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Review

Towards the Sustainable Intensification of Aquaculture: Exploring Possible Ways Forward

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Abstract: Meeting the global demand for aquatic products while maintaining sustainability is a critical challenge. This review article examines global practices of land-based aquaculture systems that could be implemented in the EU, as the EU has not yet fully realized its potential in developing the aquaculture sector. Therefore, the article examines different aspects (aquaculture systems, technological solutions and improvements, and best management practices) in achieving sustainable aquaculture and emphasizes the need for innovation and cooperation in the face of increasing environmental concerns and resource constraints. There is no one-size-fits-all solution for the sustainable intensification of aquaculture. The way forward requires a combination of different and improved-upon technological solutions complemented by technological innovation and better management practices. The sustainability of aquaculture requires a broader application of the ecosystem approach to aquaculture and the promotion of energy and resource efficiency measures in aquaculture systems.

Keywords: land-based aquaculture; aquaculture systems; technologies; EAA; bio-economy

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1. Introduction

The terms "sustainability" and "sustainable" have become frequently used words today, both in relation to environmental issues and processes and activities in connection with future development. This statement is well illustrated by the ScienceDirect search function for scientific articles. For example, when entering the phrase "sustainable" or "sustainability" in the search bar, the following message is displayed: "Due to the large number of search results, only the last three years are included" [1], and it is indicated that there are more than 1,000,000 existing results these three years. It has been argued that the term "sustainability" has lost its deeper meaning and has become an alienated cliché that is overused both inside and outside of its intended context [2]; nevertheless, the principles of sustainable practices are indisputable and need to be discussed. Despite the importance of the notion and widely discussed concept of sustainability, the meaning of the term "sustainable aquaculture" has not been clearly defined, and it is not clear when it is appropriate to refer to aquaculture as sustainable [2].

In the past, aquaculture systems were viewed as environmentally friendly because they operated according to the circular economy principle—mainly by utilizing agricultural and locally available waste and by-products, such as crop residues and animal or human manure, as nutrients [3]. Unfortunately, presently, things have changed. Although only the production of pelleted feed has been introduced relatively recently, it is already widely used in modern aquaculture systems due to its ease of handling [3]. Pelleted feed is one of the reasons why aquaculture production has made a huge leap forward in recent decades and has become the fastest-growing food production sector in the world, and it is expected that its growth will continue to increase [4–6]. This process is also known as the "Blue Revolution"—specifically, the rapid growth and intensification of fish, shellfish, and aquatic plant aquaculture production from the mid-20th century to the present day [3,7,8].

However, the increase in pond productivity has come at a cost—the excessive amount of pelleted feed in water has led to an overabundance of nutrients, affecting water quality and posing serious environmental risks [3].

Although there is a trend towards the expansion of offshore aquaculture due to the high quality of water suitable for farming, the unlimited potential, and the natural treatment of waste in aquaculture systems, it is more likely that land-based aquaculture will remain the main source of fish, shellfish and aquatic plants as opposed to mariculture [3]. This is due to the significant technological, operational, economic, legal, and political barriers that still need to be overcome before the oceans may be utilized as a significant source of farmed fish [3]. It is, therefore, estimated that the majority of farmed fish will continue to be reared in inland waters for the foreseeable future [3].

Producers' views on the need to develop aquaculture systems to increase resource use efficiency and reduce environmental impacts are changing in favor of sustainable solutions [2]. This is due to promising technologies that combine traditional and modern aquaculture practices, reducing the negative environmental impacts of modern pellet-fed aquaculture [3]. Although intensification leads to higher production and, consequently, higher profits, such practices need to be strictly monitored in order to maintain environmental sustainability [2]. The challenge for the future, therefore, is to increase production per hectare by increasing resource efficiency and resource consumption (kilograms per hectare) [2].

In tropical developing countries, fish and shellfish can generally be farmed at a lower cost, and to date, transporting these products to economically developed consumer countries has not been a significant cost factor [2]. This puts developed, temperate countries at a disadvantage due to higher cultivation, production, and labor costs, as it is difficult to compete with developing countries, which may produce and transport the products at a fraction of the cost [2]. At the same time, the proximity of developed countries with temperate climates to markets with a high demand for live and fresh produce should be seen as an advantage to be capitalized on in the future [2]. To do so, a way must, therefore, be found to reduce the costs of farming and intensify aquaculture while, at the same time, maintaining a sustainable approach to ensure continuity.

Aquaculture and the EU

The European Union (EU) has exclusive competence for marine plants and animals, governed according to the Common Fisheries Policy [9]. For aquaculture, the EU shares competence with Member States, which then set their own specific requirements enshrined in regulations and legislation [9,10]. However, at the same time, aquaculture farms and their activities are subject to several EU regulations that govern certain aspects of their activities, such as farmed fish welfare, environmental impact, water quality, spatial planning, feed requirements, and other standards [10,11]. To contribute to the implementation of the core objectives of the European Green Deal and the resulting Farm-to-Fork Strategy, the European Commission adopted, in 2013, a Communication entitled "Strategic Guidelines for the sustainable development of EU aquaculture" and, subsequently, in 2021, a Communication, entitled, "Strategic guidelines for a more sustainable and competitive EU aquaculture for the period 2021 to 2030" (hereafter referred to as the Strategic Guidelines) [10,12,13].

In the 2013 Strategic Guidelines, the EU aquaculture sector was assessed as stagnating despite the high environmental standards and the high quality of aquaculture production [13]. A similar conclusion was reached in the latest Strategic Guidelines [12], adopted in 2021, which recognize that the EU aquaculture sector is still "far from reaching its full potential in terms of growth and meeting the increasing demand for more sustainable seafood" [12]. To better illustrate the situation, according to the 2023 report "The EU Fish Market" by the European Market Observatory for Fisheries and Aquaculture Products (EUMOFA), aquaculture production and catches from the Asian continent accounted for 74% of the global market in 2021, while Europe accounted for only 8% [14]. In Asia, catches account for 30% of the total volume, while 70% of the total volume comes from aquaculture [14]. In Europe, the ratio is reversed, with 81% of the volume coming from catches and only 19% from aquaculture production [14].

The aim of this review article is, therefore, to look at and analyze global practices for land-based aquaculture systems that could be adopted in the EU. The article mainly focuses on scientific articles and solutions from Asian countries, as they are world leaders in aquaculture production [14], as well as several articles from the U.S., where several technological solutions for aquaculture (e.g., aerator technologies [15,16] and partitioned aquaculture systems [17,18]) have been developed, as well as improved. This article focuses on sustainable aquaculture practices related to the growth phase of an aquatic organism in an aquaculture system, from egg to adult [19], and the technological elements of aquaculture systems, without a detailed discussion of the feed and disease control measures or consideration of the harvesting practices and the downstream stages of the product value chain. Throughout this article, the authors will address the following subjects:

- Aquaculture systems—the most appropriate farming method;
- Technological solutions for aquaculture systems;
- Technological solutions—future perspectives;
- Development of the aquaculture sector through good management practices.

The sustainability and environmental impact of individual aquaculture systems or technologies can be measured using a variety of tools and methods. In addition, the environmental impact and sustainability of aquaculture operations depend on a variety of factors [5]: (1) species or type of aquatic organism being farmed; (2) intensity of the production system—extensive, semi-intensive or intensive; (3) density of cultivation; (4) quality of the feed; (5) management practices; (6) wastewater treatment, etc. [5]. The scientific literature refers to methods such as the life-cycle assessment (LCA) [5], emergy analysis [5], ecological footprint [5], Ecopath model [20,21], dynamic simulation models [22], and many others, depending on the research topic.

Dong et al. [20] suggest that the Ecopath model, proposed by Polovina in 1983 [21], is an effective way to assess the sustainability and environmental impact of integrated pond aquaculture systems in the context of an ecosystem. The Ecopath model quantifies factors that represent the characteristics of an ecosystem by simulating food chains, energy flows, and the trophic structure [20,21]. In their study, Dong et al. [20] propose to complement the Ecopath food web model with an evaluation index system to enable improvements in pond aquaculture—for resource and energy efficiency and environmental protection.

2. Aquaculture Systems

Traditional aquaculture consists primarily of integrated agricultural–aquaculture systems that utilize by-products, manure, and plant material from farming or agricultural activities [3]. Integrated peri-urban aquaculture systems are primarily nourished by municipal effluent and agricultural by-products [3]. Fertilized ponds, in particular, ponds fertilized with waste from other activities, are attractive because of their low dependence on external resources for food, energy, and waste treatment [2]. However, putting more feed in the ponds does not increase fish production, as most of the feed ingested is not converted into harvest but is discharged into the water as waste material, which can have a negative impact on the environment in which the fish are farmed [2]. For example, nutrient wastes such as nitrogen, phosphorus, and other minerals, as well as organic wastes such as excrement and uneaten food, stimulate biological activity within the rearing system, which can significantly lower the dissolved oxygen level, endangering the culture grown there [2]. Aquaculture wastes include uneaten feed, nitrogenous metabolites, excreta, chemicals, and therapeutics, and they produce mainly two types of residues: liquid and solid [5,23]. Liquid residues are wastewater and discharged water from operations [5,23]. Solid residues consist of feces, feed, and other solid materials [5,23]. However, aquaculture ponds are unique in that if the right balance is struck between intensification and sustainability, residues can be treated in the pond using internal processes without additional stress on external ecosystems [2].

