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Review

Aquaculture—Production System and Waste Management for Agriculture Fertilization—A Review

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Abstract: Aquaculture is the fastest growing animal food production sector worldwide and is becoming the main source of aquatic animal foodstuff for human consumption. However, the aquaculture sector has been strongly criticized for its environmental impacts. It can cause discharge and accumulation of residual nutrients in the areas surrounding the production farms. This is because, of the total nutrients supplied to production ponds, only 30% are converted into product, while the rest is usually discharged into the environment to maintain water quality in aquaculture culture systems, thereby altering the physic-chemical characteristics of the receiving water. In contrast, this same accumulation of nutrients is gaining importance within the agricultural sector, as it has been reported that the main nutrients required by plants for their development are found in this aquaculture waste. The purpose of this review article is to indicate the different aquaculture production systems, the waste they generate, as well as the negative effects of their discharge into the environment. Biofiltration and bioremediation processes are mentioned as alternatives for aquaculture waste management. Furthermore, the state of the art in the treatment and utilization of aquaculture waste as a mineral source for agricultural nutrition through biodigestion and biomineralization processes is described. Finally, aquaponics is referred to as a biological production approach that, through efficient use of water and recycling of accumulated organic nutrients in aquaculture systems, can contribute to addressing the goals of sustainable aquaculture development.

Keywords: environment; eutrophication; particulate fraction; effluent; treatment

1. Introduction

Aquaculture is an activity aimed at the cultivation of aquatic animals such as freshwater or marine fish, molluscs, crustaceans, and emerges as a strategy to replace traditional fishing, reducing the pressure exerted on natural freshwater or marine populations [1]. Aquaculture has experienced the highest average annual growth in the last 10 years, with a projected contribution of 52% of fishery products for human consumption by 2025 [2]. Every year, this sector generated around 171 million tons with an approximate value of 36,000 million US dollars, of which 47% came from the aquaculture sector, with Asia being the largest representative at 89% [3].

The aquaculture sector generates jobs and food products; however, it causes environmental problems due to the discharge of organic matter (OM) and nutrient-rich waste that pollutes the water [4]. The nutrients supplied to the farmed animals are not fully consumed, with only 30% being utilized by fish, molluscs or crustaceans, the rest settling and accumulating as a particulate fraction (commonly referred to as “sediment” or “sludge”) composed mainly of OM, nitrogen (N), and phosphorus (P) [5]. Previous research reports an annual discharge of 27.0 kg/ha of N and 9.0 kg/ha of P in Norwegian fish farms [6]. Another report an annual discharge of 84.0 kg/ha of N, 21.0 kg/ha of P and 2400 kg/ha of OM [7]. Whereas, in fish farms in Japan, the rate of OM accumulation is between 3.9 and 11.7 mg/day [8].

Generally, these nutrients are removed to maintain water quality in aquaculture systems by discharging them into the environment altering the physico-chemical characteristics of the receiving water, decreasing dissolved oxygen (DO) concentration, but increasing; the total suspended solids (TSS), the biological oxygen demand (BOD), and chemical oxygen demand (COD). Furthermore, it decreases benthic fauna [9]. In contrast, this same accumulation of nutrients is gaining importance, as it has been reported that it contains the main nutrients required by plants, with a high potential for their treatment and reuse as sources for agricultural fertilisation [10].

Therefore, this article indicates the different aquaculture production systems, the waste they generate, as well as the negative effects produced by their discharge into the environment. Biofiltration and bioremediation processes are mentioned as alternatives for the management of aquaculture waste. Furthermore, the state of the art in the treatment and use of the aquaculture particulate fraction as mineral sources for agricultural fertilisation by means of biodigestion and biomineralization processes is described. Finally, aquaponics is eluded as a biological production approach which, through the efficient use of water and the recycling of organic nutrients accumulated in aquaculture systems, can help to address the objectives of sustainable aquaculture development.

