organic pollutants into a less toxic compounds [53].

AOPs can be grouped based on homogeneity and heterogeneity as well as the presence of the irradiation. There are several established ways of AOPs for wastewater treatment process, as the basic chemical oxidation process is insufficient for extremely polluted wastewater [54]. Works of past research demonstrated that hydroxyl radicals with high oxidizing potential will be produced via different types of AOPs for degradation of dyes such as photocatalysis photolysis, ($\text{UV}/\text{H}_2\text{O}_2$), photolysis, (UV/O_3), photo-Fenton, electrochemical oxidation, ozonation and sonolysis [55].

AOPs have several advantages, including quick reaction rates, non-selective oxidation, which allows several contaminants to be treated at the simultaneously, and the ability to lower pollutant toxicity. AOPs can complete mineralization, but it may be expensive, thus biological approaches are better for the last step of dye treatment [56].

3.1. Eliminating Pollutants by Application of Photolysis and Ozonation (Photo-Ozone hybrid)

Ozone, a potent oxidant is capable of degrading organic contaminants through 2 pathways: (1) direct electrophilic attack by molecular ozone; (2) indirect attack by hydroxyl radical generated by the ozone decomposition reaction. It was noticed that elevating the ozone concentration improves the degradation rate of some pollutants while having no noticeable influence on the degradation of some other pollutants. The results might be because ozone molecules react directly with contaminants in four categories: (i) the oxidation-reduction reaction between O₃ and HO-2 (or O-2) are electron transfer process. (ii) Ozone reacts with pollutant through cycloaddition process by forming a five-member ring ozonide structure. (iii) Ozone is an electrophilic agent that attacks the nucleophilic position of the organic compounds and other groups in the aromatic molecule, such as -OH-, -NO-2 and -Cl resulting in a substantial effect on the reactivity of the aromatic ring. (iv) Ozone has nucleophilic properties, and nucleophilic reactions happen with molecules, especially when the chemical has carbonyl, double, or triple nitrogen carbon bonds [57].

Advanced oxidation processes (AOPs), such as photocatalysis and ozonation, hold significant promise for water purification. Photocatalysis is an innovative technology that harnesses the ability of semiconductors to generate hydroxyl radicals or other active agents when illuminated with the appropriate wavelength of light. This process facilitates the degradation of organic pollutants and the disinfection of water through mineralization. On the other hand, ozonation provides several advantages in wastewater treatment plants, including the activation of sludge reactions and the elimination of persistent organic contaminants from wastewater. According to Semblante et al. (2017), ozonation leads to sludge solubilization and then reduces biomass yield.

Ozonation is utilized in the upkeep of aquaria in aquaculture and in water treatment plants for drinking water purification due to its sterilizing and purifying properties. Table 3 shows the articles published on the treatment of wastewater using photolysis and ozonation treatment processes.

Table 3. Articles Published on the treatment of wastewater using Photolysis and Ozonation.

	AOP	Target Pollutant	Description of treatment	Result
[59]	Ultrasound with photolysis and ozonation	4-chloro 2-aminophenol	• Ultrasonic horn 20 kHz, 120 W. • Ultrasonic bath 36 kHz and output power of 150 W. • (Philips TUV 8W/G8T5), power rating 8 W and λ_{max} 254 nm.	• Maximum degradation of 4C2AP in both ultrasonic horn (complete removal) and bath (89.9%) with synergistic index as 1.98 and 1.29 respectively.
[60]	UV irradiation with ozone and H ₂ O ₂	geosmin and 2-methyl isoborneol (2-MIB)	• UV (LP Hg lamp 254 nm)/O₃ [oxidant] = 0.085 mg L⁻¹ • UV (LP Hg lamp 254 nm)/O₃ [oxidant] = 0.012 mg L⁻¹	• Kinetics: k_{app.} = 1.72 × 10⁻¹ min⁻¹ k_{app.} = 1.08 × 10⁻¹ min⁻¹
[61]	UV irradiation with ozone and TiO ₂	Acetaminophen, norfloxacin, metoprolol, caffeine, antipyrine, sulfamethoxazole, ketorolac, hydroxybiphenyl, diclofenac	• UV-B (313 nm), O₃, UV B & TiO₂, O₃ & UV-B, and O₃ & UV-B & TiO₂.	• The most complex system, O₃, UV-B & TiO₂, achieved the highest TOC abatement (95%)
[28]	photocatalytic oxidation, ozonation	Atenolol, Hydrochlorothiazide, Ofloxacin	• 2 15 W black light lamps	• Photocatalytic ozonation was the most efficient process for TPC

