A Systematic Review of Aquaculture Wastewater Treatment Technologies: Contaminations, Effects and Treatment Techniques

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Abstract: Aquaculture (AC) is the primary solution to global food scarcity. With the rise in world population, the need for AC escalates. The growth in fish feed, pharmaceuticals, substances, and the metabolic waste or deaths of aquatic species ultimately leads to the generation of substantial AC effluent. AC discharges comprise many pollutants, including conventional contaminants, organic substances, toxic metals, and biological chemicals, resulting in occupational dangers, food security concerns, and environmental damage. Adequate Wastewater (WW) treatment techniques are essential for eliminating dangerous contaminants to mitigate environmental and human safety effects. In circulating AC facilities, various natural and physical processes have been employed to eliminate impurities from AC-WW; their efficacy in pollutant removal necessitates further enhancement to attain zero-waste release and promote viable AC growth. Effective regulation must be instituted to guarantee the proper functioning of the AC sectors and the compliant discharge of effluent. This review seeks to furnish exhaustive data on AC-WW for academics and encourage AC's sustainable advancement.

Keywords: Aquaculture; Wastewater; Contaminations; Treatment.

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I. Introduction

Aquaculture (AC) is the predominant industry in global food manufacturing, exhibiting a median annual growth rate of 3.4% (Schar et al., 2020). The intake of farmed seafood exceeded that of wild fish output. AC has recently gained significant importance in the fish industry due to the decreasing number of wild stocks. It is acknowledged as consumers' primary source of seafood. Food availability is guaranteed by the effective implementation of AC methods, particularly in developing nations. The proportion of fish for people's consumption derived from AC is anticipated to rise from 50% to 57% by 2029. India is the second-largest global fish exporter via AC, contributing 2.05% to the Gross Domestic Product (GDP) (Nayak et al., 2023). The fisheries sector in India has attained a capital of Rs 345.5 billion, according to a recent assessment by the National Fishes Growth Board, following the Economic Movement initiated by the Blue Movement in the country. Water shortage and the loss of natural water supplies constitute significant concerns confronting the global community, particularly in emerging nations (Mishra et al., 2021).

Seafood security is interconnected with essential resources such as electricity and water, and preserving ecological integrity is necessary to guarantee a plentiful food supply. AC productivity is expected to decline due to many obstacles, with the quantity and availability of quality water being a significant restraint. This requires advancing sustainable solutions for AC Wastewater (WW) treatment (Obaideen et al., 2022). Numerous research studies have examined the interrelationship of Seafood, Energy, and Wastewater (SEW) assets (Wang et al., 2022). The study has examined the relationship by concentrating solely on the connections between shellfish and sewage. This research undervalues the viability of the seafood business, as seafood manufacturing and consumption utilize water and power. Many investigations have been undertaken to attain seafood's long-term viability, primarily concentrating on its manufacturing sector, including nutrient usage effectiveness in seafood manufacturing.

Global initiatives aim to enhance the availability of seafood, making a better seafood industry crucial for promoting the utilization of this naturally occurring resource and mitigating associated ecological repercussions (Elegbede et al., 2023). A structure for analyzing the seafood-energy-water confluence has been established to comprehensively evaluate operations and resource utilization throughout the seafood supply network (Bharathi et al., 2024). This research assessed the power and water consumption across the seafood manufacturing process, including handling, preserving, processing, wrapping, distribution, advertising, and utilization, along with their associated ecological implications. The research indicates that the fisheries supply chain's overall energy and water consumption, with minimized ecological implications, is crucial for sustaining sustainability (Fasihi et al., 2023).

This research seeks to bridge the review gaps and offers a thorough and expedited comprehension of AC-WW for novices. Initially, the contaminants present in AC-WW and their effects will be outlined to underscore the significance of AC-WW treatment. The current therapeutic methods are evaluated. Finally, the current issues in the AC business are examined, and suggestions for the sustainability growth of AC in the future are proposed.

II. Constituents of AC Effluent

The primary components of AC-WW are unused feed residues, metabolic wastes from farmed fish species, and sediment substances present in both liquid and particulate types. Elevated concentrations of organic substances, calories, poisonous chemicals, and pathogenic microbes characterize improper AC effluent. Incorporating medicines and development enhancers in fish feed has increased the array of compounds in AC-WW. The variance in the contents and levels of AC-WW is contingent upon the farming system and the water handling procedures utilized during fish cultivation, in addition to the characteristics of the feed.