2. Aquaculture Production Systems

Worldwide, the aquaculture is classified according to the degree of production intensity (balanced feed, sowing density, artificial aeration, among others), such as extensive, semi–intensive, and intensive. The extensive systems use basic management levels, since they do not make use of ingredients for the production of this type of systems, the organisms grow up on their own and productivity is limited by natural water conditions, stocking density is low, which generate a production not greater than 500 kg/ha, the semi-intensive systems make use of additional ingredients, such as feed with high protein content, therapeutic products to prevent disease, as well as chemical and organic fertilizers to increase natural productivity of the system, support stocking densities from 10–30 fish/m^3, and reach production oscillating from 1000 to 2500 kg/ha, whereas in intensive aquaculture, greater yields are achieved than what the capacity of the natural environment allows, by means of techniques, such as balanced feed, artificial aeration, as well as mechanical and biological filtration supporting densities from 60–120 fish/m^3 and reaching productions from 10,000 to 80,000 kg/ha; the aquaculture systems are classified such as flow, pond, recirculating, weir and net cages and floating and bottom farming (Table 1) [2,11].

Table 1. Aquaculture systems used in the production of marine and freshwater organisms and waste production.

Aquaculture System	Characteristics	Species Production	Waste Production	Reference
Flow	This system has rectangular canals with an outlet drop at the end of the structure allowing elevating O concentration and releasing CO_2. The flow or canal system use run-off waters coming from rivers or springs.	– Siluriformes – *Solea solea* – *Oncorhynchus mykiss*	The water is not retained the sufficient time for significant OM biological decomposition processes to develop, thus continuous waste produced is discharged to the environment.	[12]

Table 1. *Cont.*

Aquaculture System	Characteristics	Species Production	Waste Production	Reference
Pond	This system is made up of artificial structures covered with high-density plastic to retain water for long periods of time, water quality is controlled by natural, chemical, and biological processes that occur in ponds. A constant water source is necessary to guarantee sufficient capacity to achieve a daily recharge of at least 10% of total pond volume to allow eliminating NH_4^+ and OM excess.	– *Cyprinus carpio* – *Cherax quadricarinatus* – Dendrobranchiata – *Oreochromis niloticus* – Caridea	Around 80 to 90% of dry matter and C, as well as 70 to 80% of N and P end up as waste. From 1 to 100 kg/ha of daily feed rate, approximately 350 mg/m^2/day is excreted by fish as waste.	[13–15]
Recirculating aquaculture system (RAS)	This system consists of intensive fish production that uses water treatments to facilitate recycling. RAS generally include: (1) Settlers and micro-screens for collecting sediment and suspended particles, (2) Nitrifying biofilters and (3) Gas exchange devices to eliminate dissolved CO_2 and add the O.	– *Maccullochella peelii* – *Lates calcarifer* – *Oreochromis niloticus* – *Solae senegalensis* – *Coregonus lavaretus*	RAS consume a small quantity of water (only 5% per day to compensate for the loss caused by evaporation, solid elimination, and plant absorption) and generate pollutants of small volume but with a high nutrient concentrate.	[16–18]
Open-net pen or net cage	This system basically represents "fencing" a portion of water. Net cages are systems that retain farmed species in a confined area, excluding unwanted animals from the surrounding water body, this system depends on the water course where this type of system is located, in which the number of pollutants dumped in the environment cannot be controlled.	– *Salmo salar* – *Cyclopterus lumpus* – *Oplegnathus punctatus* – *Lates calcarifer*	Sites with bad circulation imply low DO concentration conditions, and the accumulation of metabolic waste promotes algal growth and many other benthic organisms that adhere and colonize around the cage, reducing water movement through the cage severely and deteriorating water quality.	[19]
Floating and bottom	This system uses similar principles to those of open–net pen or cage-net systems, which is why they also depend on water movement as well as its natural quality to supply the necessary nutrients and conditions for the development of farming bivalves.	This system is those destined for bivalve mollusk production (oysters, mussels, clams, and scallops)	Likewise, they cannot also control the number of pollutants dumped in the environment	[20]

3. Aquaculture Waste

Waste produced by aquaculture is classified into four forms: gases (H_2S), liquids (effluents), semisolids, and solids (particulate fraction), of which the last two are known as sediments or sludge [21]. Solid waste or sludge is further divided into two categories: suspended solids and settleable solids [22].