	and photocatalytic ozonation	Trimethoprim	(Lamp15TBL HQ Power Velleman ^R). λ _{max} 365 nm	and TOC removals (80% and 60% elimination after 2 h of treatment.
				• TOC removal within 80 min reached 94.7 ± 0.9%, 88.4 ± 0.9%, 97.8 ± 1.0%, and 76.3 ± 0.9%, respectively, higher than that in
[62]	Simultaneous catalytic ozonation and photocatalysis	TOC removal of sulfamethoxazole, tetracycline, ciprofloxacin, and trimethoprim	• MgMnO₃ as a bifunctional catalyst	• ozonation or photocatalysis (less than 20%). • first-order kinetics reaction constant of TOC removal in the case of tetracycline degradation by SCOP is 2.58 × 10⁻² min⁻¹
[63]	Photocatalytic ozonation	tetracycline hydrochloride (TCH)	• nanostructured Bi₂WO₆ as catalyst. • simulated solar light irradiation • 150 mL TCH solution, 80 mg L⁻¹ concentration and 75 mg catalyst • Illumination 300 W xenon lamp (AM 1.5 filter) and O₃ gas bubbling. • λ_{max} 357 nm	• The degradation rate is 97% in the presence of both light irradiation, ozone and Bi₂WO₆ catalyst. • optimal conditions: 0.5g L⁻¹ Bi₂WO₆, 10mg L⁻¹ O₃, pH = 3.8 • Cl⁻ inhibited TOC removal, presence of Mg²⁺ of • Ca²⁺ promoted the TCH degradation. • More than 55% mineralization during photolytic ozonation
[64]	Photo-assisted ozonation	Cefuroxime	• Solar photo-assisted ozonation in CPC photo reactor. • a semi-batch gas–liquid bubbled reactor. • purified oxygen was produced from the air (Lmin⁻¹ maximum) and secondly fed to an ozone generator (32g O₃ h⁻¹ maximum)	• stoichiometric ozonation ratio was estimated as zO₃ = 1.00 ± 0.06 (O₃ mol per cefuroxime mol) and the second order rate constant in the range 1.50 × 10⁶ – 4.69 × 10⁶ M⁻¹s⁻¹ for the non-dissociated and dissociated, respectively, cefuroxime molecules.
[65]	Vacuum ultraviolet photolysis and ozone	toluene	• MnO₂-rGO composite catalyst • two 4 W VUV lamps	• 2-M-rGO and the 3-M-rGO samples with ozone removal

	catalytic oxidation		- were placed in a stainless-steel reactor - concentration of ozone 65 ppm	efficiencies of 99.5% and 99.7% respectively.
[66]	Photocatalytic ozonation	Oxalic acid (OA)	- Ag₂O and ZnO modified g-C₃N₄ (Ag₂O-ZnO@CN_x) catalysts 300 W Xenon lamp (PLS-SXE300, Perfectlight, China), as visible light irradiation. - gaseous O₃, 5 mg L⁻¹ concentration, flow rate of 1.0 L min⁻¹.	- Increasing the g-C₃N₄ doping enhanced the separation of photogenerated e⁻ – h⁺ pairs, mobility of e⁻ transfer, and photocatalytic ozonation - Ag₂O-ZnO@CN_{0.4} achieved 83.43% of OA removal efficiency - highest k value (0.0311 min⁻¹), (synergy index η = 10.37) in this coupling system
[67]	Photocatalytic Ozonation	Ciprofloxacin	- Reactor equipped with a pure oxygen supply - ozone generator (5 g O₃/ h) - Light intensity 3100 μw/cm² low-pressure UVA lamp (30 W, length 46 cm, diameter 2.5 cm, Philips, Netherland)	98.5 % of CIP was degraded by the photocatalytic ozonation. - Degradation rate decreased substantially at the presence of anions as Cl⁻ > CO₃²⁻ > HCO₃⁻ > SO₄²⁻.

4-chloro-2-aminophenol (4C2AP) is a highly hazardous organic compound that is used typically for the manufacturers of dyes and pharmaceuticals. Barik and Gogate [59], did research on the degrading of 4C2AP by combining ultrasound, photolysis and ozonation processes. It was found that US + UV + O₃ combination process was the most promising technique producing maximal degradation of 4C2AP in both ultrasonic horn which was a full removal and bath (89.9%) with a synergistic index of 1.98 and 1.29 respectively. This work has clearly shown that combined processes are able to remove toxic pollutants.

Ozonation and photocatalysis generate ROS by different means and can be use in a hybrid mode either via simultaneous or sequential mode to effectively degrade recalcitrant compounds [68]. Antibiotics such as sulfamethoxazole, tetracycline, ciprofloxacin, and trimethoprim are the antibiotics commonly used in aquaculture. Lu et al. [62], conducted a study on the degradation of antibiotics commonly found in aquaculture effluent using simultaneous catalytic ozonation and photocatalysis. They employed MgMnO₃- as a bifunctional catalyst. The research revealed that the combined process generated a significantly higher amount of hydroxyl radicals compared to individual ozonation or photocatalysis. This synergy between the two processes contributed to the high efficiency of mineralization observed in this combined approach.

Similarly, Asgari et al. [67], investigated the photocatalytic ozonation of ciprofloxacin, an antibiotic, using UV A radiation. The research demonstrated that the process achieved a remarkable degradation rate of approximately 98.5% for ciprofloxacin. Photocatalytic ozonation demonstrated superior performance when compared to other treatment methods in terms of ciprofloxacin degradation

3.2. Mechanism of Photocatalytic Ozonation

The combination of UV radiation and ozonation was discovered to be an efficient catalytic system for degrading persistent contaminants in wastewater. This process begins with the photolysis of ozone, which then followed by the generation of hydroxyl (OH) radicals through the reaction of atomic oxygen (O) with water. The synergistic effect of atomic oxygen (O) and UV radiation improves the decomposition of ozone and promotes the direct and indirect production of hydroxyl radicals [69]

The hydroxyl radicals produced in an aqueous solution attack the aromatic ring of the dye molecule, producing the formation of smaller aliphatic molecules such as organic acid, aldehydes, ketones. Ultraviolet radiation enhances the degradation of resistant dyes by producing OH• radicals therefore boosting the degradation process [70]. Eq. (1) to (5) illustrate the production of hydroxyl radical



The indirect production of OH• by the following reaction is also possible.