Nutrients and Organic Matter Densities in AC-WW

This includes the WW's dissolved nutritional components, chemicals, and floating organic matter. The organic content in the WW, consisting of settleable and insoluble solids, originates from unused feed and fecal wastes. The soluble components of feed and physiological waste serve as the origins of the dissolved elements. The amount of nutritional and natural matter elements in AC-WWs is influenced by feed structure, feeding magnitude, fish feed consumption, water renewal structure, and the farming method.

Prior research indicates that 25 - 45% of the feed ingested by cultured fish is allocated for development to be retained as biomass, whilst 65 - 85% of the balance is excreted as metabolic waste. These values fluctuate based on fish organisms, feeding characteristics, and ecological circumstances. The accumulation of waste in an AC environment leads to microbial breakdown, a microbial process that produces increased oxygen request, nitrogen dioxide, and nitrogen-containing chemicals. In static-renewal and pass-on culture structures, prevalent in most AC facilities, effluent is regularly discharged during fish cultivation. The nature, volume, and amount of WW discharged differ among various cultural systems.

Microbial Elements of AC Effluent

The nutritional composition of AC effluent facilitates the growth of various microbial communities. The presence of living things in the culture supplies a nutritional foundation for microbial proliferation. The primary avenues for bringing these microbes into the growing medium are the water and feed supplies. Indigenous bacterial organisms, including Aeromonas spp. and Vibrio spp., are naturally present in fish environments. These microbes become harmful when water quality declines, nutritional deficits arise, and metabolic abnormalities occur in cultivated fish organisms.

III. AC Treatment Methods

The sustainability theory has developed to enhance the capacity of subsequent generations to fulfill their own needs. The availability of pristine watersheds, safeguarding existing water supplies, and ensuring sanitary safety are prerequisites for sustainable growth in rural and urban regions. The primary obstacles to sustained water treatment facilities in underdeveloped nations are (1) economic underdevelopment, (2) technological inadequacies, and (3) insufficient energy to implement cost-effective alternatives. This research examines recent technology advancements in sustainable AC-WW management. This analysis examines the RAS systems, subsequent modifications utilizing wetland structures, hydroponics, and micro-algae-based synergy, and the durability of these inventions.

Recirculating AC Systems (RAS)

Traditional RAC systems necessitate an ample water supply, with the conservation of this resource being the paramount consideration. RAC typically utilizes surface water, including rivers, originates, lakes, dams, and groundwater holes. The water flow in such structures must be adequate to satisfy either the soluble oxygen needs or to remove the physiological waste of the aquatic organisms. The newly sourced intake water predominantly substitutes the current water in the pass-on unit. Self-cleaning can occur if the system maintains a relatively high flow speed. The constraints of traditional AC systems can be overcome by employing an RAS.

The RAS processes WW by eliminating hazardous contaminants and reusing the cleaned water. A relatively minimal fluid volume cultivates substantial fish in RAS plants. The effluent is circulated partially or entirely to the fish tanks. A recirculating AC system typically requires a water replenishment of 6 to 13% daily, contingent upon supply and consumption rates. Implementing RASs mitigates the ecological impact of fishing and diminishes freshwater consumption, promoting environmental sustainability.

Engineered Wetlands in RAS

Built-in wetlands technique is increasingly significant in RAS due to its feasibility and cost-effectiveness in WW treatment. Figure 1 illustrates an artificially created wetland designed for a recirculating network. Energy is solely necessary for pumping and distributing WW in engineered wetland structures. The operating head primarily dictates the energy requirements, frequently much below 0.2 kWh m^{-3}. The symbiotic approach can be efficiently implemented in RAS facilities by integrating organisms with AC water to establish a beneficial, eco-friendly solution. Engineered wetland structures have excellent efficacy in treating nitrogen-laden WW. In large-scale treatment structures, wetlands efficiently eliminate nutrients such as ammonia and nitrates; however, eliminating nitrates and phosphorus is either ineffective or adversely impacted during wetland transit. An extended retention time is necessary for effective nitrogen elimination. Another drawback is that they necessitate a substantial landmass, up to 2.8 times the pond's surface area. This impacts the financial viability of wetland systems due to their reduced hydraulic feeding rate and extended hydraulic retaining time required for effective pollution removal.