3.1. Gas Emission from Aquaculture

Within the aquaculture systems, sulfur (S) is a residual chemical element that originated from metabolic waste produced by farmed organisms; its form is mainly as a sulfate ion since, in aerobic sediment conditions in suspension, S decomposes as sulfide (S^{2-}) and oxidizes to sulfate (SO_4^{2-}). However, in aquaculture, as feed applied to culture systems increases, the accumulation of organic detritus is promoted, causing severe anoxia conditions (lack of oxygen) in sediments, this situation makes anaerobic bacteria use the oxygen molecules present in sulfate ions, increasing H_2S production, any concentration of H_2S interrupts the respiration of the aquatic animals, causing them stress and making them susceptible to diseases [23].

3.2. Aquaculture Effluents

In most aquaculture systems, food supply is the main cause of water pollution and deterioration. Only 30% of the provided nutrients turn into a product, whereas the rest must be removed and generally dumped in the environment in the form of effluents (fluids loaded with solid, liquid, or gaseous waste) [24]. Aquaculture effluents include organic compounds, such as proteins, lipids, carbohydrates, vitamins, and minerals, while inorganic waste products accumulate mainly as NH_4^+, NO_2^-, NO_3^-, bicarbonates, and phosphates, of which N and P are the main components from effluents that cause environmental pollution [25]. The rate of pollutants released to the environment is directly ruled in function of the amount of feed consumed and digestibility. Generally, pond and recirculation systems produce a smaller number of effluents to be discharged but with much higher OM and nutrient concentrations, while flow, net cage, or open-net pen, floating and bottom farming systems emit greater flow but with a lower concentration of these pollutants [26].

3.3. Aquaculture Particulate Fraction

Waste conformed by N, P, and dissolved organic carbon compounds negatively affects the environment [27], these particles are mainly formed from unconsumed food, waste produced by fish, and the residual part where unassimilated forms accumulate the greatest content of incoming nutrients to the aquaculture systems. Additional treatments are thus necessary for the good use of minerals [28].

Within aquaculture production systems, up to 70% of the feed supplied may end up as a particulate fraction at a daily average of 0.4–12.3% [29]. This matter usually contains approximately 7–32% N, as well as 30–84% of P provided for the development of the cultured organisms. Furthermore, the aquaculture particulate fraction is divided into two categories; suspended solids and settleable solids [30]. Suspended solids are fine particles ranging from 30 to 100 micrometers (μm), so they do not settle and remain suspended in the water of aquaculture systems, making them very difficult to collect [22]. In contrast, settleable solids are larger particles (100 > μm), which form sediment in a short period of time, making them easier to collect and remove from culture systems [31].

4. Aquaculture Waste Effect on the Environment

One of the main effects on the environment caused by aquaculture is the eutrophication of the surrounding areas of fish farms; this is because only 30% of supplied N is used in fish farms. This is because the rest is discharged as effluent with each water recharge in this system. Nutrient levels in the receiving bodies are thus elevated above normal and start an ideal environment for anoxic sediments and changes in benthic blooms in the communities in the areas where these residuals are dumped [32].

Change is generated by suspended solids, which reduce light penetration through water, inhibiting the photosynthesis process of phytoplankton and marine grass, and thus generating an increase in mortality of these organisms [33]. Subsequently, bacterial degradation of dead plants consumes oxygen in water, affecting aquatic species farming negatively. In extreme circumstances, profiles of aquatic organisms may transform into species tolerant to sediments, which affects the aquatic food chain on its root. Furthermore, when the particulate fraction settles in the bottom, it tends to biologically degrade due to its OM content and, in consequence, transforms the bottom of ponds or cultivation areas to anaerobic conditions [34].

Alterations may provoke significant changes in the community composition of benthic organisms. For example, a report found that water quality and sediments were negatively affected by effluents dumped at 50 and, 150 m while studying the impact of shrimp effluents dumped on white clams (Dosinia ponderosa) at distances of 50, 150, and 300 m from the discharge area. Physiological and stress conditions of clams in the affected areas deteriorated from the discharge area; glucose, lactate, cholesterol, and aminotransferase alanine were altered, and thermal shock protein transcriptions were expressed in these clams [35]. Another investigation evaluated the environmental impact caused in part by yellowtail (Seriola quinqueradiata) farming on sediments and water quality during low and high feeding times. They observed that the OM charge in sediments was significantly higher than the control site (100 m in distance), covering an impact area of 10 m surrounding the fish farm, accumulating a high level of enriched organic sediments. It subsequently increases in high volatile sulfur acid in superficial sediments, as well as elevated NH_4^+ and phosphate (PO_4^{3-}) concentrations [8].