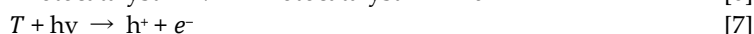
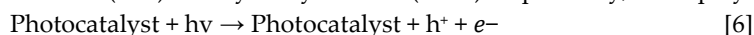
Combination of O₃ with UV improves the degradation of azo dye at all pH [71]. According to Wu [72], the O₃/UV process had a higher decolorization rate constant than the O₃ system.

According to Mehrjouei, Müller, and Möller [73], photocatalytic ozonation process consumes less ozone and are more economical than ozonation and photocatalysis. Titanium dioxide is a typical photocatalyst, yet it is photoactive in UV radiation, unlike WO₃, Fe₂O₃, In₂O₃, and BiVO₄ functioned as visible-light-responsive photocatalysts and WO₃ is an efficient catalyst for the solar photocatalytic ozonation process because it works within the solar energy wavelength range.

The synergy between photocatalysis and ozonation in water treatment has been recorded to significantly enhance oxidation efficiencies in contrast to the individual oxidation efficiencies of photocatalysis and ozonation alone. This positive synergistic effect of photocatalytic ozonation leads to the formation of hydroxyl (OH•) radicals, which effectively enhance the mineralization of organic pollutants [74]. According to Quiñones et al. [75], solar photocatalytic ozonation was found to be a cost-effective method for treating municipal secondary effluent compared to the solar photo-Fenton system.

Additionally, another benefit of photocatalytic ozonation is its potential application in disinfecting municipal wastewater. Numerous studies have reported the inactivation of bacteria and observed no resurgence of *E. coli* after 24 and 48 hours of post-treatment in the absence of light. Nevertheless, certain studies have indicated that certain bacteria can recover and resume growth following their initial inactivation [76,77]. This could have occurred because the affected bacteria could exploit the available carbon and energy sources in the treated water as substrates, allowing them to metabolize and regenerate [78].

Figure 1 shows the mechanism of photocatalytic ozonation. When light falls on the surface of photocatalyst (T), the photogenerated holes and electrons travel to the surface of the photocatalyst, participating in the redox reactions with adsorbed species resulting in the formation of superoxide radical anion (O₂^{•-}) and hydroxyl radical (OH•) respectively, as displayed by Equation below:



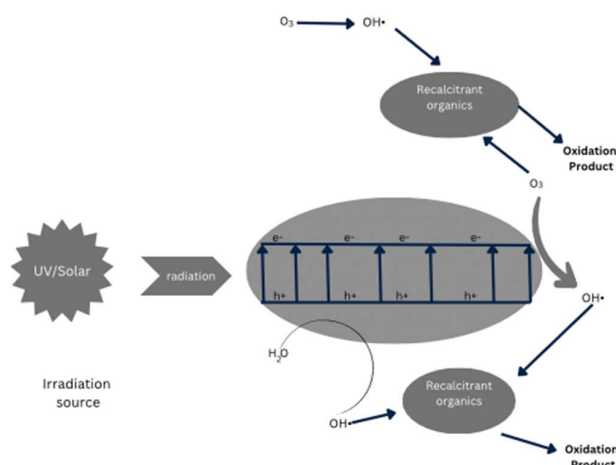


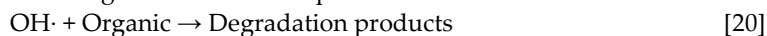
Figure 1. Mechanism of photocatalytic ozonation. [57].

The proficient trapping of photogenerated electrons by ozone contributes to the synergistic performance of photocatalysis and ozonation.



TiO₂-based photocatalysts are emerging materials that display exceptional absorption characteristics concerning organic compounds found in wastewater, primarily attributed to their remarkable inherent qualities. Rivas, Beltrán, and Encinas [61], did research on the degradation of a mixture of 9 antibiotics using UV irradiation, ozone gas and TiO₂ photocatalyst. Research outcomes have indicated that the introduction of TiO₂ photocatalyst notably enhanced the mineralization degree.

Equation 15 shows the reaction mechanism of TiO₂ photocatalyst, under light irradiation (photons), electrons and positive holes are generated in the conduction and valence band of titanium dioxide according to equation (15)[79]. The holes can either react directly with the organic molecules (equation 19) or form hydroxyl radicals (equation 17) that subsequently oxidize organic molecules (equation 20) [80]. The electrons can also react with organic compounds to provide reduction products (equation 15-21). The role of oxygen is important because it can react with the photo-generated electrons,



There exist certain constraints associated with TiO₂ photocatalysis when applied to organic pollutants in aquaculture wastewater. According to Kusiak-Nejman and Morawski [81], the surface of TiO₂ is the main site of photocatalytic ozonation, but electron transfer limitations can reduce TiO₂ efficiency as a photocatalyst. Additionally, the recombination of electron and hole charges within titania can potentially occur, resulting in the dampening of photocatalytic activity. Efficiency is limited by charge recombination after excitation. Modification of TiO₂ nanoparticles surface with metals and non-metals are promising steps that lead to increased photocatalytic efficiency [82].

