Journal of
Marine Science and Engineering

MDPI

Review

Understanding Carbon Footprint in Sustainable Land-Based Marine Aquaculture: Exploring Production Techniques

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Abstract: In aquaculture, it is crucial to understand and mitigate the carbon footprint for sustainable production. As demand for seafood increases, various production techniques compete for an eco-friendly status. This review examines the carbon footprint of various land-based marine aquaculture systems, highlighting their environmental impact. Through exploring innovations and best practices, it navigates the complexities of reducing emissions and promoting carbon sequestration. Some proposals for this purpose are based on diversification through low-trophic-level species, the preservation of high-carbon sequestration sites, polyculture, organic aquaculture and improvements in nutrition, feeding, waste and energy management. In this sense, some land-based aquaculture systems are progressively adapting and updating their zootechnical procedures. Recirculating Aquaculture Systems (RASs) offer interesting advantages such as water conservation, pollution reduction and biosecurity. Integrated Multi-Trophic Aquaculture systems (IMTAs) aim to address two major issues in aquaculture: efficient water usage and the environmental impact of effluents, which are rich in organic particles and dissolved nutrients from undigested food and feces; hence, these systems involve cultivating multiple species (polyculture). Biofloc Technology (BFT) is based on the formation of bioflocs in a culture medium. These systems can enhance feeding efficiency and waste management, thus optimizing nutrient utilization and minimizing environmental impact, achieved through reduced water and fertilizer usage. Traditional (extensive) aquaculture systems operate with minimal input of feed and chemicals, relying heavily on the natural productivity of the ecosystems; thus, the need for manufactured feed, the environmental impact associated with feed production and the transportation and overall costs are significantly reduced. Overall, while RASs, BFT and extensive systems in general offer significant sustainability benefits, IMTA's holistic approach to ecosystem management and nutrient recycling makes it, in our estimation, the most effective method in terms of ecological footprint in aquaculture. However, its quantitative evaluation is extremely complex, and there is currently a lack of references about its global carbon footprint. Therefore, further research and development are required, as well as collaboration and knowledge-sharing among stakeholders.

Keywords: best aquaculture practices; greenhouse gasses; carbon footprint; carbon sequestration; RAS; IMTA; BFT; extensive aquaculture; organic aquaculture

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Citation: Castilla-Gavilán, M.; Guerra-García, J.M.; Hachero-Cruzado, I.; Herrera, M. Understanding Carbon Footprint in Sustainable Land-Based Marine Aquaculture: Exploring Production Techniques. *J. Mar. Sci. Eng.* **2024**, *12*, 1192. https://doi.org/10.3390/jmse12071192

Academic Editors: Ana Catarina Matias and Carlos Andrade

Received: 11 June 2024
Revised: 9 July 2024
Accepted: 11 July 2024
Published: 16 July 2024

1. Introduction

Over the past few decades, the aquaculture industry has experienced exponential growth, emerging as a vital player in global food production [1]. This surge is attributed to the escalating demand for seafood, driven by population growth, changing dietary habits, and a decline in wild fish stocks [2]. While aquaculture offers a solution to meet the burgeoning seafood demand, its rapid expansion comes with environmental consequences, for instance, those concerning greenhouse gas (GHG) emissions. This has led to several innovative production techniques and policies being improved in Europe during recent years: the EU missions "Restore our Ocean and Waters" or "Green Deal", the Atlantic Action Plan or the Blue Growth strategy [3–6]. More recently, the United Nations Sustainable Development Goals aim to "take urgent actions to combat climate change and its impacts" through Goal 13. These actions imply transformative measures in energy, industrial, transport, food, agricultural and forestry systems to move towards climate-resilient development and achieve net-zero emissions [7]. To understand how the aquaculture industry can contribute to this transformation, it is necessary to understand its contribution to GHG emissions and how they can be mitigated.

According to MacLeod et al. [8], the total emissions in 2017 for all aquaculture were 245 $MtCO_2eq$ (147 $MtCO_2eq$ for marine aquaculture), which would only represent 0.49% (0.27%) of total anthropogenic emissions (53.5 Gt [9]). The low emission intensity of aquaculture, compared to terrestrial agriculture and livestock [8], highlights the importance of maintaining the consumption of fish and seafood over meat. Despite this, aquaculture emissions are lower due to the still greater amount of terrestrial livestock production, but it has been estimated that aquaculture GHG emissions are increasing and that by 2030 they will reach 383 $MtCO_2eq$ [10].

Major global GHG (CO_2, CH_4 and N_2O) emissions come from the electricity and heat production sectors (25%) and the agriculture and livestock sectors (24%) [10]. In the case of the aquaculture industry, emissions are mainly related to the production of aquafeed, energy use and biogeochemical processes occurring in the culture units.

Most aquaculture species are carnivorous or omnivorous, requiring feed with a high protein content, often derived from fishmeal and fish oil [11]. However, sustainability concerns around using wild-caught fish for feeding aquaculture fish have led to an increasing use of cereals (mainly corn, wheat, rice) and oilseeds (mainly soybean) as aquafeed ingredients [12]. The production of these raw ingredients, their transformation and their distribution involve emissions arising from different sources [8,12]. In summary, 57% of aquaculture emissions are related to the utilization of fishmeal. Promoting the culture of noncarnivorous species and replacing fishmeal and fish oil with more sustainable alternatives, such as other plant-based proteins and oils [13] and insect-based proteins [14], aim to mitigate these emissions.

Energy consumption in aquaculture operations also contributes to GHG emissions, and the type of energy source used determines the environmental impact. Fossil fuels are used for the working vessel (when needed) and the distribution of the final product. Electric energy is used throughout the whole industry in production operations and processing [15]. Depending on the farm type and the species cultivated (off-shore, land-based, fish, shellfish, etc.), facilities rely on energy for a range of activities, including harvesting, transport, the collection of juveniles, maintaining water quality, running aeration systems, providing heating or cooling, pumping, lighting and powering vehicles [16,17].

Waste management in aquaculture systems is another aspect influencing GHG emissions due to biogeochemical processes occurring in the culture units. Respiration by organisms and organic matter in the effluents undergoes mineralization, producing CO_2 [18]. In earthen ponds (>40% of global aquaculture production [19]), the sediment is a major site for methanogenic bacteria producing CH_4 from dissolved organic carbon [20]. Moreover, nitrifying and denitrifying bacteria metabolize ammonia and nitrate from effluents and release N_2O through aerobic nitrification and anaerobic denitrification, respectively [21]. The type of aquaculture system also affects GHG emissions. For instance, extensive and semi-intensive systems, where ponds are fertilized to enhance natural productivity, can result in higher emissions due to the microbial breakdown of organic matter [22]. Thus, implementing efficient waste treatment technologies can minimize the release of GHGs into the atmosphere [23]. Water parameters also have to be taken into account; the emission of

CO_2 depends on many factors, like air and water temperature and pH [10]. An increase in temperature also stimulates methanogenesis and CH_4 emissions, while high concentrations of dissolved oxygen inhibit these activities [24]. Aquaculture pond sediment pH plays a major role in the production of N_2O. Nitrous oxide production by nitrification increases with pH [25], while denitrification N_2O production increases with a decrease in pH [26]. Additionally, the choice of species influences the environmental impact of aquaculture. Some species are more feed-efficient and have lower waste production [27], contributing to reduced GHG emissions. Concerning algae/phytoplankton cultivation, their productivity contributes to CO_2 flux changes and N_2O synthesis during nitrate assimilation [28].