5. Aquaculture Waste Treatment

In order to mitigate the impacts of waste in the environment, and at the same time take advantage of the high degree of biodegradable organic substances and nutrients they contain, the main treatment methods currently used are: biofiltration by means of artificial systems made up of substrates and plants with the capacity to absorb and reduce the content of nutrients, OM and toxic substances in wastewater [36]. Another method is bioremediation by means of microbiological agents attached to a surface through a matrix of extracellular polymeric substances with the ability to remove, attenuate or transform pollutants in water [37]. This is alongside the use of deposit feeders such as polychaetes [38] and sea cucumbers [39,40] due to their ability to assimilate particulate organic residues, as they accelerate the depletion of organic matter pools through bioturbation, thus improving sediment quality [41].

Moreover, it should be noted that the particulate fraction is the most harmful type of waste produced by aquaculture systems. Therefore, if it is not removed from the ponds, it can degrade, significantly increasing the concentration of TSS, causing a detriment to water quality. In addition, the aquaculture particulate fraction is the residual part where most of the nutrients entering the aquaculture systems accumulate in a non-assimilable form. It is thus necessary to carry out additional treatments for the correct use of these minerals [42]. Biodigestion and biomineralization are 2 of the most practiced strategies for aquaculture particulate fraction treatment, where treatment results are expressed in percentage reduction in pollutants such as COD, PO_4^{3-}, NH_4^+, NO_2^-, NO_3^-, TN, and TP, as well as in quantity of recovered macro/micronutrients of agricultural interest [43–45].

5.1. Biofiltration of Aquaculture Waste

A microbial oxidative process transforms toxic metabolites such as NH_3^+ or NO_2^- into chemical forms less toxic (ammonium or nitrate) to culture organisms through the intervention of nitrifying bacteria [46]. Biofiltration of aquaculture waste consists of substrate and plant systems used for filtration, reduction, and removal of suspended solids [47] macro and micronutrients [48] as well as heavy metals [49]. Where the removal of these components depends on a complex interaction of physical, chemical, biological processes (sedimentation, adsorption, coprecipitation, cation exchange, photodegradation, phytoaccumulation, biodegradation, and microbial activity) and mainly on the type of plant used, as well as its absorption rate [50] in each retention time [51]. In recent years, the use of artificial systems associated with halophytes [52] and macrophytes has been highlighted [53–55].

5.2. Bioremediation of Aquaculture Waste

The bioremediation is defined as the elimination, attenuation or transformation of pollutants present in aquaculture waste, through the application of biological processes carried out by autotrophic and heterotrophic communities, cyanobacteria, bacteria (purple, sulphate reducing and non-reducing) and diatoms among another taxonomic groups, agglutinated in a "biofilm" or "microbial mat" [56]. Understood as any group of organisms in which cells stick together and adhere to a surface by excreting a matrix of extracellular polymeric substances, these communities act simultaneously and synergistically on each of the organic and inorganic pollutants present in the water [57]. In recent years, the use of beneficial biological agents such as bacteria [58,59], biopolymers [10,60,61], microalgae [51,62–70] and macroalgae [71,72] have been used in bioremediation.

5.3. Biodigestion of Aquaculture Waste

Biodigestion is a simple and efficient process; it is commonly used to stabilize municipal and industrial organic waste. However, in recent years this approach has gained importance as a form of aquaculture waste treatment. This process requires low energy cost, and results in high methane (CH_4) recovery, CO_2 and H_2S used in biogas production, as well as achieving a reduction in the mass and volume of aquaculture particulate fractions. In anaerobic digestion, nutrients such as NH_4^+ and P are released from the nitrogenous OM, which offers the feasibility of recovering these minerals [73].