Joseph et al. [83], on the research of photocatalytic chlorination of methylene blue using a newly synthesized titanium dioxide-silicon dioxide (TiO₂-SiO₂) photocatalyst. This is one of the

modifications of titania photocatalysts in improving the degradation of persistent pollutants in wastewater. The catalyst was synthesized using a sol-gel method followed by UV-treatment. Research outcomes indicated that the enhanced removal of methylene blue under aqueous medium was identified because of synergistic effect between chlorination and photocatalysis activated in the presence of TiO₂-SiO₂ photocatalyst.

4. Economic Aspect of Photo-Ozone Hybrid

The use of photocatalytic ozonation to remove biodegradable contaminants from water is not economically feasible because it is still one of the more expensive treatment technologies. Despite photocatalytic ozonation's effectiveness and its synergistic effects on the breakdown of contaminants in water, economic factors should also be focused on. Contrasting photocatalysis in the presence of oxygen (which needed power for UV irradiation sources) to photocatalytic ozonation (which consumes extra electrical energy for ozone generation), and the ozonation process which involves the use of an oxygen tank.

By calculating and evaluating the specific energy consumption for each oxidation system, it is possible to estimate and determine the energy consumed during the process in relation to the amount of decomposed materials.

5. Conclusions

In summary, the present review elucidates the benefits of photocatalytic ozonation in aquaculture wastewater treatment. The option of using these AOP hybrid systems in a sequential or simultaneous mode enables these systems to be fitted into existing water treatments systems thereby minimizing any required investments for plant upgrades. Further improvement can be made by exploring suitable catalyst that can be activated by ozone gas or UV irradiation or even by visible light. This will improve the mineralization ability of these hybrid systems resulting in a total mineralization of numerous contaminants including resistant pollutants present in the wastewater. The insights obtained from the literature can guide future advancements in several areas, identifying potential areas for improvement and innovation to meet the demands of the Sustainable Development Goals and the Environment Social and Governance framework.

Author Contributions: Writing—original draft preparation, NNDM; Conceptualization, methodology, writing—review and editing, supervision, project administration and funding acquisition, CGJ; resources, writing—review and editing, SHT; resources, writing—review and editing, JAG; resources, writing—review and editing, RS; writing—review and editing, SR; writing—review and editing, MS. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Project code: LRGS/1/2018/USM/01/1/3.

Data Availability Statement: We encourage all authors of articles published in MDPI journals to share their research data. In this section, please provide details regarding where data supporting reported results can be found, including links to publicly archived datasets analyzed or generated during the study. Where no new data were created, or where data is unavailable due to privacy or ethical restrictions, a statement is still required. Suggested Data Availability Statements are available in section "MDPI Research Data Policies" at <https://www.mdpi.com/ethics>.

Acknowledgments: This research was supported by the Research Management Center of Universiti Sains Malaysia (Project code: LRGS/1/2018/USM/01/1/3) in collaboration with the Research Management Center of Universiti Malaysia Sabah (Grant No. LRGS0010-2019). These contributions are gratefully acknowledged.

Conflicts of Interest: Declare conflicts of interest or state "The authors declare no conflicts of interest." Authors must identify and declare any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. Any role of the funders in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript; or in the decision to publish the results must be declared in this section. If there is no role, please state "The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results".