This introduction outlines some well-known strategies for addressing the challenge of GHG emissions in marine aquaculture. However, several gaps remain in understanding the impact of these strategies and comparing them in terms of carbon footprint. Firstly, there is limited quantitative data on their global carbon footprint, making it challenging to evaluate their overall effectiveness. Moreover, comprehensive life cycle assessments (LCAs) comparing the more sustainable production systems with traditional methods are also sparse, particularly in the marine context, due to the relatively recent application of LCAs in aquaculture [29,30]. Secondly, the long-term impacts of transitioning towards so-called eco-friendly methods have not yet been thoroughly explored. Finally, there is a need for standardized methodologies to measure the carbon footprint of the different aquaculture systems to facilitate more accurate and consistent assessments and comparisons [31]. In this context, and in order to provide a structured analysis, this review seeks to answer the following research questions: (1) What are the primary sources of GHG emissions in land-based marine aquaculture systems? (2) What are the best practices and innovations currently being implemented to mitigate GHG emissions in aquaculture? (3) Which aquaculture system shows the most promise for sustainable production with minimal environmental impact? (4) How can the aquaculture industry further reduce its carbon footprint while maintaining or increasing production?

The following sections present in detail the main mitigation measures and best practices for reducing GHG emissions. It is important to note that many of these strategies are closely interconnected and cannot exist independently. The suitability of current production technologies is then reviewed based on their application of these measures and their carbon footprint according to the literature.

2. Mitigation Strategies

2.1. Diversification through Low-Trophic-Level Species

It has been estimated that in the next decade, fishmeal and fish oil production will not be allowed to meet the demand of the growing aquaculture industry [32]. Indeed, reducing the use of wild-caught fish for this purpose is a well-known strategy for the sustainable development of the sector [33,34]. Other than research on new protein-rich alternative ingredients that can sometimes be nutrient-deficient for carnivorous species [35], diversification through low-trophic-level species has been highlighted to mitigate GHG emissions [34,36,37].

Farming extractive (nonfed) low-trophic-level marine species, such as bivalves, seaweeds or amphipods, represents a sustainable and environmentally friendly approach to aquaculture [38–40]. Gephart et al. [41] and Jones et al. [42] found that among all so-called "blue food", bivalves and seaweeds produce the lowest levels of GHG emissions, land use, N and P emissions, and freshwater use. In general, extractive species can be cultivated with low energy requirements and without inputs since they are autotrophic and/or they can extract dissolved nutrients and particulate matter from the water column, improving water quality and reducing excess nutrients [37]. Bivalves are highly efficient in converting organic matter into protein without the need for external feeds [43]. This process not only mitigates nutrient pollution but also contributes to the overall health of an aquatic ecosystem. Both bivalves and seaweeds play a crucial role in sequestering CO_2, contributing to climate change mitigation [44–46]. Additionally, seaweeds can provide a wide variety of ecosystem services [47] such as improvements in water quality by assimilating excess nutrients and providing habitats for diverse marine organisms. Amphipods constitute a low-trophic-level group and are currently being explored for their potential in aquaculture. As they are opportunistic feeders able to feed on detritus, they enhance water quality while also providing a source of protein and high-quality live food [48,49] without any additional inputs. Furthermore, it has recently been demonstrated that marine amphipods, despite being fed low-omega-3 diets (i.e., detritus), are able to preserve high levels of these dietary lipids, among others [50]. Thus, according to Krause et al. [37], the aquaculture industry provides a more sustainable alternative to red meat consumption by improving the production and consumption of these low-trophic-level marine species.

Penaeids (mostly white shrimp, *Penaeus vannamei*, and giant tiger shrimp, *Penaeus monodon*) are among the largest GHG producers in marine farming, alongside salmon production. However, farmed shrimp produce lower emissions than captured ones, and most of the emissions are associated with their land use and feed production [41]. Therefore, to make penaeid aquaculture a more sustainable blue food source, it is recommended to avoid converting mangrove areas to shrimp farms [51,52] and transition towards herbivore feeds [53].

Concerning fish, it is important to note that only about 5% of all species are herbivorous, and only 30% of these are marine, most of them living in coral reefs [54]. Despite this limitation, it has been demonstrated that they present advantages in energy transformation and resource utilization since they usually have low nutrient requirements, which they can obtain from cultivable seaweeds or microalgae [55]. Moreover, the FAO has recommended the development of aquaculture for these species since they also present high-quality meat and low production costs within a good market demand context, mostly in Asian countries [54,55]. A number of studies have been conducted globally with the objective of developing their culture for commercial or repopulation purposes. Lozano-Muñoz et al. [56] have recently demonstrated that the herbivorous fish *Medialuna ancietae*, a native species from Chile, has great potential for use in a sustainable aquaculture context. They showed that this species has low and fish-free requirements for protein. However, its meat presents a high protein content, demonstrating that *M. ancietae* is an efficient converter of feed into protein. In China, rabbitfish species (*Siganus* spp.) are now widely cultivated with high economic profitability [55] and have been demonstrated to be highly efficient in biosynthesizing long-chain polyunsaturated fatty acids (PUFAs). The milkfish (*Chanos chanos*) is an economically important herbivorous species in southeast Asia [57]. A great variety of protein sources have recently been studied for milkfish meal, such as, for instance, soybeans, insects, polychaetes or seaweeds [58–61]. This trend towards herbivorous fish aquaculture is less widespread in Europe. However, the potential of some species of the family Mugilidae (*Mugil cephalus*, *Liza* spp., *Chelon labrosus*) has been highlighted due to their omnivorous profile, rapid growth and resistance to environmental variations [62]. Martínez et al. [62] also underline the importance of the grey mullet (*M. cephalus*) in current strategies in European aquaculture. These species' culture takes place in extensive or semi-intensive ponds [63], and research efforts to improve it have increased in recent years [64,65].

2.2. Preservation of High-Carbon Sequestration Sites

Natural wetlands contribute 20–30% of global terrestrial carbon sequestration [66,67]. However, mangroves, seagrasses, estuaries and salt marshes have been disturbed in many countries by practicing commercial shrimp and fish aquaculture [51,68]. The habitat transformation of these wetlands can increase the emissions of GHGs from organic matter already stored in the system. Many studies have demonstrated greater emissions of greenhouse gasses from sites converted to aquaculture ponds [19,69–71]. For instance, mangrove-converted aquaculture in the Mahakam delta led to a loss of 1925 Mg CO_2eq ha^{-1} [68]. Similarly, conversion from paddy fields to extensive crab ponds increased the 100 yr global warming potential

(GWP) from 8.15 to 28 Mg CO_2eq ha^{-1}, mainly due to increased CH_4 emissions with a contribution of 96.3% [19].

In line with the previous section, primary producers play a crucial role in ecosystem restoration and resilience [45,72], which is integral to mitigating the impacts of climate change on aquaculture. Mangroves, seagrasses, estuaries and salt marshes not only sequester carbon [73] but also provide vital habitats for aquatic species, protect coastlines from erosion and support nutrient cycling [74,75]. By restoring and conserving these coastal ecosystems, aquaculture operations can enhance their resilience to environmental stressors and contribute to broader climate change mitigation efforts [76–78].