Fertilizing ponds with organic or chemical fertilizers that stimulate plant growth can also boost pond productivity [2]. The productivity of fertilized ponds is variable. Sometimes, it may be as high as 4 to 6 t/ha, depending on the duration of the growing season, the species cultivated, and the type of fertilization program applied [2]. In stillwater ponds, 8–10 t/ha or more can be produced with additional feeding and aeration, again depending on the length of the growing season and the physiological characteristics of the species being cultivated [2]. However, the amount of plant material that can be produced in fertilized ponds is eventually restricted by the amount of solar radiation that is available; this places a maximum limit on the amount of plant material that can be produced [2]. To improve the productivity of aquaculture beyond what is possible simply through fertilization, the essential ingredients for development must be obtained from sources other than the water itself and then transformed into feed that is both attractive and nutritious [2]. Mixtures of various plant and animal feed constituents are used in the production of commercial aquaculture feeds [2]. Not only the sustainability of the aquatic organisms produced but also the sustainability and safety of feed ingredient production, environmental impacts, potential import dependency, and food security are becoming increasingly important [2].

New filtration, recirculation, and water treatment will enable better purification of used water so that it can be re-used [2]. On the other hand, there is a lack of land resources to develop new aquaculture systems—there is no suitable land available, either the land has limited access to suitable water sources, or it is too expensive to be economically viable for conversion into an aquaculture system [2]. The release of nutrients from ponds to the external environment is inversely proportional to the rate of water exchange, as a significant amount of waste is treated on site in ponds with standing water [3]. In low-intensity pond culture, there is minimal wastewater discharge with little to no negative impact on the environment, as the pond ecosystem processes significant amounts of waste during the culture cycle [3].

In the following subsections (Sections 2.1–2.4), different technologies will be discussed and described for cultivating aquatic organisms—monoculture, polyculture, as well as three more advanced technologies such as integrated multitrophic aquaculture, aquaponics, and biofloc technologies (Figure 1).

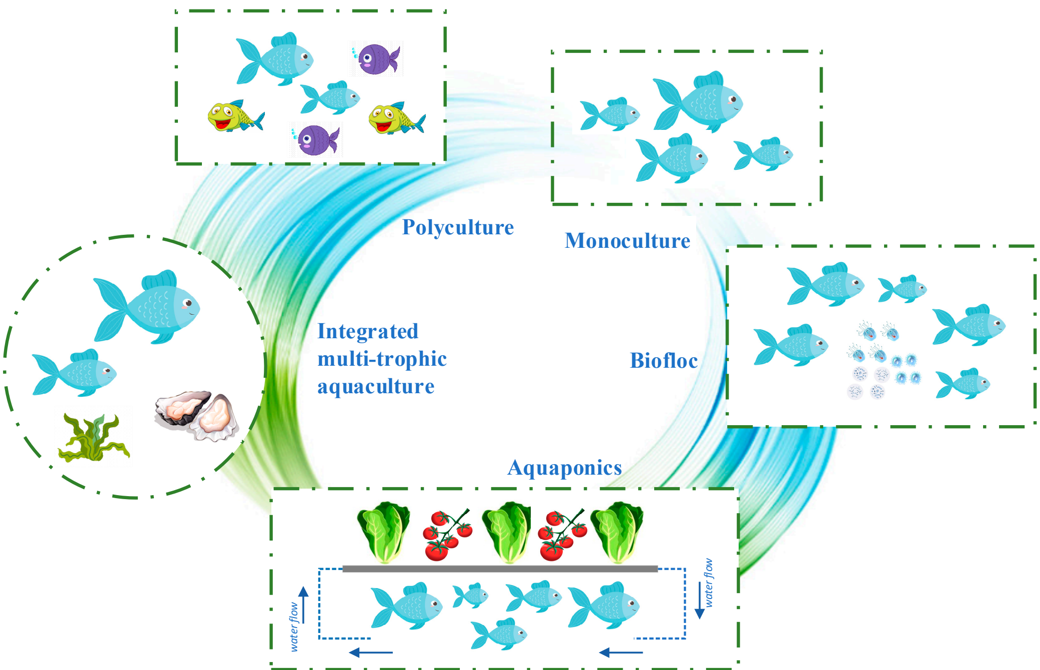

Figure 1. Simplified depiction of aquatic organism cultivation technologies.

2.1. Intensively Fed Monoculture and Polyculture

Some species, such as filter-feeding mollusks and algae, feed on the waters around them and do not need to be fed, even in extremely dense populations [2]. Other species, including most fish and crustacean species, require external food sources and are usually cultivated in intensively fed monocultures [2]. Monoculture, the cultivation of a single aquatic species at varying densities, is widely practiced throughout the globe—Europe, North America, China, and Australia [2,24,25]. Monocultures are characteristic of intensive recirculated aquaculture systems in which a species with a high market value is cultivated in high density [24]. High-quality commercial feed is fed to monocultures and usually accounts for 50–80% of production costs, and the main products are high-value fish and crustaceans [2].

Monoculture aquaculture is based on the concept of linear economy, which is not the most sustainable approach [2]. By cultivating only one species, the aquatic organisms that are farmed cannot consume all the food given to them, which is disadvantageous from the point of view of resource efficiency [24]. Monocultures have lower resistance to pathogens and viruses [24].

Polyculture can be described as the rearing of two or more species, the combination of plants and animals, fish or plants, and even aquatic and terrestrial species in the same fixed space [24,26]. Polyculture has its roots in China, where several species of carp were reared in one pond or fish farming was combined with rice cultivation [26,27]. Today, the concept of polyculture has evolved considerably, trying to combine different aquatic organisms, but the basic principle remains the same: the aquatic organisms to be cultivated must occupy different ecological niches and must not compete with each other for nutrients [26]. The simultaneous cultivation of more than one aquatic organism offers advantages such as additional resource efficiency and economic benefits from all species farmed and sold, as well as improved water quality [26].

2.2. Integrated Multitrophic Aquaculture

Integrated multitrophic aquaculture (IMTA) is an old and, at the same time, a new concept based on the principle that more than one species is farmed in the same aquaculture system (pond, tank, or cage) [3,25]. IMTA can be seen as an advanced version of polyculture, where the cultivation of fish or shrimp is supplemented by algae, which can remove inorganic nutrients, and sediment eaters such as shellfish and/or sea cucumbers, which can remove organic nutrients [5,25,26]. Another difference between polycultures and IMTAs is that polycultures have different species growing in the same body of water [27]. However, this does not mean that they form an ecosystem in which one species feeds on the waste of another [27]. One of the biggest challenges for IMTA is to create a balanced system of aquatic organisms, as it requires knowledge of each species' trophic level, feeding habits, oxygen requirements, and other specific requirements that vary from species to species [5,28].

IMTAs can be land-based and established in ponds, tanks, or open water (sea, ocean) [28]. Land-based IMTA consists of ponds or tanks arranged in order to facilitate the flow of water in a flow-through system or recirculating aquaculture system [28,29].

Research carried out by several scientific groups [25,30,31] points to the positive impacts of IMTA in all three dimensions of sustainability—environmental, economic, and social. Furthermore, IMTA systems operate according to the principles of the circular economy, improving not only resource efficiency but also energy efficiency and reducing the risk of pollution [27,32]. The resource efficiency of the IMTA system is demonstrated by its ability to produce more protein from a given amount of feed than other conventional production systems [2]. Research by Alexander et al. [32] on the perception of the European public towards IMTA showed that the level of public knowledge and awareness of this farming method is generally low. At the same time, after receiving additional information about the principles of IMTA, respondents expressed more approval than disapproval of this farming method [32].

IMTA systems are considered to be under-researched, not only in Europe but also on a global scale [30]. There are drawbacks, such as high initial costs as well as the subsequent operating costs of the system, that should be addressed in the future [28,33]. Additional support from national governments and industry, as well as evidence of financial benefits, could encourage the adoption of IMTA [28,30,33].

2.3. Aquaponics

Aquaponics is defined as the cultivation of vegetables in a soilless nutrient solution by fertilizing the plants with nutrients from fish tank effluent [3,5,23]. Aquaponics can be considered to be a derivative of IMTA, supplemented with elements from combining recirculating aquaculture systems and hydroponics [3,5,23,34]. The benefits of aquaponics systems include nutrient uptake by the plants and improved quality of the water that is returned to the fish tanks [5,23]. The water from aquaponics systems can be used to grow a variety of vegetables such as lettuce, spinach, tomatoes, cucumbers, and other plants like water hyacinth (*Eichhoria crassipes*) or water fern (*Azolla* sp.) [5,35]. Henares et al. [5] and Zimmermann et al. [34] point out that closed aquaponics improves the quality and productivity of vegetables through a better controlled nutritional value and reduces the spread of pests and diseases.