References

1. E. Tilley et al., "Compendium of sanitation systems and technologies," Development, 2014.
2. A. B. Dauda, A. H. Bichi, H. I. Ibrahim, and A. S. Tola-Fabunmi, "Assessment of Fish Farming Practices, Operations, Water Resource Management and Profitability in Katsina State, Nigeria," *Journal of Northeast Agricultural University*, vol. 24, no. 4, 2017.
3. J. E. P. Cyrino, Á. J. De Almeida Bicudo, R. Y. Sado, R. Borghesi, and J. K. Dairiki, "A piscicultura e o ambiente - o uso de alimentos ambientalmente corretos em piscicultura," *Revista Brasileira de Zootecnia*, vol. 39, no. SUPPL. 1, pp. 68–87, Jul. 2010, doi: 10.1590/S1516-35982010001300009.
4. Omofunmi O E, A. F. Adewumi, S Adisa O, and Alegbeleye, "To Assess the Impact Catfish Farm Effluents on Water Quality of Majidun Stream, South-West, Nigeria," *IOSR Journal of Environmental Science*, vol. 10, no. 2, 2016.
5. R. K. Horton, "An Index Number System for Rating Water Quality," *Journal of the Water Pollution Control Federation*, vol. 37, no. 03, 1965.
6. "A-Water-Quality-Index-Do-we-dare-BROWN-R-M-1970".
7. Canadian Council of Ministers of the Environment., "Canadian water quality guidelines for the protection of aquatic life: CCME Water Quality Index 1.0, Technical Report," Canadian Council of Ministers of the Environment 2001. Publication No. 1299; ISBN 1-896997-34-1, 2001.
8. C. G. Cude, "Oregon water quality index: A tool for evaluating water quality management effectiveness," *J Am Water Resour Assoc*, vol. 37, no. 1, 2001, doi: 10.1111/j.1752-1688.2001.tb05480.x.
9. "Standard Kualiti Air Kebangsaan – Jabatan Alam Sekitar." <https://www.doe.gov.my/standard-kualiti-air-kebangsaan-3/> (accessed Aug. 14, 2023).
10. J. Hu, Y. Qiao, L. Zhou, and S. Li, "Spatiotemporal distributions of nutrients in the downstream from Gezhouba Dam in Yangtze River, China," *Environmental Science and Pollution Research*, vol. 19, no. 7, 2012, doi: 10.1007/s11356-012-0791-6.
11. A. G. J. Tacon, M. J. Phillips, and U. C. Barg, "Aquaculture feeds and the environment: The asian experience," *Water Science and Technology*, vol. 31, no. 10, 1995, doi: 10.1016/0273-1223(95)00425-M.
12. A. E. Turcios and J. Papenbrock, "Sustainable treatment of aquaculture effluents-What can we learn from the past for the future?" *Sustainability (Switzerland)*, vol. 6, no. 2. 2014. doi: 10.3390/su6020836.
13. A. B. Dauda, A. Ajadi, A. S. Tola-Fabunmi, and A. O. Akinwale, "Waste production in aquaculture: Sources, components and managements in different culture systems," *Aquaculture and Fisheries*, vol. 4, no. 3. KeAi Communications Co., pp. 81–88, May 01, 2019. doi: 10.1016/j.aaf.2018.10.002.
14. C. E. Boyd and A. A. McNevin, *Aquaculture, Resource Use, and the Environment*, vol. 9780470959190. 2015. doi: 10.1002/9781118857915.
15. C. Y. Cho and D. P. Bureau, "Reduction of Waste Output from Salmonid Aquaculture through Feeds and Feeding," *Progressive Fish-Culturist*, vol. 59, no. 2, 1997, doi: 10.1577/1548-8640(1997)059<0155:ROWOFS>2.3.CO;2.
16. N. Logunova, T. Glechikova, and A. Kotenev, "Investment Attractiveness of the Area for Marine Farming and Marine Aquaculture Target Species," in *Transportation Research Procedia*, 2021. doi: 10.1016/j.trpro.2021.02.051.
17. J. F. Muir and J. A. Young, "Aquaculture and marine fisheries: Will capture fisheries remain competitive?" *Journal of Northwest Atlantic Fishery Science*, vol. 23, 1998, doi: 10.2960/J.v23.a10.
18. M. Martinez-Porchas and L. R. Martinez-Cordova, "World aquaculture: Environmental impacts and troubleshooting alternatives," *The Scientific World Journal*, vol. 2012. 2012. doi: 10.1100/2012/389623.
19. P. C. Citation Liong, H. B. Hanafi, Z. O. Merican, and G. Nagaraj, "Perspectives in Aquaculture Development in Southeast Asia and Japan: Contributions of the SEAFDEC Aquaculture Department," 1988. [Online]. Available: <http://hdl.handle.net/10862/140>
20. M. Shariff, G. Nagaraj Syndel Asia Sdn Bhd, F. H. C Chua, and Y. G. Wang, "The Use of Chemicals in Aquaculture in Malaysia and Singapore," *Use of Chemicals in Aquaculture in Asia*, 2000.
21. R. C. Okocha, I. O. Olatoye, and O. B. Adedeji, "Food safety impacts of antimicrobial use and their residues in aquaculture," *Public Health Reviews*, vol. 39, no. 1. 2018. doi: 10.1186/s40985-018-0099-2.
22. J. W. Fritz and Y. Zuo, "Simultaneous determination of tetracycline, oxytetracycline, and 4-epitetracycline in milk by high-performance liquid chromatography," *Food Chem*, vol. 105, no. 3, 2007, doi: 10.1016/j.foodchem.2007.03.047.
23. H. Hao et al., "Benefits and risks of antimicrobial use in food-producing animals," *Frontiers in Microbiology*, vol. 5, no. JUN. 2014. doi: 10.3389/fmicb.2014.00288.
24. M. K. Chattopadhyay, "Use of antibiotics as feed additives: A burning question," *Frontiers in Microbiology*, vol. 5, no. JULY. 2014. doi: 10.3389/fmicb.2014.00334.
25. P. A. Bradford and C. H. Jones, *Antimicrobial Therapy in Veterinary Medicine Fifth Edition*, vol. 9781461414. 2012.