2.3. Polyculture

The simultaneous cultivation of multiple species in a single aquaculture system emerges as a strategic measure to mitigate GHG emissions in aquaculture [10,79]. Thomas et al. [80] outlined that polyculture requires species compatibility (species sharing the same space without detrimental interactions) and complementarity (compatible species using all available resources). According to these authors, complementarity can be enhanced based on trophic interactions or based on commensalism or mutualism [80]. Multi-trophic interactions provide more advantages for sustainability in a polyculture context: the recycling of water, the preservation of water quality, wastewater valorization through improvements in the nutrient cycle (resources become products, products become waste and waste becomes resources [81]) or the diversification and improvement of production (with economic interest) [80].

Concerning carbon footprint, polyculture systems capitalize on the complementary interactions among different species, improving the nutrient cycle and acting as natural bioremediators [42]. This not only improves water quality within the aquaculture system but also reduces the environmental impact on surrounding ecosystems. This nutrient cycling reduces the need for external inputs, minimizes waste and the need for waste management, and enhances overall system efficiency [82,83]. Additionally, by relying on the ecological interactions among species, the need for supplemental feeds is minimized. This results in cost savings and reduces the overall environmental footprint associated with aquafeed production.

Therefore, selecting suitable species is a key issue in polyculture systems for ensuring sustainability. For instance, the oyster *Crassostrea angulata* seems to be a CO_2 generator through calcification and respiration (153 and 349 g C m^{-2}, respectively), though oyster harvesting sequesters ca. 258 g C $m^{-2}y^{-1}$ due to shell formation [79]. This negative balance can be attenuated by culturing the seaweed *Gracilaria lemaneiformis*, which would act as an efficient sink for CO_2. Zhang et al. [84] reported that a polyculture with the crab *Portunus trituberculatus* and the shrimp *Marsupenaeus japonicus* was much more sustainable than those species and the clam *Ruditapes philippinarum* (-79 versus 194 g CO_2 m^{-2}).

2.4. Nutrition and Feeding Efficiency

Feeding practices in aquaculture are crucial in determining its environmental impact. Inefficient feeding not only increases operational costs for farmers but also contributes significantly to the sector's GHG emissions [85]. Research efforts have been made to reevaluate feeding strategies, with a focus on minimizing the environmental impact of aquafeed production through using new ingredients, optimizing nutrient utilization, and valorizing waste.

As previously mentioned, the production of aquafeed is one of the primary contributors to the carbon footprint in marine aquaculture [8]. Advancements in aquaculture nutrition science have highlighted alternative and sustainable feed ingredients. These ingredients, such as plants and insects, mitigate the impact on wild fish populations and ecosystems and often require less energy in processing [38]. Plant-based proteins have been widely used in aquaculture during the last two decades [86], mostly from soybean, wheat, corn or rice. These plant-based aquafeeds have been demonstrated to present a favorable essential amino acid (EAA) profile, a high content of protein and great digestibility for fish [35,87–89]. Nevertheless, plants also present some challenges and are far from being a net-zero emission ingredient. Some important plant anti-nutrients have been identified [90,91]. Moreover, crops' GHG emission sources are diverse: the use of fertilizers (N_2O), the increasing use of flood-cultivated rice, whose anaerobic conditions are prime sites for CH_4 production [13], or the expansion of soybean cultivation (CO_2 derived from land use change [14,15]). The competition for plant protein resources for human consumption and terrestrial animal feed has led to a rise in prices and the necessity to develop new ingredients [86]. Insect flour has been demonstrated to be highly nutritious and rich in protein, lipids and EAAs [92,93]. From a sustainability point of view [94,95], the main advantages of growing insects for aquafeed purposes are that they can use organic byproducts (wastes), promoting a circular economy, and the environmental benefit associated with land use. However, the mass production of insects is still in a developing stage [35] and needs to be improved, especially in terms of energy use [95]. In addition to the acquisition of any raw ingredient, energy consumption during fishmeal production and distribution is a significant contributor to the carbon footprint of aquafeeds. [8].

The use of additives can improve feeding efficiency [96,97]. Living additives and additives extracted from organisms are preferred over hormones or antibiotics due to their eco-friendly nature [96]. Single-cell protein and oil based on bacterial, microalgal or yeast biomass can also be grown from byproducts from other industries and are widely used as a protein/omega-3 source for aquafeeds [98,99]. These additives have also been demonstrated to have probiotic and inmunostimulant effects on the cultured species [99]. This is also the case with some molecules extracted from seaweeds, such as the polysaccharide ulvan [100]. Enzyme supplementation in feed fish also improves digestibility and feeding efficiency [101]. There have been relatively few studies on the application of enzymes in the diets of marine species [102]. However, the potential of animal byproducts like fish viscera has been highlighted as an enzyme source for marine fish diets [103].

Feeding efficiency also extends beyond the choice of ingredients to the feeding practices employed on aquaculture farms [104]. Precision feeding technologies, such as automated feeding systems and real-time monitoring, allow farmers to tailor feed delivery to the specific nutritional needs of their fish. This not only reduces excess feed and nutrient wastage but also ensures that the fish receive optimal nutrition at the right time, promoting healthier and faster growth. Furthermore, as highlighted above (cf. 2.3), the implementation of polyculture is an example of an approach to improving feeding efficiency.

2.5. Implementing Waste Management Technologies

Aquaculture operations generate significant amounts of inorganic waste, mainly ammonium, nitrate and phosphate, from degraded uneaten feed and fecal matter. When left unmanaged, these wastes contribute to environmental degradation, such as eutrophication and algal blooms [105]. On the other hand, the degradation of organic solids in wastewater can also lead to a high biological oxygen demand and the production of ammonium due to mineralization [106].

Inorganic waste management technologies offer effective solutions to mitigate these potential impacts. One of these technologies is the use of biofilters that allow for the conversion of ammonia wastes [107,108] into less harmful compounds through nitrification [109]. This reduces the need for water exchange and minimizes nutrient discharge into the environment. Additionally, advancements in waste treatment technologies such as UV and ozone treatment [110,111] allow for the more efficient removal of pollutants from aquaculture wastewater. As highlighted above in the *low-trophic-level* and *polyculture* sections, the incorporation of nutrient recovery technologies allows aquaculture facilities to extract valuable nutrients [112], such as phosphorus and nitrate, and recycle them for use as fertilizers in agriculture [113] or in aquaponics systems [81] to produce plant or algal biomass.

Organic waste includes feces and uneaten food, dead organisms, algae waste, etc. [114]. Effluent treatment primarily involves mechanical filtration through sand filters. Sludges are then stored in decantation tanks and recovered for reuse as fertilizers or for transformation into biofuels [115,116]. The valorization of algae, crustacean and fish waste through the recovery of biomolecules such as proteins, polysaccharides and biosurfactants has also been highlighted [114]. Additionally, recent research has focused on the development of eco-friendly enzyme-assisted methods for the extraction of these molecules [117–119]. In conclusion, the management of waste through its valorization reduces the carbon footprint of aquaculture activities while also contributing to the circular economy.

2.6. Energy Efficiency

Some of the previous strategies are linked with energy efficiency. The use of filtration, biofiltration and water treatment technologies minimizes water consumption and reduces the energy needed for water pumping and heating. In addition, implementing precision feeding techniques allows for precise control over feed delivery, minimizing waste and waste management operations.