Previous studies in the treatment of aquaculture particulate fractions have used anaerobic digesters such as batch-fed sequencing digesters [74] and fully stirred tank reactors [75]. They have been shown to facilitate the release of intracellular material, increasing its biodegradability, thereby improving the biogas production obtained, with a shorter retention time for complete digestion. Evaluating the anaerobic digestion of particulate fractions of a rainbow trout culture by batch reactors, found that, at 10 days, anaerobic digestion solubilized 23.5% of the total Kjeldahl N as total ammonia nitrogen (TAN) and 53.0% of the total P as orthophosphates, and the biochemical methane potential was 318 g CH_4 g TVS_0, representing 65% digestion [74,76]. Otherwise, the addition of carbohydrates at a C/N ratio 1 to 15 as a pre-treatment for anaerobic digestion of brackish aquaculture particulate fractions in an anaerobic sequencing reactor (ASBR) increased gas production and COD removal efficiency by 80% compared to untreated residuals. In addition, the concentrations of soluble oxygen and PO_4^- increased, generating an average gas production of 0.08 g COD/L per day [77]. By gradually increasing the organic load (OLR) in aerobic digestion of particulate fractions from brackish media, observed a 45% improvement in the yield of methane produced was observed [78]. Another report, by applying four different pre-treatments (chemical, mechanical, thermal, and biological), as elements of improvement for anaerobic digestion of Nile tilapia waste, observed an increase in TAN release, as well as an improvement in NO_2^- and STT removal of 90 and 20%, respectively [76]. The applied biodigestion processes in Atlantic salmon (*Salmo salar*) aquaculture waste and a resulting solution as nitrogen fertilization source on barley (*Hordeum vulgare*) cultivation, expressed aquaculture sludge reduction average of 20%, as well as relative agronomic efficiency from 50–80% in compared with the traditional mineral fertilizers [77]. Studying the effect of anaerobic digestion on particulate fractions of Nile tilapia culture as fertilizer sources in lettuce (*Lactuca sativa*) culture, plants grown in the system supplied with the anaerobic solution expressed significantly higher yields than the hydroponic control. This result was attributed to the presence of NH_4^+, OM, rhizobacteria, fungi and humic acids predominantly in the anaerobic residues. They play an important role in nutrient uptake and are utilized by agricultural crops [79]. Another report, studying anaerobic digestion in particulate fractions of lesser weever (*Echiichthys vipera*), observed that CH_4 production increased in relation to the amount of particulate fraction used, achieving an 8% increase in yield by increasing the maximum methane potential and maximum methane production rate from 66.8 mL CH_4/g VS_{fed} a 70.9 mL CH_4/g VS_{fed} y de 4.40 mL CH_4/g $VS_{fed\text{-}d}$ a 5.59 mL CH_4/g $VS_{fed\text{-}d}$, respectively [42].

5.4. Biomineralization of Aquaculture Waste

This is a strategy used for aquaculture particulate fraction treatment that consists of any reaction series such as hydrolysis, acidogenic, and methanogenic. These have as an objective to recover macro/micronutrients of the particulate organic fractions by means of aerobic and anaerobic bioreactors (organic matter containers) that lead to the formation of assimilable mineral elements for plants. By using organic carbon contained in residual OM per microorganism in aerobic and anaerobic environments, transformation of organic phosphorus into phosphates occurs whose accumulation in aquaculture systems may reach similar levels to hydroponic solutions [80].

By valuating nutrient mobilization under aerobic and anaerobic conditions for aquaculture particulate fractions, we found that treatment resulted in a 3.2-fold increase in reactive soluble P, while anaerobic treatment was unaffected. Both aerobic and anaerobic treatment resulted in an increase in K^+ concentrations from 1 to 28.1 and 36.8 mg/L, respectively. It is concluded that conditions support the mobilization of P and K^+ with lower losses of NO_3^-, improving the delivery of these nutrients for plant production, thus reducing the emission of nutrients by the aquaculture particulate fractions. In contrast, anaerobic conditions revealed a complete loss of NO_3^-, posing the risk of unwanted by-products and more complicated to manage under commercial conditions [45]. In determining the organic reduction (COD and TSS) and nutrient recycling performance of a Nile tilapia culture, observed that, the system was able to remove at least 50% of TSS and COD, as well as obtaining consistent mineralization in the range of 10–60% for all of the macro and micronutrients [81]. Moreover, aerobic reactor yield in aquaculture particulate fractions and mineralization of macro/microelements as a nutrient supplement for commercial hydroponics and demonstrated that acid conditions (pH below 6) could increase nutrient mineralization and mobilization significantly, such as P, K and, Ca. However, the opposite effect was observed with respect to waste particulate reduction. A better elimination yield was obtained in the high pH reactor [82].