Aquaponics Inside RAS Systems

Aquaponics is a food manufacturing method that integrates traditional AC methods with RAS. The approach involves cultivating aquatic organisms such as slugs, fish, clams, or shrimp in hydroponics tanks. This is accomplished by growing plants in water inside a symbiotic ecosystem. Traditional AC wastes from cultivated animals might be collected in the water, elevating toxin levels. In an aquaponics structure, water from an AC structure is supplied to a hydroponic structure, where microorganisms decompose by-products into nitrate and ammonia, which serve as plant nutrients. The water is recirculated into the AC structure. Thus, an aquaponic setup integrates aquatic fauna and plants under a single framework. Vegetables can be cultivated concurrently in AC systems outdoors, in adequately illuminated buildings, or within greenhouses. Three categories of plants utilized in aquaponics include suspended emerging and subterranean species. Floating plants possess natural buoyancy, with foliage rising above the water's surface and their roots submerged.

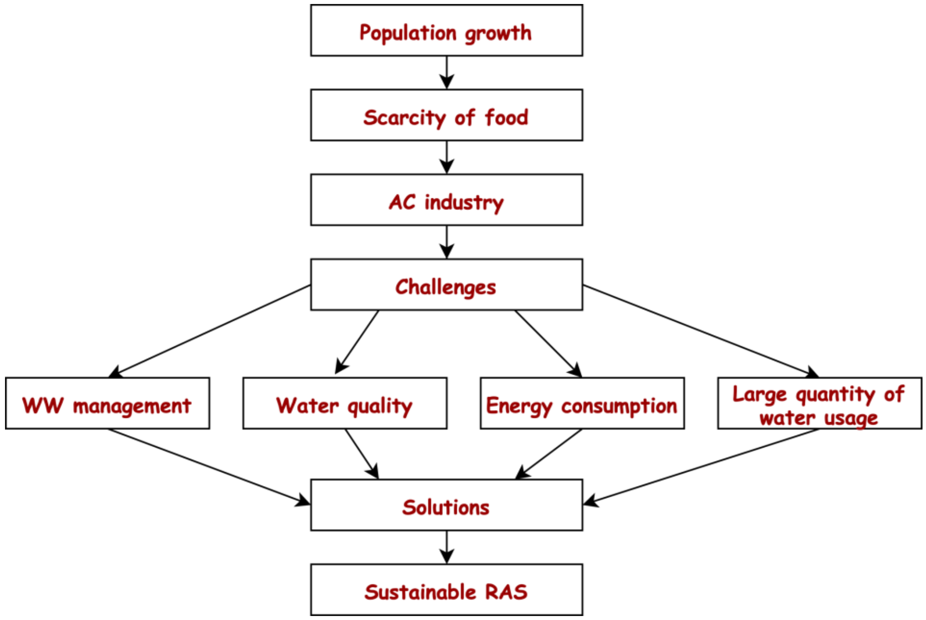

Figure 1: RAS Workflow

Microalgae-Enhanced AC

The principle of microalgae-assisted AC involves transforming organics in saturated pollutants into biomass by phytoplankton proliferation, utilizing the value-added biomass to partially substitute AC feed and bolster the defenses of aquatic organisms. Establishing the microalgae systems enhances carbon dioxide absorption and facilitates oxygen discharge, functioning as a bio-pump and fostering an ideal atmosphere for marine organisms. The microalgae assimilate nutrients from AC sewage, allowing for the harvesting of algal biomass, which can serve as a value-added AC feeding. All these attributes of microalgae-assisted AC surpass the traditional AC structure—the visual representation of the system's advantages and the cyclic growth chain. The primary constraints of the RAS method are the substantial investment and upholding expenses, which can be alleviated by transforming minerals from AC-WW into algal biomass, thereby reducing the manufacturing of biomass and AW therapy costs while concurrently streamlining the AW cleanup procedure.

Combined Technological Developments in AC Systems

The coordinated strategy of employing diverse complementary species on the farm has enhanced nutrient equilibrium and diminished organic matter in the WW and soils. This represents a symbiotic method for treating AC-WW. In these connected structures, organisms at below-trophic levels absorb and process organic matter and fluid nutrients in WW. This adheres to the ecological symbiosis principle whereby waste from one activity transforms into an energy supply for another. This method effectively eliminates all inorganic and natural contaminants from agricultural WW. It can be utilized with aerobic-anaerobic processing units, decreasing costs and energy consumption and enhancing sustainability. The integrative multi-trophic AC system combines fed AC with natural extraction AC. It offers the benefit of strengthening particle organic material and inorganic extraction AC, augmenting dissolved inorganic micronutrients.

IV. Management and Regulations Regarding AC-WW

Enhancing Feed Quality and Nutrition

Feed wastage is a significant factor that influences fertilizers and organic waste in AC effluent. Waste varies from 1 to 35% based on the type of supply, feeding protocols, culture methods, and species involved.