Transitioning to alternative fuels for vessels (electricity, natural gas, biodiesel, methanol, etc. [120]), fully electric and hybrid trucks and renewable energy sources using solar panels, photovoltaics or wind turbines in aquaculture facilities can significantly reduce the carbon footprint of these operations [15,121]. Aquaculture activities often require heating to maintain optimal water temperatures, especially in cold climates or during the winter months. Heat recovery systems can capture waste heat from the aquaculture process itself (water recirculation or effluent treatment [122]) or from industry [123]. This waste heat can then be reused to heat the culture units. Indeed, the utilization of waste heat from industrial or agricultural sources has been studied, with the resulting energy savings being due to minimal or even no use of carbon-based heat [124]. Furthermore, the controlled production costs resulting from the use of waste heat have been evidenced. Finally, a reduced environmental impact has been observed, with a decrease in CO_2 emissions by more than 26% and the valorization of liquid and solid effluents within a “zero waste” objective [124]. Another promising approach is the utilization of waste-to-energy technologies, such as anaerobic digesters and gasification systems. The production of biogas in methanogenic reactors from sludges through anaerobic digestion to obtain energy and heat [115], which could even be returned to the system to maintain the temperature, promises to make land-based aquaculture even more circular and sustainable [125]. Finally, upgrading to energy-efficient equipment and infrastructure and monitoring energy consumption can result in significant energy savings [126].

2.7. Organic Aquaculture Standards

Organic aquaculture production must be taken into consideration in this section since it has recently attracted significant interest from consumers and investors [127,128]. According to the International Federation of Organic Agriculture Movements (IFOAM), “organic agriculture is a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic Agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and good quality of life for all involved” [129]. This definition may be applied to aquaculture through the principles of health, ecology, fairness and care [130]. The European Union (EU) Organic Aquaculture Standards, established under Regulation (EC) No. 710/2009 [131], outline specific criteria and obligations for aquaculture operations to be considered organic within the EU. Certification processes and regulatory frameworks may differ between regions. However, common standards and requirements of organic aquaculture include the following [130]:

- System design and location are related to contamination from outside sources, the introduction of exotic species, escapes, contamination with effluent discharges, the use and reuse of water and maintaining water quality.
- Sources of stock, breeds and breeding concern the preference for local species and the prohibition of polyploidy, the use of hormones and the handling of the daylight period.
- The feeding and nutrition of aquaculture animals concern the efficient use of food to minimize loss and the use of organic feed ingredients sourced from certified organic sources whenever possible.
- Health and welfare are related to measures designed to provide adequate space, shelter and environmental enrichment, with the aim of promoting natural behaviors and minimizing stress. Practices such as overcrowding, confinement and the use of stressful handling techniques are prohibited (including during harvest and transportation).
- Processing and labeling operations must maintain detailed records of all inputs, practices and activities related to production. This includes the documentation of feed ingredients, water quality monitoring results, stocking densities and health management practices.

3. Land-Based Aquaculture Farming Systems: In the Race for an Eco-Friendly Status

Traditional intensive flow-through aquaculture systems utilize natural water sources to provide a continuous flow of water to aquaculture ponds or tanks [130]. In the marine context, examples of flow-through systems include raceways and tanks where species such as turbot (*Scophthalmus maximus*), sea bass (*Dicentrarchus labrax*) or sole (*Solea* sp.) are grown [132–134]. These systems operate by diverting water from a natural source, passing it through the culture units and then discharging it back into the environment. The constant flow of water serves to sustain optimal oxygen levels, remove waste and provide a stable environment for the fish [132]. However, this method has a significant impact on the wild environment due to its high densities, which result in high inputs and enriched discharges. Consequently, it has been refined over centuries to enhance production while maintaining water quality, animal welfare and the minimization of ecological disturbances [130]. Here, we discuss some of these improved systems and technologies.

3.1. Recirculating Aquaculture Systems (RASs)

The development of RASs has been characterized by innovation since the 1950s [135], driven by the need to address environmental concerns, optimize resource use and meet the growing demand for seafood production. The main feature and advantage of RASs is water recycling and, consequently, its low water consumption [130]. Figure 1 illustrates an RAS and its main water treatment equipment.

The seawater reservoir tank (1) is equipped with a pH sensing line and a pump to supply a buffer solution that is added to keep the pH stable. Water is first pumped (2) from this tank to a mechanical filter (3), i.e., a sand filter. This filter is regularly backwashed, and the water with sludge is discharged. In other RASs, sludge can be stored in decantation tanks, recovered and reused as fertilizer or for biogas production [115,116]. The water is then pumped into the biological filter (4), where plastic bio-balls are colonized by nitrifying aerobic bacteria [136] that convert ammonia (NH_4^+) to nitrate (NO_3^-). From here, the effluent is also discharged, and the filtered water is (i) returned to the reservoir tank (1) or (ii) pumped into a protein skimmer (5), which removes dissolved fine organic solids [137]. In this filter, small air bubbles are injected at the bottom to attach to the organic compounds and lift them to the top. The skimmer foam is then removed with the effluent, and the skimmed water is returned to the cycle. A final filtration of microparticles and microbial biomass [138] is then carried out by UV irradiation (6). Finally, the water is heated (7) if necessary before it reaches the culture tanks (8).

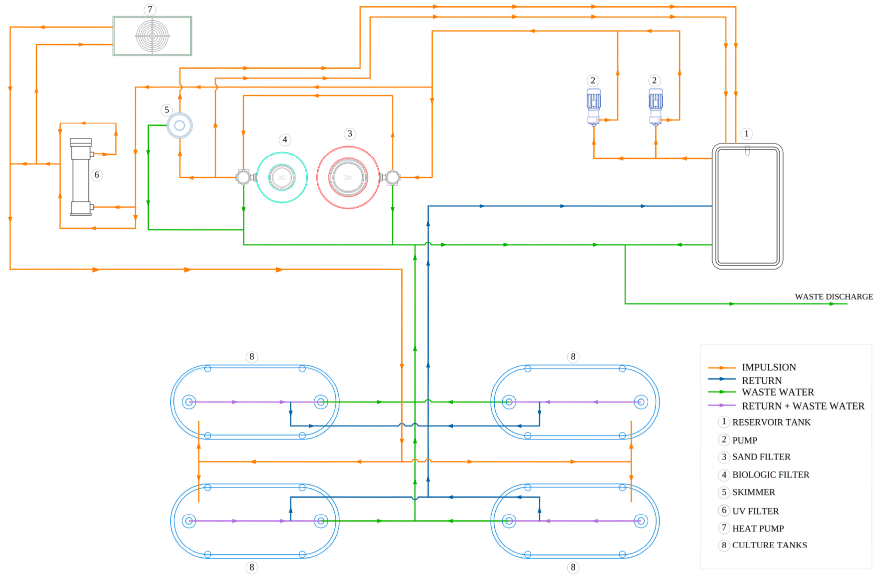

Figure 1. Diagram of a Recirculating Aquaculture System (RAS). Numbers are detailed (in brackets) in the text. Source: SCA Blennius, Puerto Real, Spain.