26. D. F. Maron, T. J. S. Smith, and K. E. Nachman, "Restrictions on antimicrobial use in food animal production: An international regulatory and economic survey," *Global Health*, vol. 9, no. 1, 2013, doi: 10.1186/1744-8603-9-48.
27. I. Chopra and M. Roberts, "Chopra, I. and M. Roberts. 2001. 'Tetracycline Antibiotics: Mode of Action, Applications, Molecular Biology, and Epidemiology of Bacterial Resistance.' *Microbiology and Molecular Biology Reviews*. Tetracycline Antibiotics: Mode of Action, Applications, Molecu," *Microbiology and Molecular Biology Reviews*, vol. 65, no. 2, 2001.
28. E. M. Rodríguez, G. Márquez, E. A. León, P. M. Álvarez, A. M. Amat, and F. J. Beltrán, "Mechanism considerations for photocatalytic oxidation, ozonation and photocatalytic ozonation of some pharmaceutical compounds in water," *J Environ Manage*, vol. 127, 2013, doi: 10.1016/j.jenvman.2013.04.024.
29. V. Perreten and P. Boerlin, "A new sulfonamide resistance gene (sul3) in *Escherichia coli* is widespread in the pig population of Switzerland," *Antimicrob Agents Chemother*, vol. 47, no. 3, 2003, doi: 10.1128/AAC.47.3.1169-1172.2003.
30. M. H. Lee, H. J. Lee, and P. D. Ryu, "Public Health Risks: Chemical and Antibiotic Residues ** -Review- * Address reprint request to," *P. R. China. (Asian-Aust. J. Anim. ScL*, vol. 14, no. 3, 2001.
31. A. Immelman, "Veterinary applied pharmacology and therapeutics," *J S Afr Vet Assoc*, vol. 62, no. 4, 1991, doi: 10.4102/jsava.v62i4.1907.
32. M. Vass, K. Hruska, and M. Franek, "Nitrofurantoin antibiotics: A review on the application, prohibition and residual analysis," *Veterinarni Medicina*, vol. 53, no. 9. 2008. doi: 10.17221/1979-VETMED.
33. R. Draisci et al., "Determination of nitrofurantoin residues in avian eggs by liquid chromatography-UV photodiode array detection and confirmation by liquid chromatography-ion spray mass spectrometry," in *Journal of Chromatography A*, 1997. doi: 10.1016/S0021-9673(97)00247-1.
34. J. F. Huang, H. J. Zhang, and Y. Q. Feng, "Chloramphenicol extraction from honey, milk, and eggs using polymer monolith microextraction followed by liquid chromatography-mass spectrometry determination," *J Agric Food Chem*, vol. 54, no. 25, 2006, doi: 10.1021/jf062246e.
35. N. J. Vickers, "Animal Communication: When I'm Calling You, Will You Answer Too?," *Current Biology*, vol. 27, no. 14. 2017. doi: 10.1016/j.cub.2017.05.064.
36. I. C. Romero-Soto et al., "Degradation of Chloramphenicol in Synthetic and Aquaculture Wastewater Using Electrooxidation," *J Environ Qual*, vol. 47, no. 4, 2018, doi: 10.2134/jeq2017.12.0475.
37. A. Naeem, S. L. Badshah, M. Muska, N. Ahmad, and K. Khan, "The current case of quinolones: Synthetic approaches and antibacterial activity," *Molecules*, vol. 21, no. 4. 2016. doi: 10.3390/molecules21040268.
38. A. R. Millanao, A. Y. Mora, N. A. Villagra, S. A. Bucarey, and A. A. Hidalgo, "Biological effects of quinolones: A family of broad-spectrum antimicrobial agents," *Molecules*, vol. 26, no. 23, 2021, doi: 10.3390/molecules26237153.
39. L. Burridge, J. S. Weis, F. Cabello, J. Pizarro, and K. Bostick, "Chemical use in salmon aquaculture: A review of current practices and possible environmental effects," *Aquaculture*, vol. 306, no. 1-4. 2010. doi: 10.1016/j.aquaculture.2010.05.020.
40. L. Tollefson and M. A. Miller, "Antibiotic use in food animals: Controlling the human health impact," *J AOAC Int*, vol. 83, no. 2, 2000, doi: 10.1093/jaoac/83.2.245.
41. F. Cañada-Cañada, A. Muñoz De La Peña, and A. Espinosa-Mansilla, "Analysis of antibiotics in fish samples," *Analytical and Bioanalytical Chemistry*, vol. 395, no. 4. 2009. doi: 10.1007/s00216-009-2872-z.
42. K. N. Woodward, "Hypersensitivity in humans and exposure to veterinary drugs," *Veterinary and Human Toxicology*, vol. 33, no. 2. 1991.
43. "Food Chemical Safety | FDA." <https://www.fda.gov/food/food-ingredients-packaging/food-chemical-safety> (accessed Aug. 14, 2022).
44. M. L. Vranic, L. Marangunich, H. Fernández Courel, and A. Fernández Suárez, "Estimation the withdrawal period for veterinary drugs used in food producing animals," *Anal Chim Acta*, vol. 483, no. 1-2, 2003, doi: 10.1016/S0003-2670(03)00257-5.
45. Y. Deng and R. Zhao, "Advanced Oxidation Processes (AOPs) in Wastewater Treatment," *Current Pollution Reports*, vol. 1, no. 3. 2015. doi: 10.1007/s40726-015-0015-z.
46. J. A. Garrido-Cardenas, B. Esteban-García, A. Agüera, J. A. Sánchez-Pérez, and F. Manzano-Agugliaro, "Wastewater treatment by advanced oxidation process and their worldwide research trends," *Int J Environ Res Public Health*, vol. 17, no. 1, 2020, doi: 10.3390/ijerph17010170.
47. J. J. Pignatello, E. Oliveros, and A. MacKay, "Erratum: Advanced oxidation processes for organic contaminant destruction based on the fenton reaction and related chemistry (*Critical Reviews in Environmental Science and Technology* (2006) 36, (1-84))," *Critical Reviews in Environmental Science and Technology*, vol. 37, no. 3. 2007. doi: 10.1080/10643380601163809.
48. A. Saravanan et al., "A detailed review on advanced oxidation process in treatment of wastewater: Mechanism, challenges and future outlook," *Chemosphere*, vol. 308, 2022, doi: 10.1016/j.chemosphere.2022.136524.