6. Aquaponics

Currently, the aquaculture sector has been searching for alternatives in development and technology transfer with a vision directed to treatment and maximum use of resources (food, water, soil, and energy) to achieve sustainability of this productive activity [83]. The use of aquaponics recirculating systems has been identified as a biological productive approach, which, through the efficient use of water and recycling of organic nutrients accumulated in the aquaculture systems, may help to deal with the objectives of sustainable aquaculture development [84–86] (Figure 1).

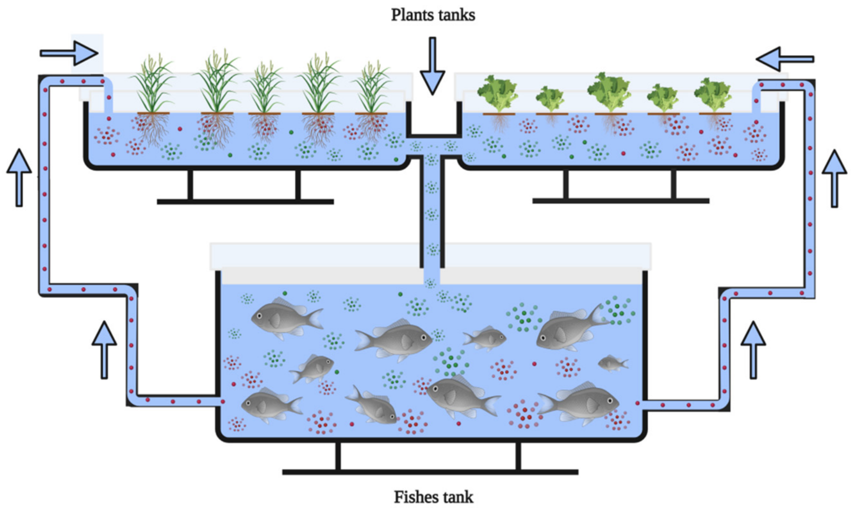

Figure 1. Aquaponic system for food production: Plants and fishes.

In particular, these systems should be helpful for arid regions with non-cultivable soil [87] with greatly brackish waters not suitable for irrigation [88], as well as for marginal land and urban areas [89]. The efficiency of these systems have been demonstrated to achieve an efficiency of 99% in water recycling, reaching demand of use lower than 100 L/kg of harvested fish [90].

In aquaponics, the metabolic waste produced by an aquatic organism is converted to NO_2^- through nitrifying bacteria (*Nitrosomonas* and *Nitrobacter*), which are used as a fertilizer source for plant production [44]. For example, used an aquaponics system for Nile tilapia and tomato (*Solanum lycopersicum*) production, tilapia production was similar to that of the conventional RAS systems while tomato production was similar to that obtained by conventional hydroponics [91]. Furthermore, with a conventional RAS system, 3.4 t of fish can be produced per year, as well as sufficient residual nutrients to harvest 35 t of tomato per year [92]. Another report compared lettuce production between cultivated in conventional hydroponic and aquaponic solutions of Nile tilapia revealed that the aquaponics solution increased plant growth by 39% [93]. A study evaluated the nutritional quality obtained in basil (*Ocimum basilicum*) hydroponic and aquaponic production associated with crayfish (*Procambarus* spp.), where chlorophyll and nutrient content in leaves did not show significant differences between the productive systems [94].

Comparing the quality and production of aquaponics and hydroponics tomato fruit, the different cultivation systems reached similar production yields. Furthermore, the parameters, such as lycopene and ß–carotene were similar in both systems [95]. A study reported the potential of aquaponics systems in the reduction in aquaculture particulate fractions and their use was as a fertilizer source in tomato (*S. lycopersicum*) cultivation [96], these authors found that the system assessed expressed a weekly collection capacity of dry OM, of 2.7–3.0 kg, as well as a production yield of 36% higher than hydroponics. Another report contrasted lettuce cultivation yield by fertilizing with only one traditional hydroponics and aquaculture solution made from the waste of common carp farming. They observed that on average, final fresh and dry weights were 7.9 and 33.2%, respectively, higher than in the fertilized culture with the aquaponics solution [97].