Recirculating Aquaculture Systems are considered a sustainable production method [108,139]. The advanced water treatment technologies employed in RASs enable the cultivation of high-value species at high stocking densities and high economic profitability while simultaneously ensuring animal welfare and maintaining water quality [130]. Therefore, RASs represent one of the most productive aquaculture methods. As an example, they are the most efficient in terms of land and feed use across major species and production systems in US aquaculture [140]. By treating and recirculating water within the system, an RAS minimizes the discharge of pollutants, such as excess nutrients and fecal matter, into the environment, reducing the risk of water pollution, eutrophication and ecosystem degradation [141]. Its land-based and indoor nature prevents effects on biodiversity due to escapes, diseases and parasite transmission [141]. Concerning the GHG mitigation strategies cited in Section 2, Table 1 summarizes the application of these strategies in RASs. In a marine context, RASs are mainly monospecific and used for carnivorous fish species [142–145]. In terms of their use for rearing low-trophic-level species, these systems have been used with some invertebrates such as shrimps [146–148] or sea urchins [149–151], but this remains a minor use. Regarding feeding strategies, Godoy-Olmos et al. [143] found that feeding by auto-demand feeders led to higher NH_4^+ removal rates, preserving water quality and reducing water consumption. In an RAS context, precision feeding technologies are widely employed [152], as they allow the amount of food and the feeding frequency to be carefully controlled. This is an important advantage of RASs, as it has been shown that overfeeding can lead to an increase in uneaten food, particulate organic matter, ammonia, nitrite and nitrate in the culture units [153,154], which can pollute the water and cause diseases in aquatic organisms [155,156]. Finally, as previously mentioned, the choice of protein sources in the diet for each cultivated species is crucial. A low digestibility of nutrients can again result in an increase in uneaten food and a decrease in water quality [157,158]. The technical complexity of RASs requires high energy consumption, resulting in high costs that may compromise the economic viability of operations and contribute to higher GHG emissions. These are the two most significant constraints of RASs [159]. Therefore, enhancing energy efficiency is critical to ensuring their sustainability. Energy-saving measures, such as energy audits and the use of software with energy performance data, have been identified by some authors [160,161]. These measures can provide valuable information for decision-making. Kucuk et al. [162] recommended upgrading to energy-efficient equipment, particularly pumps, in line with Badiola et al. [163], who identified heat pumps as a major energy consumer in RASs. On the contrary, Bergman et al. [125] show a case study in Sweden, where they cultivate warm-water tilapia and where renewable energy sources are employed. They demonstrated that cultivation in RASs was possible without requiring significant energy compensation. This was accomplished through the valorization of byproducts to produce biogas. In summary, these studies suggest that while further research and improvements are necessary to improve the energy efficiency of RASs, these systems are suitable for implementing advanced technologies that could enhance their sustainability in the future.

Table 1. The synthesis of measures applied in each farming system and estimations of their carbon emissions: ★: few studies address this strategy; ★★: at least half of the studies reviewed address this strategy; ★★★: most of the studies reviewed address this strategy; ★★★★: all studies reviewed address this strategy.

Farming System	Low-Trophic-Level Species	Polyculture	Feeding Efficiency Strategies	Waste Management	Energy Efficiency	Carbon Sequestration	Carbon Emissions
RAS	★☆☆☆	★☆☆☆	★★★☆	★★★★	★★☆☆	☆☆☆☆	6109 kg CO_2e t^{-1} WW [42]
IMTA	★★★★	★★★★	★★★★	★★★★	★★★★	★★★☆	no data
BFT	★★★★	★★★★	★★★★	★★★★	★★☆☆	★★★☆	5945 kg CO_2e t^{-1} of shrimp [164]
Extensive systems	★★★★	★★☆☆	★★★★	★★★☆	★★★★	★★★★	392 kg CO_2e t^{-1} of bivalves WW [42] ~65 t CO_2e ha^{-1} y^{-1} [165]

Carbon sequestration is only achievable through finfish production in off-shore cages, not in RASs, although this capacity has been poorly studied and quantified [164]. Additionally, few studies have calculated the carbon footprint of RAS. According to a review by Jones et al. [42], fed marine finfish cultivation in RASs emits 6109 kg CO_2e per ton of finfish wet weight on average. However, these values can vary between 1382 and 44,400 kg CO_2e per ton of finfish wet weight. These variations are due to different species, foods, locations or energy sources.

In summary, RASs inherently offer advantages such as water conservation, pollution reduction and biosecurity. However, RASs rely on high stocking densities, are disconnected from the natural marine environment and require a high input of external energy. These facts mean that RASs are not in line with the UE organic aquaculture standards [130], and additional measures are needed to ensure compliance with organic principles and regulations. This may include sourcing organic feed ingredients, implementing disease management strategies, maintaining detailed records of inputs and practices, etc.

3.2. Integrated Multi-Trophic Aquaculture Systems (IMTAs)

The origins of Integrated Multi-Trophic Aquaculture (IMTA) systems can be traced back to farmers in ancient civilizations such as China and Egypt, who wanted to raise fish and at the same time use waste to produce complementary products and income [165]. Modern IMTA development gained importance in the 1970s [166], and by the early 2000s, IMTA practices were increasingly adopted globally, promoting ecosystem-based management and resource efficiency [167–169]. Today, IMTAs are a cultivation technology that is currently being driven by the EU due to its efficiency. These systems aim to address two major issues in aquaculture: efficient water usage and the environmental impact of effluents, which are rich in organic particles and dissolved nutrients from undigested food and feces. IMTAs involve cultivating multiple species of different trophic levels (with or without terrestrial organisms) in the same or separate compartments connected by nutrient flows [170]. Thus, the waste (organic and inorganic matter) from the main fed species at a higher trophic level can be utilized by the extractive species at a lower trophic level/levels

(Figure 2). In these "designed ecosystems", nutrient loss and water usage are minimized, and waste is valorized in a circular economy model: resources become products, products become waste and waste becomes resources, in line with UN Sustainable Development Goal 12 [171]. In the example (Figure 2), discarded water from an indoor fish RAS is pumped into an IMTA array placed in a greenhouse. The water with organic solids is first transferred to a solids retention compartment with deposit feeders (e.g., polychaetes) and then to a distribution tank with aeration. Finally, the water reaches the primary producer (e.g., halophytes) compartments for dissolved inorganic nitrogen and phosphorous uptake.

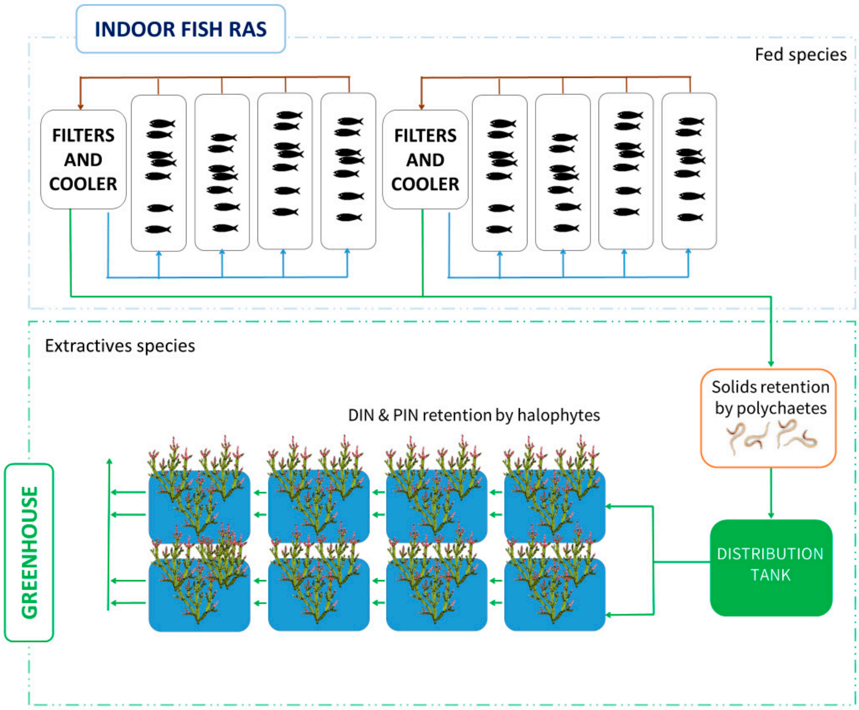

Figure 2. Diagram of a land-based IMTA. Modified from Castilla-Gavilán et al. [81].