Aquaponics is one of the latest trends that has attracted the attention of both scientists and companies. Nevertheless, there are currently very few commercially successful aquaponics systems [3]. Aquaponics systems primarily produce vegetables, not fish, so the high-quality fish feed used to “fertilize” the plants is not cost-effective [3]. Moreover, aquaponic systems have greater capital and operating costs, energy consumption, and greenhouse gas emissions per unit of production than pond and cage culture [3,23]. It is, therefore, argued that growing hydroponic vegetables with inorganic fertilizers in fertilized low-cost farming systems are more cost-effective and simpler than integrating them into a fish recirculation system [3].

Aquaponics is predominantly practiced as a hobby and in small-scale backyard agriculture [3]. Although aquaponics may have potential in countries with limited freshwater resources or in the commercialization of fish and vegetables produced in such systems as niche products for which consumers would be willing to pay a higher price, it is not expected that such systems will be intensified in the near future [3].

2.4. Bioflocs

Biofloc aquaculture or biofloc technology (BFT) consists of a controlled environment system that combines suspended phytoplankton, heterotrophic bacteria, algae, protozoa, feces, and uneaten food to produce an organic fish diet [2,5,23,36]. The concept of BFT was developed in the 1970s and aims to solve the two main environmental problems in aquaculture: wastewater recovery and protein extraction [23,26]. There are several reasons there is hope for the BFT to be one of the primary aquaculture paths to a sustainable future [36–39]:

- minimal or no external water exchange;
- less feed is needed, which reduces feed costs by 30%;
- natural microbial biomass improves water purification;
- enhanced growth, performance, and immunity of cultured aquatic organisms;
- some bacterial species are useful in sequestering atmospheric CO_2.

In addition to the waste treatment function of BFT, it is a nutrient-rich food source made entirely from recycled waste materials and can be used as an in-pond food source or supplement [2,5,23,39]. Plant-based proteins as a supplementary feed source can be used in BFTs to make the system as environmentally friendly and sustainable as possible [37]. The nutritional value of BFT is largely determined by the microbial community in the water body [37].

The construction and operation of BFT are both very costly and energy-intensive. Therefore, it requires a high level of technical competence [2,37]. Outdoor BFT can be established in tanks or ponds as well [36]. However, when deploying outdoor BFT systems, the location of the water body, the light intensity, and the time of year should be carefully considered, as these factors can have a strong influence on the internal balance of the system [37]. BFT needs to be monitored as it tends to accumulate [36]. Water quality parameters, especially dissolved oxygen, pH, and ammonia levels, must be monitored regularly as elevated levels can stress aquatic organisms and impair their growth [5,36]. Therefore, BFT must be supplemented with intensive aeration [5,26,36].

From a consumer perspective, the preference for aquatic organisms cultured in BFT could be undermined by the presence of metabolites such as geosmin and 2-methylisoborneol in the water, which give the cultured product a muddy or earthy taste [37,40,41]. In addition, consumers may be skeptical of aquaculture products from BFT, as nutrient extraction is based on converting the excreta of aquatic organisms into feed [39].

The use of BFT can be combined with IMTA, therefore increasing economic benefits [37]. Although BFT applications are no longer rare, further research is needed to balance and improve understanding of the microscopic mechanisms involved in bioflocculation [36,39]. It is also important to explore the microbial sources responsible for the formation of geosmin and 2-methylisoborneol in BFT and to find ways to eliminate them [41]. Ogello et al. [36] point to the need to improve aquaculture policies to promote innovative aquaculture techniques for sustainable production and the viability of aquaculture enterprises.

3. Engineered Ponds and Tanks for Increased Productivity

The regenerative capacity of pond ecosystems is not unlimited, and this limit of self-regeneration coincides with the upper limit of intensification of aerated aquaculture ponds [2]. To go beyond the limit of self-regeneration, it is necessary to find a way to clean the water mechanically or to increase the self-cleaning capacity of the ponds [2]. The internal waste removal capacity of a pond can be increased by using BFT or by redesigning the pond and using different technologies to gain more control over the internal biological processes [2]. The environmental impacts of ponds with water exchange are different from those of ponds with no or limited water exchange [2]. The amount of water exchanged in different types of ponds can vary from none to several volume exchanges per day [2]. Water exchange increases water consumption, the risk of runoff, and the spread of infectious diseases, and shifts the environmental and economic burden of waste treatment from the pond to other water bodies, which has ethical implications and may be subject to legal regulation [2].

Promising technologies that reduce or even eliminate the negative impact of pond effluent on the environment are the partitioned aquaculture system—split ponds and in-pond raceway system—both closed aeration systems that do not discharge water [3].

3.1. Traditional Pond Aquaculture Systems

Surprisingly, there is not much scientific literature dealing specifically with pond types and their hydrological systems, apart from simplified manuals or guides by FAO [42] and C.E. Boyd of Auburn University. Boyd et al. [43,44] describe three main commonly used hydrological pond types—watershed ponds, embankment ponds, and excavated ponds (Figure 2). The average depth of aquaculture ponds varies between 1 and 4 m, and ponds in intensive aquaculture systems are typically no larger than 1 ha [44].

Watershed ponds, also known as rain-fed ponds or terrace ponds, are created by building an embankment to collect runoff [43,44]. These types of ponds are usually filled with water throughout the year because water is constantly flowing in from nearby springs or streams or mechanically fed from other nearby external sources [43]. Water levels may fluctuate seasonally due to evaporation or lack of rainfall [43,44]. Runoff from this type of pond either percolates into the groundwater or seeps through dams into the surrounding area, where it evaporates or flows downstream [43].

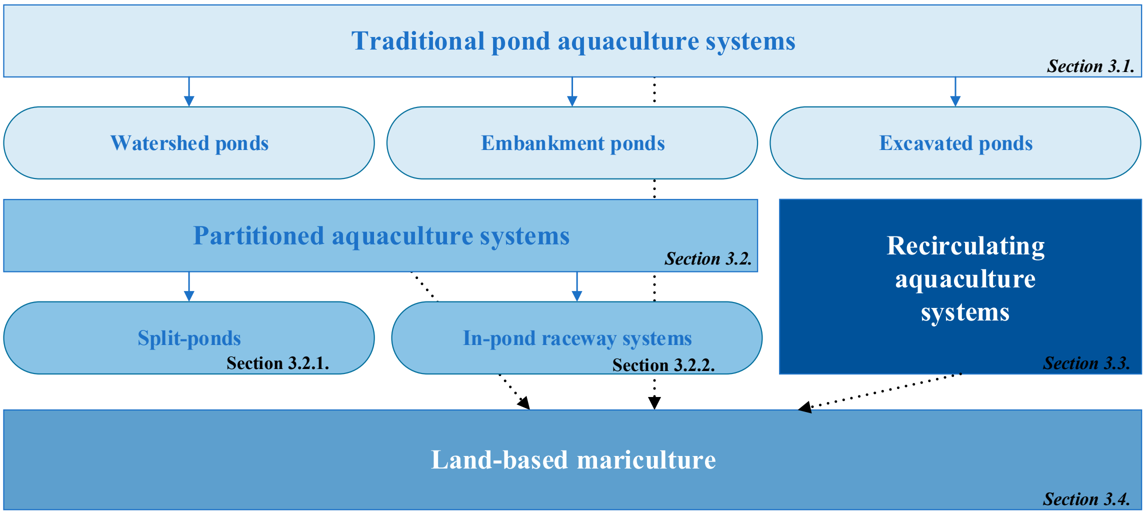

Figure 2. Land-based aquaculture systems (freshwater and saltwater). The blue arrows in the figure indicate a further breakdown of the above aquaculture systems. The black dotted arrows indicate the possibility of using these aquaculture systems as land-based mariculture.

The embankment ponds are constructed on flat ground by removing enough topsoil to build dams that enclose the area where the water is discharged [43]. At their highest point, the embankments are usually 2–3 m high and 2–5 m wide [44]. The water catchment areas of the reservoirs are formed by the inner slopes of the dams and the tops of the dams [43]. It is difficult to fill and maintain embankment ponds with rainwater alone, so water to fill the pond is taken from nearby streams, wells, lakes, and river estuaries [43]. The advantage of this type of pond is that the water level can be more easily controlled, and the aquatic organisms can be harvested by draining the pond [43,44].

The excavated pond is formed by creating a basin in the ground [43,44]. If the groundwater level is high enough, the excavated pond fills up to the current groundwater level and is also replenished by rainwater [43]. The main disadvantage of this type of pond is that the water level cannot be controlled, so the water must be mechanically pumped out of the pond to collect the cultured organisms [43,44]. This type of pond is more suitable for small-scale farming due to its small size and lack of water level control [43,44].

More attention should be paid to the environmental impact of pond aquaculture to avoid endangering nearby ecosystems, as nutrient-rich pond water and organic matter can lead to eutrophication of the watershed [44].