49. L. P. Ramteke and P. R. Gogate, "Treatment of toluene, benzene, naphthalene and xylene (BTNXs) containing wastewater using improved biological oxidation with pretreatment using Fenton/ultrasound based processes," *Journal of Industrial and Engineering Chemistry*, vol. 28, 2015, doi: 10.1016/j.jiec.2015.02.022.
50. N. K. Sharma and L. Philip, "Combined biological and photocatalytic treatment of real coke oven wastewater," *Chemical Engineering Journal*, vol. 295, 2016, doi: 10.1016/j.cej.2016.03.031.
51. S. Malato, P. Fernández-Ibáñez, M. I. Maldonado, J. Blanco, and W. Gernjak, "Decontamination and disinfection of water by solar photocatalysis: Recent overview and trends," *Catalysis Today*, vol. 147, no. 1, 2009, doi: 10.1016/j.cattod.2009.06.018.
52. S. W. da Silva, C. R. Klauck, M. A. Siqueira, and A. M. Bernardes, "Degradation of the commercial surfactant nonylphenol ethoxylate by advanced oxidation processes," *J Hazard Mater*, vol. 282, 2015, doi: 10.1016/j.jhazmat.2014.08.014.
53. P. S. Roshini, R. Gandhimathi, S. T. Ramesh, and P. V. Nidheesh, "Combined Electro-Fenton and Biological Processes for the Treatment of Industrial Textile Effluent: Mineralization and Toxicity Analysis," *J Hazard Toxic Radioact Waste*, vol. 21, no. 4, 2017, doi: 10.1061/(asce)hz.2153-5515.0000370.
54. M. Muruganandham et al., "Recent developments in homogeneous advanced oxidation processes for water and wastewater treatment," *International Journal of Photoenergy*, vol. 2014, 2014, doi: 10.1155/2014/821674.
55. S. M. Anisuzzaman, C. G. Joseph, C. K. Pang, N. A. Affandi, S. N. Maruja, and V. Vijayan, "Current Trends in the Utilization of Photolysis and Photocatalysis Treatment Processes for the Remediation of Dye Wastewater: A Short Review," *ChemEngineering*, vol. 6, no. 4, MDPI, Aug. 01, 2022, doi: 10.3390/chemengineering6040058.
56. S. Vilhunen, M. Vilve, M. Vepsäläinen, and M. Sillanpää, "Removal of organic matter from a variety of water matrices by UV photolysis and UV/H₂O₂ method," *J Hazard Mater*, vol. 179, no. 1–3, 2010, doi: 10.1016/j.jhazmat.2010.03.070.
57. C. V. Rekhate and J. K. Srivastava, "Recent advances in ozone-based advanced oxidation processes for treatment of wastewater- A review," *Chemical Engineering Journal Advances*, vol. 3, 2020, doi: 10.1016/j.cej.2020.100031.
58. G. U. Semblante, F. I. Hai, D. D. Dionysiou, K. Fukushima, W. E. Price, and L. D. Nghiem, "Holistic sludge management through ozonation: A critical review," *Journal of Environmental Management*, vol. 185, 2017, doi: 10.1016/j.jenvman.2016.10.022.
59. A. J. Barik and P. R. Gogate, "Degradation of 4-chloro 2-aminophenol using combined strategies based on ultrasound, photolysis and ozone," *Ultrason Sonochem*, vol. 28, 2016, doi: 10.1016/j.ultsonch.2015.07.001.
60. K. Zoschke, N. Dietrich, H. Börnick, and E. Worch, "UV-based advanced oxidation processes for the treatment of odour compounds: Efficiency and by-product formation," *Water Res*, vol. 46, no. 16, 2012, doi: 10.1016/j.watres.2012.07.012.
61. F. J. Rivas, F. J. Beltrán, and A. Encinas, "Removal of emergent contaminants: Integration of ozone and photocatalysis," *J Environ Manage*, vol. 100, 2012, doi: 10.1016/j.jenvman.2012.01.025.
62. J. Lu et al., "Efficient mineralization of aqueous antibiotics by simultaneous catalytic ozonation and photocatalysis using MgMnO₃ as a bifunctional catalyst," *Chemical Engineering Journal*, vol. 358, 2019, doi: 10.1016/j.cej.2018.08.198.
63. T. Lu et al., "Efficient degradation of tetracycline hydrochloride by photocatalytic ozonation over Bi₂WO₆," *Chemosphere*, vol. 283, 2021, doi: 10.1016/j.chemosphere.2021.131256.
64. R. R. Solís, A. M. Chávez, O. Monago-Maraña, A. Muñoz de la Peña, and F. J. Beltrán, "Photo-assisted ozonation of cefuroxime with solar radiation in a CPC pilot plant. Kinetic parameters determination," *Sep Purif Technol*, vol. 266, 2021, doi: 10.1016/j.seppur.2021.118514.
65. S. Wu, H. Hu, Y. Lin, J. Zhang, and Y. H. Hu, "Visible light photocatalytic degradation of tetracycline over TiO₂," *Chemical Engineering Journal*, vol. 382, 2020, doi: 10.1016/j.cej.2019.122842.
66. J. Liu et al., "Insights into the photocatalytic ozonation over Ag₂O-ZnO@g-C₃N₄ composite: Cooperative structure, degradation performance, and synergistic mechanisms," *J Environ Chem Eng*, vol. 10, no. 2, Apr. 2022, doi: 10.1016/j.jece.2022.107285.
67. E. Asgari, A. Sheikhmohammadi, H. Nourmoradi, S. Nazari, and M. Aghanaghad, "Degradation of ciprofloxacin by photocatalytic ozonation process under irradiation with UVA: Comparative study, performance and mechanism," *Process Safety and Environmental Protection*, vol. 147, pp. 356–366, Mar. 2021, doi: 10.1016/j.psep.2020.09.041.
68. M. Gagol, A. Przyjazny, and G. Boczkaj, "Wastewater treatment by means of advanced oxidation processes based on cavitation – A review," *Chemical Engineering Journal*, vol. 338, 2018, doi: 10.1016/j.cej.2018.01.049.
69. K. H. Hama Aziz et al., "Degradation of pharmaceutical diclofenac and ibuprofen in aqueous solution, a direct comparison of ozonation, photocatalysis, and non-thermal plasma," *Chemical Engineering Journal*, vol. 313, pp. 1033–1041, 2017, doi: 10.1016/j.cej.2016.10.137.