There is a wide variety of IMTAs, both offshore (based on net cages, longlines, rafts. . .) [167,172] and land-based (based on RASs, flow-through systems, extensive earthen ponds. . .) [81,173–176]: combinations between finfishes, bivalves, gastropods, decapods, amphipods, seaweeds, phytoplankton, echinoderms, sponges, plants, etc., are possible (see Guerra-García et al. [177]). IMTAs can combine high-value species, such as salmon, oyster and sea urchins, with others of lower value, including seaweeds and mussels. From an economic perspective, it is noteworthy that IMTA products are generally well received by consumers, with many willing to pay a premium for products bearing an IMTA label [178]. Numerous studies have demonstrated the high efficiency, productivity and sustainability of IMTAS. It has been suggested that among the different types of IMTAS, recirculation land-based IMTAs have the highest potential for nutrient retention [179]. These authors suggest that a four-species marine IMTA consisting of fish as fed species and algae, bivalves and detritivores as extractive species would achieve the highest theoretical nutrient retention efficiency. This system would absorb between 79% and 94% of the nitrogen, phosphorus and carbon supplied with the aquafeed. This approach has been demonstrated on a large scale in Pacific fish farms producing milkfish (*Chanos chanos*), shrimp (*Penaeus monodon*), clams (*Meretrix lusoria*) and seaweed (*Gracillaria* sp.) [180]. Thus, IMTAs, by definition, use low-trophic-level species and polyculture, which makes these systems highly advantageous in terms of sustainability and GHG mitigation strategies. Feeding efficiency and waste management strategies are enhanced by the use of a deposit feeder link [49,181], which reduces carbon from organic wastes (uneaten aquafeed and feces) and primary producers that maintain and improve water quality, even more so when combined with

RASs [182]. It is important to highlight that, in IMTAs, the feed input is usually similar to that of monoculture systems but with an additional output due to polyculture [183]. Furthermore, in a land-based context, the energy efficiency of IMTAs is mainly related to the energy efficiency of the system used to produce the fed species (i.e., RAS, flow-through system, extensive ponds. . .). Checa et al. [183] determined that water recirculation for the production of extractive species allows water exchange to be reduced and, consequently, the energy required for pumping and the energy costs. Cunha et al. [184] also showed energy savings for pond aeration in IMTAs with filter feeders. In any case, any lower energy efficiency (or higher energy costs) in IMTAs is offset by the fact that the water treatment produces multiple species, making farms more environmentally and economically resilient [80,185,186].

Carbon sequestration is possible in IMTAs, especially through seaweed and shellfish cultivation [42,184,187,188]. Macroalgae cultivation has been highlighted for its potential to contribute to global blue carbon sequestration due to its capacity for photosynthetic CO_2 assimilation [189,190] and has been recommended as a climate change mitigation strategy [191]. Regarding shellfish, Cunha et al. [184] observed that carbon sequestration was higher in land-based IMTAs (fish + phytoplankton + seaweeds) when oysters were also present (0.50–0.53 mg L^{-1} 8 h^{-1}). Liu et al. [192] also observed that large-scale shellfish–macroalgae IMTAs act as CO_2 sinks and play an important role in the local carbon cycle. However, it is important to note that although these farms can store large amounts of carbon, when the algae and shellfish are harvested, carbon is released through the food chain [44]. In this sense, the benefits of these systems are still being investigated, but their low ecological footprint compared to monospecific aquaculture techniques is unanimous [186,193]. Although IMTAs are currently employed in numerous countries [51] and have been the subject of numerous studies, due to the considerable diversity of these systems (open-water or land-based) and the inherent difficulty in measuring the ecological footprint in circular systems [183], there is currently no global evaluation of their GHG emissions. For instance, Nobre et al. [194] observed a reduction in GHG emissions of between 290 and 350 t CO_2e $year^{-1}$ when abalone were cultivated in IMTAs. In contrast, the work of Chary et al. [195] illustrates the challenges of assessing the impact of IMTAs on climate change. In their study of an open-water IMTA involving red drum and sea cucumbers, they estimated emissions of 2341 kg CO_2eq per t of fresh aquatic product. However, they found few differences between the IMTA and a monospecific red drum farm due to the unbalanced design of the finfish and sea cucumber compartments.

The potential for IMTAs to facilitate the ecointensification of aquaculture has been demonstrated. These systems offer the dual benefits of producing safe products for human consumption and meeting the standards for organic aquaculture [178,196,197].

3.3. Biofloc Technology (BFT) Systems

Biofloc Technology (BFT) originated in the 1970s at Ifremer-COP (French Polynesia) on penaeid species, with the aim of identifying sustainable methods to improve water quality in aquaculture [198]. The initial phase of its development was focused on reducing nitrogen levels through microbial processes [199]. The concept progressed in the 1990s and 2000s, with significant scientific contributions [200,201], promoting its application in shrimp and fish farming in areas where water limitation, land costs and environmental issues were major concerns. Today, BFT is widely adopted for its environmental and economic benefits, particularly in intensive shrimp aquaculture systems [202]. Although shrimp is a species with a high market value, it should be noted that the BFT system can result in the production of off-flavors, which may be attributed to high turbidity, filamentous cyanobacteria and actinomycetes. These factors can negatively impact the quality and market value of BFT-produced shrimps [203]. However, several strategies have been proposed to alleviate this problem, including the introduction of certain microorganisms, such as those from the Bacillaceae family, into BFT system designs as bioreactors [204,205].

BFT systems are based on the formation of bioflocs in a culture medium (Figure 3). These are microscopic ecosystems where uneaten food, excess inorganic nutrients, and feces aggregate along with microorganisms (bacteria, microalgae, diatoms, protozoa. . .). This aggregation is enabled by a matrix of extracellular polymeric substances secreted by the microorganisms [206]. By maintaining a high carbon/nitrogen ratio [206] through the addition of a carbon source (molasses, glycerol, flours [207]) to the culture medium, the colonies of chemoautotrophic bacteria present in the bioflocs assimilate the ammonium excreted by the cultured species during the nitrification process, transforming it into nitrate. Furthermore, heterotrophic bacteria can also directly assimilate the ammonium into bacterial biomass. Additionally, microalgae contribute to nitrogen absorption during photosynthesis [208]. In this manner, BFT serves to maintain water quality by reducing the ammonium concentration, which is toxic to the cultured species, and transforming it into nitrate, which can accumulate but does not pose a health risk to the cultures. This reduces water consumption, its purification and the associated costs. Moreover, nitrogenous organic wastes are employed in the synthesis of microbial protein, making biofloc a rich source of quality protein that can be used as supplementary feed for the cultured species [209]. Thus, BFT also promotes low-protein diets, reducing the cost and environmental impact associated with the formulation of protein-rich feeds [200]. The addition of organic carbon sources can result in fluctuations in dissolved oxygen levels due to the metabolic processes of aerobic microorganisms [210]. In order to prevent stress on the cultured organisms, it is possible to separate the biofloc reactors from the culture tank [211]. The effluent is then transferred to these reactors, where a carbon source is added in order to stimulate the growth of bioflocs. Subsequently, the water and bioflocs from the reactors are transferred to the culture tanks, where they are consumed [210,212].