3.2. Partitioned Aquaculture Systems

The main feature of partitioned ponds, also known as partitioned aquaculture systems (PAS), is the partitioning or physical separation of the pond between the fish farming and water treatment areas [45]. PAS was developed in the 1990s to allow water to be recirculated between intensive fish farming raceways and effluent treatment channels to treat effluent without discharging it [2,34,46]. PAS can be characterized by the use of shallow tanks, pond-wide mixing, and continuous cultivation of phytoplankton and zooplankton biomass [45]. Fish are reared in concrete tanks divided into raceways, smaller channels, or ponds that occupy about 5% of the total tank area, with the remaining 95% used for water circulation and re-use [34].

PAS use the high productivity of phytoplankton to extract inorganic nutrients from fish cultivation, increase algal growth, remove waste, and produce oxygen while serving as a water filter [45,46]. Fish aquaculture waste is recycled through a large, well-mixed pond modeled on the "high-rate algal ponds," originally developed to treat wastewater from municipal sources [2,34]. PAS allow for higher capacity ponds and operate without water exchange, allowing for higher fish production per unit area [17]. Tilapia is the most commonly farmed species in PAS, with the main advantage being its adaptability and lower feed quality requirements [45].

3.2.1. Split Ponds

According to Tucker et al. [47], split ponds based on PAS were introduced in the US in the 2000s. Its main objective was to make the management of the system easier for catfish farmers. Split ponds are essentially a lower-cost version of PAS, consisting of two ponds with different functions working in tandem [2,18,45,47]. The smaller pond, which is about 15–20% of the total area of the two ponds, is used for rearing [17,18,48]. The other pond is about four times the size of the first one, contains no fish or other cultured organisms, has a high algae density, and is used for water treatment [2,18,45]. The load of nitrogen, phosphorus, and other plant nutrients is higher in split ponds than in traditional catfish ponds because fish stocking and feeding rates are higher [18,47].

Split-pond construction involves the construction of an earthen levee to divide an existing pond into two unequal sections, with high-volume turbines circulating water between the two sections [2,18,34]. It is not always necessary to build a new pond to switch from a traditional pond system to a split-pond system [49,50]. It is possible to upgrade an existing pond to a split-pond system by renovating it and adding the necessary elements [49,50]. When constructing split ponds, the openings between the ponds should be separated so that fish cannot migrate from the smaller pond to the larger pond [2,49]. If necessary, the flow of water between the two ponds can be stopped completely so that the smaller pond can be harvested without draining the larger pond [2,49]. Water is circulated between the two basins of the split ponds using water circulators, which increase water mixing during the day [18,48]. At night, water exchange between the two ponds is stopped, and aerators are switched on in the small pond to maintain the required dissolved oxygen (DO) concentration [17,47]. For water circulation, farmers usually choose circulators/aerators with a large slow-rotating paddlewheel, a modified paddlewheel aerator, a screw pump, or an axial-flow turbine pump [17,48]. One of the disadvantages of split ponds is the high initial cost, which is quickly recouped through high productivity [17,47,50].

Interestingly, Schrader et al. [18,51] describe cases where geosmin and 2-methylisoborneol, off-flavor metabolites that are more common in traditional ponds, were detected in fish from some of the split ponds. This means that the conversion of aquaculture from traditional ponds to split ponds is not an absolute escape from these “earthy” and “musty” flavors [51]. Therefore, even in the case of a split-pond system, it is recommended that samples are taken before harvesting to determine the presence of off-taste cyanobacteria in the farmed fish [51]. Also, the use of algicides such as diuron and copper-based products in pond management practices is recommended [51].

3.2.2. In-Pond Raceway Systems

In-pond raceway systems (IPRS) have their roots in the U.S., where they were developed for channel catfish aquaculture [34]. Research on a floating IPRS began in the 1990s at Auburn University, where attempts were made to build an improved version of cage culture systems to increase fish production and to be able to collect and remove fish waste [52,53]. The successful design and ability to integrate the IPRS into existing infrastructure have led to its widespread and successful use in the farming of carp, tilapia, and other omnivorous fish [34,54].

Only 5% of the total surface area of the IPRS is used for fish cultivation, with the remainder used for water treatment [34]. The IPRS consists of a water flow mechanism that circulates the water around the fish, which are enclosed in a flowing water system [55]. The IPRS consists of a floating rectangular box or container equipped with air-lift pumps at one end and a water discharge system at the other end of the container [52,53]. The advantage is that the floating IPRS containers can be made in different sizes and materials—plastic or plywood—which are then attached to a floating pier [53,56]. The containers are closed with openable lids to prevent fish from escaping or, conversely, to prevent access by various predators [53,56]. In addition, walkways are added to the fish-holding tanks to allow workers to access the fish [53,56]. Air-lift pumps, usually powered by a high-volume, low-pressure regenerative blower, move the water through the container, ensuring water flow and necessary DO level [53,54]. Water treatment in IPRS is managed by various mechanical and biological systems [53,56].

IPRS offer comparable advantages to PAS, including simplified feeding, sped-up harvesting, improved fish protection, and more cost-effective construction [2,53]. One of the major advantages of IPRS is that they can be deployed in almost any body of water [53]. They have higher yields than traditional ponds and can be operated with less labor force [53,56]. IPRS systems can recover waste from cultured aquatic organisms, making the system environmentally friendly [53,56,57]. Masser and Lazur [56] point out that IPRS systems can be used as a caging system for already cultured fish, where the grown fish can be purged of off-flavors developed during farming within about a week.

A disadvantage of the IPRS is the need for constant water circulation, and water circulators are usually powered by electricity [55]. It is, therefore, important to install emergency power systems so that cultured aquatic organisms are not affected in the event of a power failure [55,56]. Like the other PAS mentioned in earlier chapters, IPRS have high initial and operating costs (although these vary depending on the technological solution of the IPRS containers and energy source used to power the water circulators) [52,55]. With IPRS, as with other PAS, the potential impact on the control of environmental parameters such as light, temperature, and water quality is limited [54].

An interesting result by Nagy et al. [54] is a study on the possibility of farming pikeperch (*Sander lucioperca*) in Central and Eastern European countries using IPRS. The study confirms that high-value fish species such as pikeperch can be farmed in IPRS, and in this system, it even shows better growth performance than the same fish species farmed in a recirculating aquaculture system [54]. Although Nagy et al. [54] point out that further research is needed in winter conditions, IPRS is considered to be a potential future development option.

3.3. Recirculating Aquaculture Systems

Recirculating aquaculture systems (RAS) can be characterized as intensive closed-system aquaculture [23,58]. The main advantage of RAS is the relatively low environmental impact, as 90–99% of the water can be re-used in the more efficient systems, and they require less territory compared to a flow-through system [3,23,35,59]. On the basis of the water exchange rate of the system, the following classification of RAS is proposed: flow-through (>50 m^3/kg feed); re-use (1–50 m^3/kg feed); conventional recirculation (0.1–1 m^3/kg feed) and "next generation" or "innovative" systems (<0.1 m^3/kg feed) [60]. RAS typically consists of elements such as rearing tanks, solid waste removal, wastewater treatment, filtration systems, power generators, oxygen suppliers, water pumps, etc. [23,34,58]. Disinfection can be achieved by ultraviolet treatment, which destabilizes the microbial composition and inactivates pathogenic bacteria [34,58]. Tanks for rearing fish and other aquatic organisms can be placed indoors or outdoors, depending on what species are being reared and their temperature requirements [60].

The most distinctive feature of RAS is the high density of fish cultivated in a relatively limited volume of water [3,5,60]. The water is treated to remove the toxic metabolic wastes of the fish and is then re-used in the system [3,5,35]. RAS can be very simple, with the water passing through a single biological filter, or complex, with multiple treatment steps such as mechanical, biological filters, oxygen enrichment, and ultraviolet disinfection [5]. Unlike ponds, a RAS system is isolated from the external environment, allowing better control of water quality, temperature, and nutrients and reducing the risk of exposure to pathogens and parasites from wildlife, as well as the environmental impact of the systems themselves [5,60,61].

The disadvantage of RAS is the relatively high initial and operating costs, as well as the complexity of the system, which discourages companies from opting for such aquaculture systems [3,5,34,35,60]. The material flow processes and the constant supply of oxygen in RAS make the system very energy-intensive and require structural and functional coordination of several mechanical units [23,35]. The RAS can accumulate toxic waste and sludge that need to be removed periodically [3,61]. In the event of a power failure, the system may shut down with serious consequences [23].

Due to the small amount of additional water required and the high level of wastewater treatment, RAS is considered an environmentally friendly and sustainable system [35,61]. From a circular bio-economy perspective, RAS is not optimal because the nutrients (nitrogen, phosphorus, carbon) in the water are not returned to the production cycle after treatment [23]. However, in terms of promoting a circular bio-economy, hazardous nitrogen waste from aquaculture could be collected and converted into high-value-added, protein-rich products [23,60].