Assessed growth rates of juniper (*Anethum graveolens*), eruca (*Eruca sativa*), coriander (*Coriandrum sativum*), and parsley (*Petroselinum crispum*) between hydroponics and aquaponics systems associated with herbivore carp (*Ctenopharyngodon idella*) farming and found that throughout the three seasons the aquaponics method had similar productions to those of the hydroponics method [98]. A study reported the use aquaponics solutions as an alternative to those of hydroponics in lettuce production and found that leaf mineral content did not show significant differences between both treatments. Furthermore, in the fertilized system with aquaponics solution, water savings of 62.8% were obtained, as well as a reduction in fertilization demand of 72% [99]. Another study reported the nutrient recovery starting from particulate fractions in an aquaponics system of crucian carp (*Carassius auratus*), observing a recovery capacity of macronutrients of up to 46% and 18% for micronutrients [30]. Comparing aquaponics with hydroponics in the distribution of N and P, as well as their use efficiency in cherry tomato, basil, and lettuce crops, observed that, in aquaponics between 59–70% of the total N input was lost and between 30–41% was assimilated as biomass, while in hydroponics a loss of 76–87% was estimated, and only 14–24% was assimilated. Of the total P input, in aquaponics 38–54% was lost and 46–62% was assimilated as biomass, while in hydroponics 79–89% was lost, and only 11–21% was assimilated. It is concluded that hydroponics is less efficient in nutrient use by expressing a 2 times higher N loss through off-gassing and up to 3 times higher P loss through inorganic P compared to aquaponics [100]. Evaluating the yield of common chicory (*Cichorium intybus*), grown in aquaponics, in soil fertilized with particulate fractions from Nile tilapia farming, as well as with chemical fertilization, observed that, the aquaponic system expressed higher yields during the first harvest cycle, during the second harvest cycle, the parameters of number of leaves, fresh matter and dry matter showed higher values for the plants fertilized with the aquaculture particulate fractions than those treated with chemical fertilization. These results suggest a cumulative effect of nutrients in the soil after successive applications of aquaponic particulate fractions, therefore, they can be a viable option to fertilize vegetables in the soil and obtain similar and possibly higher yields than those of traditional mineral fertilization [101]. Therefore, metabolic waste generated in aquaculture aquaponics practices is not seen as a pollutant but rather as a strategic sector to make fertilizing sources for culture nutrition, avoiding the damages caused by eutrophication in the environment generated by aquaculture [18,43,102].

7. Conclusions

Achieving sustainable development in the aquaculture sector means allowing a certain permissible level of pollutants in water, but without reaching values that deteriorate the waters of the culture systems, thus avoiding their discharge into the environment. For this reason, the aquaculture sector is currently looking for alternatives in the development and transfer of technologies, with a vision directed towards the treatment and use of these wastes. In this sense, several treatment technologies have been presented to mitigate the problem mentioned above in this work. As a first approach, biofiltration using artificial systems associated with halophytic and macrophyte plants was studied as one of the most efficient and straightforward methods to implement in aquaculture systems to reduce and eliminate suspended solids, macro and micronutrients, as well as heavy metals. Furthermore, bioremediation was discussed through beneficial biological agents such as biopolymers, bacteria, microalgae, and macroalgae for the transformation of pollutants through the application of biological processes. Besides, anaerobic biodigestion protocols were set in perspective as systems representing a low energy cost in reducing the mass and volume of aquaculture waste and produce a high recovery of CH_4, CO_2 and H_2S used in biogas production. With regards to biomineralization through aerobic and anaerobic bioreactors, this leads to the formation of plant-assimilable mineral elements by utilizing the organic carbon and phosphorus contained in the aquaculture waste. Finally, aquaponics practices have been addressed as an alternative to create a more sustainable aquaculture industry, in which the flora not only acts as a treatment system, but also provides a valuable source of food and energy. Therefore, in aquaponics, metabolic wastes generated in aquaculture practices are not seen as a pollutant but rather as a strategic sector for the manufacture of fertilizer sources for crop nutrition, thus avoiding eutrophication damage to the environment generated by aquaculture.

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