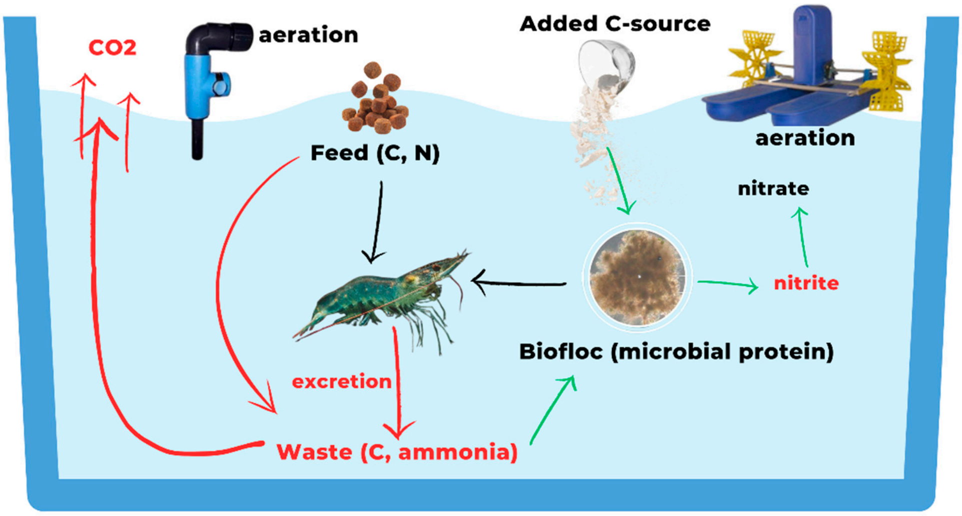

Figure 3. Diagram of a BFT system with a biofloc within the culture unit. Source: authors.

BFT systems have been identified as a promising technology for sustainable food production, contributing to the development of a circular economy. This technology is currently primarily employed in the cultivation of penaeids, as they are omnivorous species that can feed on biofloc [213]. These species are also tolerant to changes in the concentrations of dissolved oxygen in the water and nitrogenous compounds and can withstand high culture densities and high concentrations of suspended solids [214,215]. Like IMTAs, BFT promotes low-trophic-level species cultivation and polyculture. Indeed, some authors have proposed this technology as a form of IMTA [183,197,216] because of the presence of microorganisms in the fed species. A wide variety of integrated BFT systems have been studied, showing higher efficiency than monospecific BFT: shrimp in BFT with Nile tilapia [217], with mullet (*Mugil liza*) and seaweeds (*Ulva fasciata*) [218], with *Ulva lactuca* [219], or with tilapia and the halophyte *Sarcocornia ambigua* [220]. Feeding efficiency and waste management are also enhanced by definition in these systems, as they have the capacity to enhance nutrient utilization and minimize environmental impact, achieved through reduced water and fertilizer usage [178,202]. In BFT systems, food requirements are reduced, and an increase in the survival and growth rates of cultivated species has been observed. Bioflocs present a favorable nutritional profile for numerous aquaculture species, including filter feeders, detritivores and even some herbivorous or omnivorous finfish, which are able to feed directly on particulate organic matter [212]. Other studies have demonstrated that the consumption of bioflocs can enhance growth and fortify the immune system of cultivated species by increasing the activity of their digestive enzymes, resulting in an increase in the feed conversion rate [221]. Concerning energy efficiency, the aeration of BFT systems requires much more energy than conventional tanks and most recirculation systems, which represents a significant cost [206]. However, the need for water exchange is minimized, thereby reducing pumping costs. In general, maintaining the water temperature in BFT systems may not require significant energy input due to the minimal water exchange, which prevents variations in temperature. However, when this technology is employed for the cultivation of tropical species in cold countries, maintaining the temperature can be costly in terms of energy [198,222]. This issue can be resolved by recovering waste heat from the industrial sector or by manufacturing biogas from the farm’s own waste [223].

It has been demonstrated that carbon sequestration can occur in BFT ponds, as the phytoplankton present in bioflocs are able to use carbon through photosynthesis, acting as carbon sinks [224,225]. This phenomenon, in conjunction with the reduction in the feed conversion ratio (FCR) observed in BFT, has led to the suggestion that these systems could be employed as a strategy for reducing the GHG emissions associated with shrimp farming, even when a carbon source is added to the ponds [226–228]. Indeed, Huang et al. [226] estimated that GHG emissions in a shrimp BFT system were 5945 kg CO_2e t^{-1} of shrimp, which represents one-quarter of the emissions of a super-intensive system, while BFT production represented 60% of the super-intensive yield. Finally, shrimp production is frequently incompatible with organic labels. The application of BFT, the use of organic feed and surveying animal density and welfare could collectively help to achieve organic standards and certification [130].

3.4. Extensive Aquaculture: Earthen Ponds and Intertidal Aquaculture

Extensive aquaculture is the most traditional mode of production and involves raising aquatic organisms in natural or semi-natural settings with minimal human intervention [130]. It includes earthen ponds and intertidal aquaculture of bivalves (Figure 4). Earthen ponds are shallow, man-made ponds where organisms are raised using natural resources such as algae and plankton for food. An example is the use of salt marshes and their seawater reservoirs built by enclosing a piece of salt marsh to guarantee a constant supply of water from the saltworks [229,230]. The macroinvertebrate community naturally inhabiting these ponds includes small molluscs, crustaceans, polychaetes and chironomids, among others, which constitute the main food for nonintensively reared fish [231]. These systems promote the welfare of cultured fish which feed on natural prey. Intertidal bivalve aquaculture is one of the most important aquaculture industries [1] and involves cultivating bivalves in intertidal coastal areas where they filter feed on plankton and organic matter present in the water. These systems operate with minimal input of feed and chemicals, relying heavily on the natural productivity of the ecosystems [83]. Both systems produce high-quality products that can achieve high prices in the market in comparison to products from semi-intensive or intensive systems if they are differentiated through appropriate labeling.

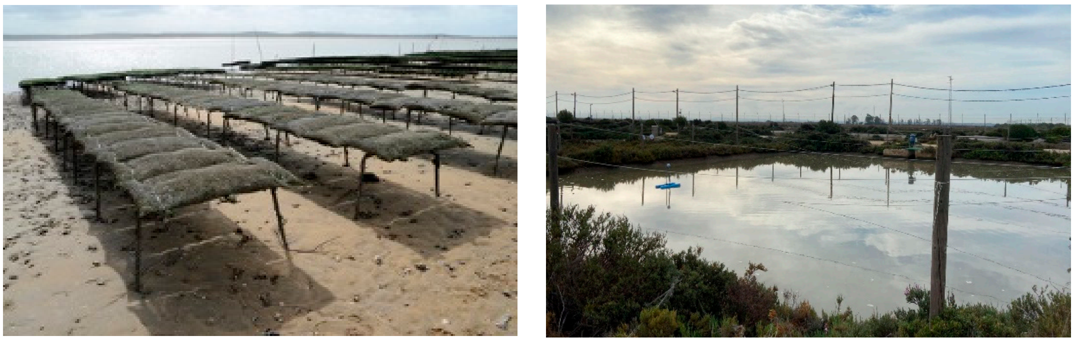
(**a**) (**b**)

Figure 4. (**a**) Oyster trestle tables placed in the intertidal zone; (**b**) marsh ponds in Cadiz Bay.