70. M. Tichonovas, E. Krugly, D. Jankunaite, V. Racys, and D. Martuzevicius, "Ozone-UV-catalysis based advanced oxidation process for wastewater treatment," *Environmental Science and Pollution Research*, vol. 24, no. 21, 2017, doi: 10.1007/s11356-017-9381-y.
71. C. V. Rekhate and J. K. Shrivastava, "Decolorization of Azo Dye Solution by Ozone Based Advanced Oxidation Processes: Optimization Using Response Surface Methodology and Neural Network," *Ozone Sci Eng*, vol. 42, no. 6, 2020, doi: 10.1080/01919512.2020.1714426.
72. C. H. Wu, "Decolorization of C.I. Reactive Red 2 by ozonation catalyzed by Fe(II) and UV," *Reaction Kinetics and Catalysis Letters*, vol. 93, no. 1, 2008, doi: 10.1007/s11144-008-5200-2.
73. M. Mehrjouei, S. Müller, and D. Möller, "A review on photocatalytic ozonation used for the treatment of water and wastewater," *Chemical Engineering Journal*, vol. 263, 2015. doi: 10.1016/j.cej.2014.10.112.
74. J. Xiao, Y. Xie, and H. Cao, "Organic pollutants removal in wastewater by heterogeneous photocatalytic ozonation," *Chemosphere*, vol. 121, 2015. doi: 10.1016/j.chemosphere.2014.10.072.
75. D. H. Quiñones, P. M. Álvarez, A. Rey, and F. J. Beltrán, "Removal of emerging contaminants from municipal WWTP secondary effluents by solar photocatalytic ozonation. A pilot-scale study," *Sep Purif Technol*, vol. 149, 2015, doi: 10.1016/j.seppur.2015.05.033.
76. F. Demir and A. Atguden, "Experimental Investigation on the Microbial Inactivation of Domestic Well Drinking Water using Ozone under Different Treatment Conditions," *Ozone Sci Eng*, vol. 38, no. 1, 2016, doi: 10.1080/01919512.2015.1074534.
77. J. M. Sousa et al., "Ozonation and UV254nm radiation for the removal of microorganisms and antibiotic resistance genes from urban wastewater," *J Hazard Mater*, vol. 323, 2017, doi: 10.1016/j.jhazmat.2016.03.096.
78. J. C. Lou, C. J. Chang, W. Bin Tseng, and J. Y. Han, "Reducing the concentration of assimilable organic carbon (AOC) in treated drinking water," *Urban Water J*, vol. 12, no. 8, 2015, doi: 10.1080/1573062X.2014.955857.
79. S. G. Pouloupoulos and C. J. Philippopoulos, "Photo-assisted oxidation of chlorophenols in aqueous solutions using hydrogen peroxide and titanium dioxide," *J Environ Sci Health A Tox Hazard Subst Environ Eng*, vol. 39, no. 6, 2004, doi: 10.1081/ESE-120037840.
80. R. Ahmad, Z. Ahmad, A. U. Khan, N. R. Mastoi, M. Aslam, and J. Kim, "Photocatalytic systems as an advanced environmental remediation: Recent developments, limitations and new avenues for applications," *Journal of Environmental Chemical Engineering*, vol. 4, no. 4. Elsevier Ltd., pp. 4143–4164, Dec. 01, 2016. doi: 10.1016/j.jece.2016.09.009.
81. E. Kusiak-Nejman and A. W. Morawski, "TiO₂/graphene-based nanocomposites for water treatment: A brief overview of charge carrier transfer, antimicrobial and photocatalytic performance," *Appl Catal B*, vol. 253, 2019, doi: 10.1016/j.apcatb.2019.04.055.
82. A. Kwiecień et al., "Roxithromycin degradation by acidic hydrolysis and photocatalysis," *Analytical Methods*, vol. 6, no. 16, 2014, doi: 10.1039/c4ay00708e.
83. C. G. Joseph, Y. H. Taufiq-Yap, E. Letshmanan, and V. Vijayan, "Heterogeneous Photocatalytic Chlorination of Methylene Blue Using a Newly Synthesized TiO₂-SiO₂ Photocatalyst," *Catalysts*, vol. 12, no. 2, 2022, doi: 10.3390/catal12020156.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.