The search for more sustainable and environmentally friendly solutions for RAS continues and is also described in the scientific literature. For example, it is possible to combine RAS with constructed wetland systems, where pollutants are absorbed by plant roots and leaves [5,35]. Bio-RAS or systems combining BFT and RAS technologies have been explored with the aim of achieving zero water exchange and reduced disease risk [62]. Monocultures are characteristic of RAS, but to optimize water use, the possibility of using RAS as a polyculture cultivation mechanism is being explored [24]. Xu et al. [63] briefly describe the recirculating pond aquaculture system (RPAS) as "an innovative mode of pond culture for its environmentally friendly characteristics". In a pilot study, Xu et al. [63] compared the performance of a traditional pond with an RPAS design, where the RPAS developed consisted of elements such as rearing ponds, a treatment pond, an inlet ditch, an outlet pipe, an ecological ditch, and an electrically driven pump. In the experiment, the RPAS showed improved water quality, growth, and muscle quality, as well as physiological conditions [63]. These are just a few examples of attempts to optimize and improve RAS.

3.4. Land-Based Mariculture

Mariculture is seawater aquaculture that can take place in the sea, in the ocean, or even on land [64]. Setting up land-based mariculture systems a few kilometers inland and pumping seawater into specially designed ponds or tanks could be an option for developing aquaculture in coastal regions. Mariculture farms on land are considered to be a more environmentally friendly and sustainable option, as wastewater management, nutrient recycling, and improved feed conversion are easier and cheaper on land than in open water [65]. Transmission of pathogens and genes between cultivated and wild species is prevented, there is no need to worry about weather damage, and the public's right to access the sea is not compromised [65]. Land-based mariculture can be designed according to IMTA principles, for example, by combining marine fish and mollusks with phytoplankton as a biofilter and food for the mollusks in a single system, making it even more sustainable [64,65].

The construction of a land-based mariculture is technically not very different from the construction of a freshwater aquaculture, except for the need to establish it near the coast and to find a good location for a pumping station [2]. Establishing mariculture inland is less environmentally damaging, and pumping costs are predictable [2]. However, local conditions and the mechanics of filtering and pumping huge volumes of saline water must also be assessed [2]. The hydrogeology of potential pumping sites must be thoroughly investigated, as pumping seawater inland could contaminate freshwater [2]. Cultured organisms can be managed, fed, and harvested in raceway systems, but raceways produce effluents [2]. However, these can be treated with halophytic plants, which are suitable for the treatment of saline wastewater [35,66]. To treat wastewater with halophytic plants, a wetland system can be constructed where the plants act as biofilters [35,66]. Another option could be RAS, which can provide near-zero water exchange, but investment and operating costs are relatively higher [2]. Another advantage of recirculation systems is that they do not require seawater, so the marine organism farming facility does not need to be on or near the coast [2]. Ponds are probably the best option for establishing a marine aquaculture system, although there are several difficulties with their installation [2]. In addition, the split-pond system may be the optimal production system for near-shore facilities [2]. If the soil is barren, the bottom of ponds constructed near the coast often needs to be lined with a special material [2].

4. Technological Improvements—Energy Efficiency and Renewable Energy Resources

Developments in aquaculture technology over the last century have led to an intensification of pond production processes [3]. Although manure and chemical fertilizers were initially used to supplement natural feed, pond farms later switched to pelleted feed to provide more valuable nutrients to the fish [3].

Improving resource and energy efficiency in aquaculture operations has been identified as key to optimizing operations, although energy accounting has been relatively underrepresented in the scientific community [23]. The sources and intensity of energy used in aquaculture vary from system to system, ranging from renewable solar energy to nonrenewable fossil fuels [23].

4.1. Technological Solutions—Aeration

The amount of dissolved oxygen (DO) required is different for different aquatic organisms. To maintain viable conditions for fish, the DO concentration in the water must generally be 5 mg/L or more for warm-water fish, the same for a raceway or circular tank, and 6 mg/L or more for cold-water fish at their optimum temperature [67–69]. Sustained oxygen concentrations below 3 mg/L are potentially lethal, while oxygen concentrations of 0.5 mg/L are considered non-survivable for most aquatic organisms [67,70–72]. Aerators are devices that introduce oxygen into the water by mechanical circulation [5], increasing the amount of dissolved oxygen, which means better water quality and more nutrients [3,67]. This also means improved fish health, which is a critical factor in achieving economic sustainability [2]. Aeration also allows for much more efficient use of land and water at an agricultural level, supporting sustainable production practices compared to the level achievable in unaerated ponds [2].

In the past, fish farmers sometimes added more organic matter to ponds than the ponds could assimilate, resulting in low DO concentrations or other water quality problems [2]. It was not until fish farmers started using commercially produced feeds in the 1950s and 1960s that low DO concentrations became a common problem hindering the success of pond aquaculture [2]. In the early days, aeration equipment was primitive and often made from farm equipment available on the farm [16]. This later led to the invention of the tractor impeller-powered aerator [2]. The tractor-powered paddlewheel aerator consisted of a trailer with a truck differential and axles that supported the impeller [2]. The trailer was driven backward into the water, and the water was agitated by the impeller wheels, causing oxygen exchange [2]. Later, farmers began to use tractor-powered pumps mounted on a trailer and fitted with a hose to distribute the water into the air for aeration [16].

Initially, the tractor impeller-powered aerator was a good solution to provide DO to the fish during the warm season and prevent them from dying, but it was expensive and inefficient to use over long periods [16]. Therefore, aquaculture quickly moved to permanently installed electric aerators that could provide a constant supply of oxygen [16]. In later years, various types of floating electric aerators were invented, but most were not efficient enough [16]. Research at Auburn University, in close collaboration with several engineering firms interested in manufacturing fish farming equipment, led to the development of an efficient floating electric paddlewheel aerator [2,16].

The choice of the right aerator model for aquaculture farms today depends on several factors, such as the aquatic organisms to be cultured in the pond, the geometry of the pond, and the type of water treatment or water exchange, not least the cost of purchasing and installing the aerator, the cost of its operation and maintenance, and finally the energy consumption of the aerator [67]. More energy-efficient use of aerators reduces maintenance costs, saves energy, and reduces emissions [67]. Therefore, the criteria for selecting an aerator cannot be limited to the most efficient improvement in the DO concentration in the water [67].

Ponds are naturally aerated by atmospheric diffusion and plant photosynthesis, which contributes to a natural increase in DO [72]. Natural aeration alone is not sufficient to intensify cultivation in ponds and during warmer seasons; mechanical aerators must be used to increase DO concentrations [72]. According to Boyd et al. [16] and Roy et al. [72], in addition to natural aeration, there are three main aeration systems or types of aerators used in aquaculture: splash aerators, aerators that release air bubbles into water or bubbling aeration, and gravity aerators. The most common types of aeration systems are summarized in Table 1, and the main components, as well as the advantages and disadvantages of each type of aerator, are described. Technology is constantly evolving, and improvements are being made to existing types of aerators, as well as improved designs and solar-powered aerators. For example, the Solar Updraft Aeration (SUpA) system, which passively promotes DO destratification using solar heat [73]. As proposed by Mahmoud et al. [73], the SUpA is powered by a solar thermal collector that heats a metal pipe immersed in a pond, heating the lower layers of oxygen-poor water. This creates a natural convection current that drives the oxygen-poor cold water to the surface [73]. The supersaturated water sinks to the bottom, reducing oxygen losses and increasing total DO [73]. Existing types of aerators are being improved in terms of efficiency and functionality [67,74–76], as is the off-grid use of aerators with renewable energy sources, particularly solar energy [77–79].

Table 1. Types of aeration systems used in aquaculture ponds.