Concerning our climate change mitigation strategies, extensive aquaculture systems often focus on low-trophic-level species, such as bivalves and herbivorous or omnivorous fish or crustaceans, requiring few resources for growth and reducing the ecological footprint of production [231]. Bivalves, in particular, do not need external feed inputs, relying instead on natural phytoplankton, which enhances their sustainability [232]. Many extensive aquaculture systems employ polyculture or IMTAs [233–235], combining, for example, the extensive culture of fish and crustacean amphipods associated with marsh ponds [48,236]. Fish cultured in marsh ponds are usually produced in polyculture systems (e.g., mugilids, seabream, seabass and sole), especially under extensive conditions, but the monoculture of gilthead seabream (*Sparus aurata*) is being increasingly conducted in marsh ponds. In fact, extensive systems provide a fish product more similar to wild conspecifics, with similarities in the trophic niche and the concentrations of trace metals [231]. Feeding efficiency in extensive aquaculture is inherently high due to the reliance on natural food sources. In these systems, organisms consume naturally occurring plankton and detritus, which are replenished through natural processes like sunlight and nutrient cycling. This reduces the need for manufactured feed, lowering costs and minimizing the environmental impact associated with feed production and transport [75,231]. Extensive earthen ponds can exhibit efficient waste management through natural processes or through their association with constructed wetlands [237]. Waste settles and is broken down by microbial activity, which recycles nutrients back into the pond ecosystem, promoting further algal growth. On the other hand, bivalves filter and clean the water, removing excess nutrients and particulates while promoting biodeposition and enriching the sediment [238]. Regarding energy efficiency, these systems utilize sunlight and natural biological processes for production. Their reliance on natural sunlight for algae growth, which forms the base of the food web, significantly reduces the need for external energy inputs, which are reduced to downstream production stages such as processing, packaging, refrigeration or transport [42].

Extensive aquaculture can also contribute to carbon sequestration, especially in the case of bivalve farming, as previously noted. Bivalves incorporate carbon into their shells, effectively removing it from the atmosphere. However, it is important to be cautious with these statements since some studies affirm that the amount of CO_2 released through respiration is higher than the amount stored in a calcium carbonate shell [79,239]. According to Willer and Aldridge [240], global bivalve production (all systems included) emissions reach 11.1 tons of CO_2e per ton of protein, but excluding transport, emissions range between −5 (when bivalves are a net sink of carbon) and 1874 kg of CO_2e per ton WW (with a median of 392 kg CO_2e). Furthermore, extensive pond systems generally emit fewer GHGs than intensive systems due to their lower energy and feed inputs. However, the precise impact of extensive aquaculture on GHG emissions can vary depending on the specific practices and management of the systems [42]. In China, Zhang et al. [241] have estimated GHG emissions from extensive aquaculture in wetlands and inland ponds to be approximately 65 t CO_2e ha^{-1} y^{-1}. They also showed that coastal wetland systems have the lowest CO_2 emission impact, functioning as a net carbon sink when polyculture is conducted.

These extensive earthen ponds are, above all, providers of ecosystem services, including economic benefits, nutrient absorption (N, C) and habitats for birds, fish and invertebrate species. They also meet the criteria for organic labeling, enabling premium prices and ensuring economic viability [75]. Indeed, in this study, Walton et al. [75] demonstrated that aquaculture can mitigate the ecological degradation of natural wetlands, which represents an ecosystem restoration strategy of the EU [242].

4. Conclusions, Challenges and Implications

In this study, we compared several aquaculture systems in terms of their strategies to reduce GHG emissions. This review demonstrates the proactive approach of the aquaculture industry towards sustainability. The transition from intensive systems to more sustainable and extensive practices and methods, such as RASs, IMTAs and BFT, represents a significant advancement. Nevertheless, the results of our investigation indicate considerable variability between different studies of the same system, which represents an important limitation when evaluating their sustainability and comparing them with other systems.

Despite efforts to quantify emissions accurately, several potential errors and uncertainties must be acknowledged. Methodologically, the reliance on emission factors derived from various sources introduces uncertainties, as these factors can vary based on local conditions, species and management practices [243]. Moreover, these authors highlight that some of these factors are generally not considered (including bubbles released from sediments, aeration-induced emissions, emissions from dry and drying sediments, and emissions from effluent and waste). Data limitations, particularly in certain regions or specific aquaculture practices [164], hindered our ability to provide precise estimates. Future research should focus on improving data quality and homogenizing estimation techniques to enhance the reliability of emission assessments in aquaculture [244,245].

The geographical context also influences emission outcomes in aquaculture [42,241]. Local environmental factors, such as temperature, water quality and ecosystem resilience, play crucial roles in determining emission rates [10,24]. Economic conditions also influence production practices and thus emissions [164,246], with higher-income regions often investing in advanced technologies that may mitigate environmental impacts. Social factors, including regulatory frameworks and community engagement, further shape sustainability outcomes. Techniques like RASs tend to be more prevalent in developed countries [141], whereas extensive systems are more common in developing regions due to economic considerations and resource availability [247,248].

It is widely acknowledged that the systems we have reviewed here are more sustainable than traditional intensive systems [186,193]. In our opinion, while RASs, BFT and extensive systems in general offer significant sustainability benefits, IMTAs represent the most sustainable option due to their holistic approach and the fact that they apply, by definition, all GHG emission mitigation strategies. The FAO supports sustainable aquaculture practices globally and promotes IMTAs as a viable option for improving the environmental and economic performance of aquaculture operations [249]. However, in addition to the methodological limitations encountered in estimating the emissions explained above, there are still limits to the development and expansion of these systems. Polyculture requires technical knowledge about the cycles of two or more species, which can act as a brake in the transition from traditional farms towards these systems. They require complex management practices and tailored system designs, which can be barriers to their adoption [177]. Moreover, the interactions between different species need to be carefully managed to avoid unforeseen ecological impacts [250], and the benefits of IMTAs may vary significantly depending on local environmental conditions [178,251]. In Europe, the regulatory framework for IMTAs has not yet been fully developed or standardized across all member states [177]. However, there are several initiatives and regulations that indirectly support and influence the development of IMTAs (the EU missions “Restore our Ocean and Waters” or “Green Deal”, the Atlantic Action Plan, the Blue Growth strategy, the United Nations Sustainable

Development Goal 12 [3–6,171]). Globally, the regulatory frameworks for IMTAs vary significantly, with some regions advancing more rapidly than others. For instance, Canada is one of the leaders in IMTA research and implementation. Their regulatory framework includes provincial and federal oversight, with agencies supporting IMTA through research and development programs [252,253]. In other countries, such as the United States, Chile, China, Japan, South Africa, New Zealand or Australia, the regulatory frameworks are evolving, with increased emphasis on sustainability and environmental protection, which supports the adoption of IMTAs [186,254–257].

In conclusion, while there is growing interest and support for IMTAs worldwide, challenges remain in terms of regulatory harmonization and technical knowledge. Developing specific regulations and guidelines for IMTAs, providing targeted funding and support and fostering international collaboration can help overcome these challenges and promote the wider adoption of IMTAs globally. In addition, improving standardization and transparency in reporting emission data to facilitate more accurate assessments in future studies is crucial for the development of IMTAs and global low-impact aquaculture. Finally, it is important to highlight that sustainable systems (RASs, BFT, IMTAs and other extensive methods) can be combined with one another, contingent on the availability of resources, for enhanced efficiency. Labeling and/or compliance with organic aquaculture standards appear to be crucial factors in achieving profitability with these systems.

Author Contributions: Writing—original draft preparation, M.C.-G.; writing—review and editing, J.M.G.-G., I.H.-C. and M.H.; supervision, M.H. All authors have read and agreed to the published version of the manuscript.

Funding: M.C.-G. was supported by a "Margarita Salas" individual fellowship from the Spanish Ministry of Science, Innovation and Universities, funded by the European Union—NextGeneration EU program.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

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