Recent enhancements in feed quality, by incorporating reduced quantities of feed additives like bacterial phytase, have increased the volume of fecal particles generated and enhanced the absorption of phosphorus and ammonium. Giving fish high-energy diets with enhanced pellet credibility and feed that has elevated fat levels, reduced protein content, and diminished carbohydrates has been shown to reduce feed disintegration speeds while boosting digestion and waste production.

Moreover, improving fish feed can significantly decrease the amount of unused feed and substantially mitigate water contamination. In AC, optimal feed usage and waste management can be achieved by following feeding protocols and employing technology that detects feed pellets in fish tanks and dispenses appropriate feed rations. To enhance AC viability and minimize the release of nutrients into the surroundings, fish feeds must be optimized for superior digestion, reduced nitrogen elimination, and decreased dietary protein content.

Government Participations

Given the existing comprehension of the sustainable and health ramifications linked to the ecological release of AC-WW, coupled with its status as an affiliate state and adherence to numerous worldwide and regional regulations concerning water resource preservation and management. It is necessary to reassess its laws and regulations to incorporate legislation that mandates the appropriate therapy and release of AC-WW into the environment. The research emphasized the current fisheries and AC regulations and the governmental agencies advocating for fishery and AC policy that assist with AC-WW treatment.

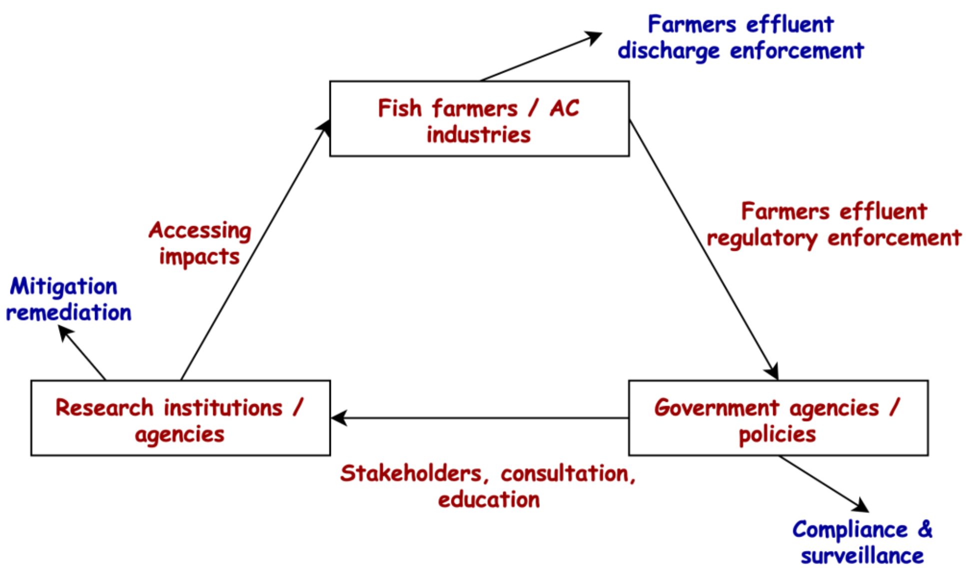

Figure 2: AC-WW Management Scheme

Figure 2 presents a proposed AC-WW management strategy. The proposed plan for management recommends sufficient engagement of fishermen, AC sectors, universities, government departments, and other participants in the AC and fishery sub-sector. AC practitioners are anticipated to guarantee that WW is discharged into aquatic environments and that channels are adequately treated via their relevant organizations (effluent regulatory authorities for farms). Research organizations must undertake further investigations into enhanced and restricted methods for fishermen to successfully treat AC-WW while providing platforms to educate them about the ecological consequences of releasing untreated or semi-treated AC-WW. Government departments should engage with stakeholders to identify the most effective methods for assuring adherence to existing regulations while simultaneously seeking to modify these policies and guarantee surveillance and adherence. Relevant governmental entities must be able to uphold environmental laws governing sewage discharge and evaluate and execute financial and administrative mechanisms to diminish the release of unprocessed WW.

V. Conclusion

As AC fish output rises, a significant volume of AC effluent is generated. AC emissions contain several pollutants that harm the ecosystem, resulting in toxicological consequences, eutrophication, antibiotic resistance, and soil deterioration. Effective WW treatment techniques are essential for eliminating dangerous contaminants to mitigate their environmental and human safety effects. Present treatment methods utilized in AC-WW can eliminate specific contaminants; however, their efficacy in pollutant removal needs enhancement to attain zero-waste release and ensure sustainable AC expansion. Effective regulation and licensing must be instituted to guarantee the proper functioning of the AC sectors and the compliant discharge of effluent.

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