Mechanical Aeration Systems	Aerator Types	Basic Information about Aerator Type	Pros	Cons
Splash aeration	Vertical turbines/pumps	Basic configuration consists of an impeller connected to a shaft and a submersible motor [72]. Water is splashed into the air from the center of the float through an opening [72]. Photovoltaic panels can be used for power supply [72].	useful in aeration of hatcheries [72]	improved DO concentration in aerator proximity and near the surface [78]
Splash aeration	Pump-sprayer	Submerged propeller in a vertical tube attached to an electric motor suspended by floats. Propeller draws water into the vertical tube and pumps it upwards. Water is then discharged at high velocity, deflected radially through orifices, and falls back on the water surface in an umbrella-like pattern. [72,77,78].	very effective in aerating the bottom part of the pond [77] simple and do not require much maintenance [72,77]	increase the DO in a small area, but a large area cannot be aerated [72]; horizontal influence is very limited [72]
Splash aeration	Paddlewheel aerator	Surface aerators, can be divided into 2 broad groups: electrical floating and power takeoff driven [72]. Consists of a frame, motor, floats, coupling, speed reduction mechanism, bearing, and paddle wheel [72]. The most commonly used type of aerator for ponds larger than 0.5 ha [43].	the most effective surface aerators performance−wise [72] high standard oxygen transfer rate, suitable for use in emergency situations [72]; solar−powered aerators are a result of recent research [80]	high purchase and operating costs of a tractor impeller-powered aerator [16] sometimes powered by a diesel generator, which releases emissions and increases operating costs [80]

Table 1. *Cont.*

Mechanical Aeration Systems	Aerator Types	Basic Information about Aerator Type	Pros	Cons
	Spiral aerator	Aeration obtained by constant splashing of water into the atmosphere by the spiral rotation (tangential) of the impeller. Consists of an electric motor, a reduction gearbox or a reducer, handles, cups, connecting shaft, a base frame, movable joints, cover spines, and floats [72].	can be used in intensive and semi−intensive cultures [72]; solar−powered aerators are a result of recent research [80]	sometimes powered by a diesel generator, which releases emissions and increases operating costs [80]
Bubbling aeration	Diffused-air systems/diffused aerator	Releases air bubbles to affect aeration near the bottom or top of a water body using a blower or compressor to supply air to diffusers [72]. High oxygenation rates can be achieved if diffusers use pure oxygen [72].	energy-efficient and with lower operating costs compared to other aerators [72] can be used for sensitive cultured animals as it has no moving parts [72]	pipelines installed at the pond bottom hinder pond management [72]; high cost if pure oxygen is used [72]; not suitable for shallow ponds [74]
	Propeller-aspirator	Consists of a frame, air suction pipe, propeller, and a motor [72,81]. The pump draws in atmospheric air through a rotating hollow shaft connected to an electric motor at one end and a propeller at the other end submerged under water [15,81]. Propeller accelerates the water to create a pressure drop across the diffuser surface [15,81]. This forces air to pass through a diffuser in the hollow shaft and enter the water as fine bubbles [15,81].	used in small water bodies [72]; one of the most often used aerator type [74]; suitable for use in intensive aquacultures [74]	performance depends on the shaft submergence depth, positional angle, propeller design, and rotational speed [72]
	Submersible aerators	Consists of a hollow pipe above the water, a submersible pump attached to the propeller [72]. As the propeller rotates in the water, it sucks in air and mixes it with the water, which facilitates aeration [72].	efficiency depends on angular position and submergence depth of the propellers [72]	
Gravity aeration—Cascade aeration	Weir aerator	Aeration takes place above a dam by splashing, where gravity breaks up the water droplets, which then flow over various screens [72]. These water droplets are sucked under the dam in a current, creating a large inflow of air [72]. Used for general water treatment, fish hatcheries, and flowing water or in raceways [72].	no additional power supply needed [72]	feasible for small ponds [72]
	Circular stepped cascade	The system consists of a circular stepped cascade and a pump. The pump lifts the water to the top of the cascade and drops it over the steps of the aerator. This creates turbulence in the water, breaking the air-water interface and resulting in aeration [75]. Used to treat wastewater before or after filtration [72].	no pumping is required if natural elevation is available for gravity flow [72]; very economical [72]; most economical for ponds with less than 1000 m^3 capacity [76]	low efficiency, has to be combined with other aerator types [72]

It is particularly important to study the relationship between aeration and water velocity to manage DO and improve optimum growth conditions and other factors relevant to pond intensification [2]. A possible disadvantage of excessive use of aerators is that the water currents generated can lead to severe erosion of the pond bottom and, in particular, the inside of the embankments [5]. Meanwhile, water velocity that is too high or too low can hinder the growth and well-being of the fish to be cultured or cause additional stress [82,83]. Research to determine the conditions under which water circulators could be effectively combined with aeration practices should be given high priority [2], as different species of aquatic organisms require different water flow rates for optimal living conditions [2,82–84].

Automatic aerator control systems have been developed to activate and deactivate aerators in response to signals from a DO monitoring probe placed at a selected location in the pond [2]. Switching to automatic operation of aerators based on the DO concentration in the pond saves energy [43] and thus improves the sustainability of aquaculture.

Wiranto et al. [85] describe an automatic aerator control system using wireless sensors and an application as a monitoring tool for an aquaculture system measuring four water quality sensors (pH, temperature, conductivity, and DO). The measured data are transmitted via a wireless transmitter to a smart data logger and then a web server [85]. The study concluded that the smart data logger was able to activate the aeration system automatically to reduce the energy consumption of the aquaculture [85]. Several similar studies have been carried out to develop remote measurement, reading, and operation of aerators [86–88]. However, it has been pointed out that the monitoring programs still need to be improved to ensure the accurate and reliable operation of aeration control systems [2,86].

The knowledge required to contribute to sustainable production systems through the effective use of aerators is not yet fully established [2]. This includes the need for further research into the placement of aerators in ponds, as different aquaculture species require different minimum DO concentrations that can be maintained without reducing feed consumption and feed conversion efficiency and without increasing disease susceptibility to disease [2]. Research is strongly dominated by studies and trials carried out in Asian countries, while in the EU, technological developments in aquaculture—in this case, aeration—can be considered to be under-researched. For a sustainable intensification of the existing aquaculture in the EU, additional attention should be paid to necessary research and updating the development of knowledge-based aquaculture systems.

4.2. Energy from Renewable Sources

Aquaculture faces sustainability barriers due to its inability to transition away from fossil fuels as a primary energy source [2]. Ideally, aquaculture should reduce the use of fossil resources at all stages of production and replace them with bio-based and renewable resources [2]. Currently, fossil fuels are still used as the main energy source in aquaculture, although the use of renewable energy sources, especially solar energy, is increasing due to the advantages of low operating costs, long life-cycle, environmental friendliness, no CO_2 emissions and low soil pollution [79]. Solar energy applications in aquaculture continue to develop and include power generation, aeration systems, feed dispensers, pumps, and water-heating systems [79]. Tropical aquaculture ponds have the advantage of sunny weather and can use dynamic waste treatment powered by solar energy with a minimal environmental footprint and a nature-based approach [23]. On the other hand, countries without year-round sunshine are still lagging behind in introducing solar energy or other renewable resources into their energy mix.

Another reason for integrating energy production and aquaculture is the increased use of water surface, which allows land to be used for other purposes, such as agriculture [79,89]. Aquaculture systems combined with solar PV technologies are referred to as floatovoltaics (FV) [79,89], while other sources refer to them as aquavoltaics or AquaPV [90]. FV systems consist of the same photovoltaic panels as land-based PV systems, but the panels float in the water, usually attached to floats or moored to land [79]. The advantage of such systems is that installation is not limited by the body of water, and they can be installed in different bodies of water, inland as well as on the sea or ocean [79,89]. More importantly, aquaculture can be developed in combination with FV in sparsely populated areas with no or poor grid access [89]. In addition, PV installed on the water surface also has a direct practical benefit, reducing water loss through evaporation by up to 70–85% [89,90] and can reduce algal growth rates [90,91].

Badiola et al. [92] suggest that geothermal energy can be used to produce both electricity and hot water, as well as waste heat from other industries. The use of waste heat in aquaculture is not new, and the scientific literature dates back to the 1970s [93–95], although it has become relevant again due to climate change and the high cost of energy sources [96,97]. According to Lund and Toth [98], the use of geothermal energy in aquaculture has actually increased over the years, with an installed capacity of 950 MW in 2020. Leading countries using geothermal energy in aquaculture systems are China, the United States, Iceland, Italy and Israel [98]. Instead of geothermal energy, solar collectors and heat pumps can also be used to keep the water at the right temperature for the aquatic organisms being cultured [92,97].

4.3. High Technologies and Aquaculture

The Internet of Things (IoT) and artificial intelligence (AI) are expected to become more widespread in the future and are the way forward for sustainability [23,76,99]. Modern technologies have the potential to be used to collect and analyze data, communicate with process supervisors, and even make decisions [23,76]. This is because AI systems are now so advanced that they can predict the exact amount and timing of feeding based on fish movements, growth rates, and other technical data [23]. Sensor-based AI systems can predict potential water quality deteriorations and disease outbreaks [23]. High technologies in aquaculture have been and are being developed in the following main categories: water quality, nutrition, water recirculation, transport and traceability, and welfare [100].

Technological advances are also increasing, with the development of new hatchery technologies, automated feeding, sensors to monitor water quality, and CCTV cameras to monitor feeding [101]. The latest technologies help automate processes and enable the regular, comprehensive, and reliable collection, storage, and analysis of data on water quality, cultured fish, energy, and feed consumption [76]. Innovative sensors can accurately measure variables such as dissolved oxygen, temperature, pH, ammonia, turbidity, and water level [100]. AI can be combined with solar PV to provide power for aquaculture, e.g., to monitor feeding, growth, and health status [101]. Some commercial aquaculture operations use drones to monitor fish health and growth, helping to determine optimal feeding tactics and reduce feed waste [23]. Drones also facilitate regular water quality monitoring and record real-time data for decision-making [23].

Automation of various processes and information technology (IT) have been slow to take off in aquaculture because most aquaculture owners, especially in developing countries, are reluctant to invest large sums of money in new technology for fear of not recovering their investment if the technology fails [23,99,101]. At the same time, further research is needed to improve the quality of sensors and minimize their cost to make them more affordable for smaller aquaculture operations [100,102].

The high-tech solutions mentioned above are just some of those available to today's aquaculture farms. Other more specific solutions can modernize, optimize, and make aquaculture more sustainable, such as cloud computing, machine learning, Big Data, virtual reality, robotics, cyber-physical systems, etc. [103]. In addition to high-tech advances, research is also addressing challenges such as the development of genomic platforms to accelerate genetic improvement, molecular methods to identify genes for resistance to iridoviruses and other diseases [101], selective breeding [104], sustainable fish feeds [105] and many other advances.

5. Towards Best Management Practices

The development of the aquaculture industry in the 1970s could be described as a "technological regime with a poor degree of control and labor-intensive production processes" [19], whereas the aquaculture industry today can be described as "biological manufacturing" [19,106]. Sustainability is a growing concern that is driving innovative best management practices (BMP) for the benefit of the environment, economy, and society [23]. In aquaculture, BMP means that aquatic organisms are farmed according to standards set by various governmental and non-governmental organizations with the aim of reducing the environmental impact, reducing harm to local communities, and controlling and improving animal welfare [5]. There have been improvements in the use of renewable energy sources and the primary production of alternative feed sources—wastes and by-products of human activities such as insects, algae, molds, fungi, bacteria, etc. [2].

The Strategic Guidelines, adopted by the European Commission, provide a vision for the future and encourage the use of BMP for sustainable development at the national level [12]. One of the directions is to build resilience and competitiveness, which includes the need to coordinate spatial planning for both freshwater and land-based aquaculture systems based on several criteria, such as the impact on the local ecosystem, the carrying capacity of the area, water quality indicators, etc. [12]. At the same time, licensing procedures should be facilitated by providing legislation and administrative guidance for aquaculture activities, if possible, through the establishment of a one-stop shop in the public administration [12]. There should be a focus on animal health and public health research to improve breeding and husbandry conditions, reduce the use of various types of pharmaceuticals, and improve disease control, data collection, and monitoring [12], adaptation to and mitigating climate change, and participating in the green transition in line with the objectives of the Green Deal [12]. Promoting social acceptance and recognition of the benefits and value of aquaculture activities and EU aquaculture products [12]. One of the ways to achieve greater public support for aquaculture products is to integrate aquaculture systems into local communities, increase knowledge of sustainable practices and products, and promote innovation [12].

One way to incentivize BMPs is through appropriate national policies. Afewerki et al. [19] describe the case of Norway, where development licenses were introduced as one of the innovation policy instruments to promote further sustainable development of the aquaculture industry, including pollution control and reduction [107]. The introduced licensing scheme was designed to actively encourage aquaculture enterprises to participate in the development of new knowledge and/or to use existing knowledge from research or practical experience to develop new sustainable aquaculture production technologies [19]. According to Afewerki et al. [19], there are several aquaculture licensing schemes in Norway, with each license having its own objective, such as limiting the amount of fish to be farmed, the location, the technological solution to be applied or, like the development license mentioned above, the development of technologies that can address important challenges for the sustainability of the industry.

The environmental, animal welfare, and social standards of aquatic food products are increasingly important considerations for producers, buyers, and sellers [6]. Sustainable aquaculture certification schemes (also eco-certification schemes) incorporate the concept of sustainability by requiring aquaculture producers to comply with a set of pre-defined indicators, which are then measured and monitored, thus providing a method to influence the adaptation of BMPs and sustainable practices [6,108,109]. International certification schemes put sustainability into practice, provide clear sustainability roadmaps, and encourage the adoption of BMPs [108]. They also allow producers to communicate their standards and values to stakeholders and consumers [108]. The solution would, therefore, be to encourage aquaculture companies to certify their activities and thus take the initiative to move towards sustainability and safe production for consumers [109]. Sustainability certification should preferably be combined with the principles of the ecosystem approach to aquaculture (more on this in Section 5.2) in order to improve social and environmental sustainability at different levels [109]. The role of certification in promoting sustainable aquaculture could also be strengthened by involving local communities (social sustainability) in the certification process and using criteria that promote continuous improvement of the business [109].

Information and communication technology (ICT) is one of the easiest ways to improve BMPs in small-scale pond farms [110]. Ntiri et al. [110] describe a case study conducted in Ghana where fish farmers using ICT were found to harvest 0.5 kg more fish per square meter than those not using ICT. The biggest contributors to the adoption of BMPs and increased productivity were mobile phone users (SMS and WhatsApp, the free messaging application owned by Meta (formerly Facebook)) and TV [110]. Therefore, for the development of small and less intensive aquaculture farms and the wider use of BMPs, educational materials on disease control, feed, markets, etc., can also be developed and disseminated using ICT technologies [110].

In addition to the development of BMPs, proteomics (the study of all the proteins present in a cell, tissue, or whole organism to identify and quantify their structure and function) could improve disease diagnosis and targeted drug delivery and reveal potential protein biomarkers of stress, reproduction, disease or the immune system, in the aquaculture industry, according to Jaiswal et al. [111].

5.1. Traceability and Transparency

As consumers become more affluent, there is growing concern about ethical issues related to the welfare of those involved in the production and distribution of aquatic food, the environmental sustainability of production systems, the use of genetically modified feed or fish, and animal welfare [6]. Safe food and food supplies ensure nutritional value while minimizing risks to consumer health [6,108]. Traceability of products in supply chains is therefore essential to ensure that contaminated products or products at high risk of contamination, including substandard products, are not passed off as products without such risks [6,112]. Meat from farmed fish can be contaminated during production with a variety of chemicals, including authorized veterinary pharmaceuticals, disinfectants, other biocidal chemicals used for disease control, feed additives, contaminated feed ingredients, and antifouling agents used on farms (e.g., copper oxide) [6,112]. Even though the EU strictly regulates and controls food growing conditions to prevent the presence of various harmful substances and contaminants in food, unscrupulous producers continue to find ways to circumvent the system. It is, therefore, very important to know "where" (traceability) and "how" (transparency) food has been produced and to be able to trust the information provided by the farmer or producer [2,112]. Traceability and transparency are essential to demonstrate accountability and the pursuit of sustainability [2,108]. Therefore, the aquaculture industry should adopt radical transparency and traceability as the absolute standard [2]. Radical transparency means owning both your sustainably farmed product and its environmental impact while encouraging others to help find solutions to improve the sustainability credentials of your products [2]. Thus, one of the future challenges for sustainable aquaculture is the implementation of transparency and traceability as well as corporate social responsibility through open dialogue with relevant stakeholders [2,113].

At the same time, significant quantities of fish and other aquatic organisms are imported into the EU from other countries [114], some of which have been criticized for lack of transparency and traceability in their operational systems [112]. One example is the Global Aquaculture Alliance, which owns and manages the certification of best aquaculture practices [2]. In addition to certifying aquaculture companies, it also certifies its own board members [2]. At the same time, consumers are not sufficiently informed about human rights violations in Asia, the environmental damage caused by the West African fishing industry, "the salmon wars" in Norway, and the apparent lack of traceability of many seafood products [2,113]. Even in relatively well-regulated supply chains, food fraud in aquaculture is a common phenomenon [6,112]. The visual similarity of white muscle from different fish species makes fraud possible, and there are many processed fish products whose appearance or taste is altered by the addition of other ingredients [6]. In the near future, food fraud could be prevented, and traceability and transparency could be improved through blockchains, as this technology can record different transactions such as values, different complementary information, or digital events without the possibility of deleting them [115]. Currently, the lack of knowledge about blockchains and the resulting lack of trust in them is an obstacle to their wider use [115]. This could be changed by further research into how aquaculture companies and farmers perceive blockchain technologies and how they implement them in practice [115].

In the future, it would be important to ensure that the aquaculture industry drives the idea of sustainability rather than expecting consumers to regulate it through their demand [112]. Through national government and regulatory frameworks, it is possible to give the industry an additional push towards more sustainable farming and production practices [112].

5.2. Ecosystem Approach to Aquaculture

As defined by the Food and Agriculture Organization of the United Nations (FAO), the ecosystem approach to aquaculture (EAA) is "a strategy for the integration of the activity within the wider ecosystem such that promotes sustainable development for both present and future generations, equity and resilience of interlinked social-ecological systems" [116,117]. The EAA and the technical guidelines for its implementation have been developed in particular to support Articles 9 and 10 of the FAO Code of Conduct for Responsible Fisheries [117]. There is a strong link between science, policy, and governance, as well as the integration of the concept into national development policies, strategies, and plans for EAA implementation [11,117]. The main objective of the EAA guidelines [117] is to assist countries, institutions, and policymakers in developing and implementing sustainability in the aquaculture sector, the integration of aquaculture with other sectors, and its contribution to social and economic development [7].

In principle, EAA is not a new concept, as aquatic organisms have been farmed on a small scale in inland aquaculture in the past, especially in Asian countries [118]. Aquaculture of carp and other freshwater fish has typically used poultry or other organic waste as a feed source [118]. However, in modern times, it is difficult to implement EAA when intensive and industrial farms are operated in this way [118]. In addition, the regulatory framework in many countries prohibits or discourages the circulation of resources and by-products or residues of bioresources that would allow aquaculture to operate under the EAA [118]. In addition, the ecosystem approach requires that community development planning include physical, ecological, social, and economic systems, as well as other stakeholders, thus addressing all three dimensions of aquaculture sustainability in a social, economic, and environmental context [118]. Figure 3, based on the table created and described by Soto et al. [118], shows the three main principles on which the EAA is based, the degree of its impact, and the main problem areas that need to be addressed for the further development and sustainability of the EAA. Another obstacle to the development of economically sustainable aquaculture is currently the lack of a sufficiently efficient calculation of environmental services [3]. Aquaculture systems are mainly evaluated in terms of financial benefits to farms and businesses but not in terms of socio-economic benefits to society, which could be completely transformed by the introduction of the EAA [3].

A significant shift towards more environmentally sustainable aquaculture could be achieved by implementing policies that require companies to externalize the costs of environmental services in a realistic way, i.e., a properly functioning polluter pays principle [3]. The EAA can overcome the identified barriers by implementing a precautionary approach and adaptive management [118,119]. This approach is crucial for managing ecosystem changes that are slow to reverse, difficult to control, and poorly understood [118]. Adaptive management is the best approach, and interdisciplinary research is essential for long-term success [118].

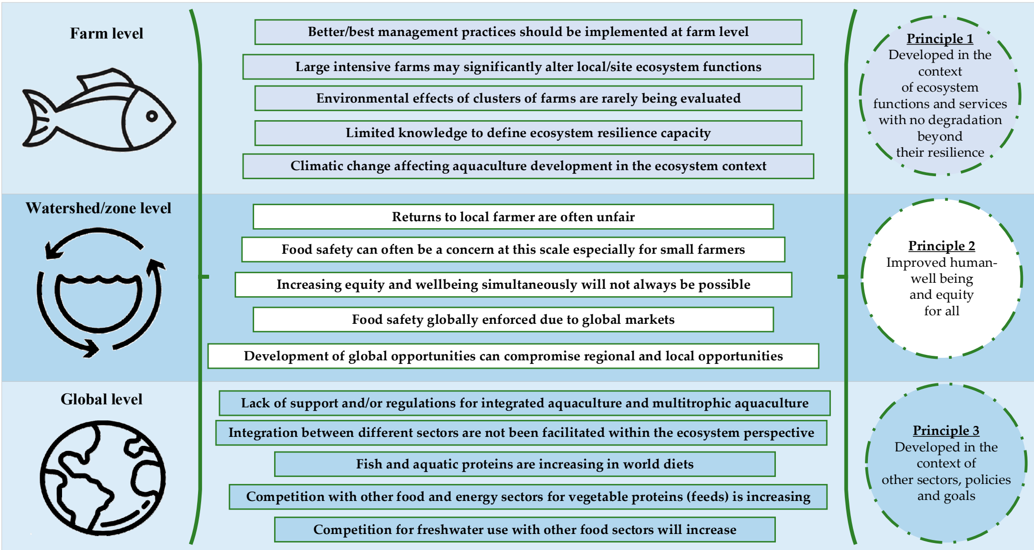

Figure 3. EAA development—scales (on the left), key issues across all three levels and principles (center), and three guiding principles (on the right) (adapted from Soto et al. [118]).

Simulation models can be used to support decision-making tools at different scales, and research on ecosystem service valuation is critical for effective planning and mitigation [118]. Integration of aquaculture, including integrated multitrophic aquaculture (IMTA), is essential to increase productivity and reduce risks associated with by-products [118].

Proactive management agencies should ensure effective training of all staff involved in EAA implementation [118]. Policymakers should ensure that farmers, workers, and other stakeholders are adequately involved in policy decisions and regulations [118]. Incentives should be participatory, timely, and transparent, involve other stakeholders and sectors, and should focus on watershed certification, eco-labeling, eco-certification, and promoting integration and awareness of the ecosystem approach [118,119]. Education and training should be targeted at the farm level and focus on management-oriented knowledge and collective values [118]. At the same time, global consumer and public education are crucial to promoting sector integration [118].

According to Brugere et al. [120], on the relevance of the EAA topic in the scientific literature, the concept has had the greatest impact on spatial planning for aquaculture, including site selection and ecosystem carrying capacity at both the watershed and farm levels. Although EAA has also led to significant advances in land use and spatial planning in practice [11], it has not been used by decision-makers and planners to understand and resolve the more complex institutional issues that also influence aquaculture development [120].

6. Discussion

At this stage, none of the options described above is universally applicable to meet the growing global demand for food from aquatic organisms. In the future, this could be achieved mainly through the combination and improvement of different technological solutions, better management practices, and better siting of aquaculture farms so that they do not exceed the carrying capacity of ecosystems. Henares et al. [5] discuss that the potential sustainability of an aquaculture enterprise could be improved by the choice of aquatic species and location, as well as production and management practices before production begins. Such a practice would be in line with Edwards [3], who argues that the future belongs to the EAA, which promotes ecologically and socially responsible development and operation of aquaculture systems. However, there are still several challenges that need to be overcome if the EAA is to become the future of sustainable aquaculture governance. One of these is balancing the different levels of impact (farm, watershed, global) to minimize the impact at each level. Solutions could include eco-certification schemes that, under the guidance of qualified auditors, can assess the impact of aquaculture on ecosystems at the farm or organizational level over a period of time.

Roy et al. [72] note that farmers often empirically use aeration systems without considering suitability, efficiency, and management costs, which can lead to high management costs and prevent maximum efficiency. In addition, energy efficiency measures should be promoted in aquaculture businesses, especially in RAS, to help business representatives identify weaknesses and improve electricity and heating consumption behavior. Energy efficiency measures have helped to address the energy consumption patterns of several other energy-intensive industries [121–123].

Aquatic organisms cultured in ponds or recirculation systems integrated into a farming operation can be compared to the same principles used by IMTA. Integrated farming models maximize the use of infrastructure, labor, and natural resources in a circular and resource-efficient manner, therefore increasing the environmental and economic sustainability of aquaculture. Das et al. [23] argue that circular aquaculture can improve fish productivity, provide livelihoods and food, reduce environmental impacts, and make aquaculture cost-effective. Circular aquaculture practices can help address climate change, resource scarcity, environmental challenges, and high cost of living [34].

For sustainable land-based aquaculture under changing conditions, research on scientific and management aspects of the bio-economy needs to be more collaborative and involve stakeholders. Technology transfer from universities and research institutes to aquaculture companies is inefficient [5]. More attention should be paid to practical research on technical improvement of aquaculture systems, as some of the most significant research dates back to the 1970s to 1990s [15,56,93,95,124], but since then, there has been a huge leap in technology development, especially in the field of IOT. The scientific field is also dominated by some scientific heavyweights, notably Boyd of Auburn University, USA, who, according to the authors, has made an invaluable contribution to the technological development of aquaculture.

To overcome the identified barriers and challenges, the literature mentions solutions such as better cooperation between universities, research institutes, and aquaculture companies to improve knowledge transfer. A quick look at the education opportunities for aquaculture or aquaculture engineering in Europe does not seem to offer much—training in this area is available in Norway, Denmark, Spain, and the Netherlands. Consequently, the authors are of the opinion that aquaculture education needs to be expanded and promoted at the same time to contribute to the growth of the sustainable aquaculture sector as a whole.

Edwards [3] argues that future contributions to the global fish supply from aquaculture technologies such as RAS, aquaponics, and IMTA are doubtful. This is because of the technological improvements required, which make the end product less competitive due to high production costs. This is in line with Henares et al. [5], who argue that more research is needed to develop and improve aquaculture systems and that it is then quite possible that these systems will prove competitive in the future. If the necessary leap forward in aquaculture technology is achieved, it is possible to talk about forward-looking options for developing aquaculture in line with trends in food production, which are increasingly taking place in cities, by growing aquatic organisms on the rooftops of supermarkets and in urban industrial facilities, where the future circular economy is represented by advanced technologies that combine aquaponics, RAS, industrial waste heat and renewable energy sources [34].

7. Conclusions

A potential obstacle to the development of aquaculture in the EU is probably the lack of relevance of the sector so far, as well as the changing seasons and cold winters, which make it impossible to farm aquatic organisms in open systems and ponds all year round. RAS, on the other hand, are often complex and energy-intensive. The EU's long coastline and access to the seas and oceans have probably also played an important role in the lack of development of fisheries in the past. In the future, there is an urgent need for more in-depth case studies of land-based aquaculture enterprises in Europe to determine the current state of knowledge on available technical solutions and the interest and need for technical solutions. To keep pace with the global leap in aquaculture production, the EU should emphasize the need for practical research to improve the energy and resource efficiency and utilization of renewable resources of the technologies used in aquaculture.

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