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Review

The Development of Sustainable Saltwater-Based Food Production Systems: A Review of Established and Novel Concepts

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Abstract: The demand for seafood products on the global market is rising, particularly in Asia, as affluence and appreciation of the health benefits of seafood increase. This is coupled with a capture fishery that, at best, is set for stagnation and, at worst, significant collapse. Global aquaculture is the fastest growing sector of the food industry and currently accounts for approximately 45.6% of the world's fish consumption. However, the rapid development of extensive and semi-extensive systems, particularly intensive marine-fed aquaculture, has resulted in worldwide concern about the potential environmental, economic, and social impacts of such systems. In recent years, there has been a significant amount of research conducted on the development of sustainable saltwater-based food production systems through mechanical (e.g., recirculatory aquaculture (RAS) systems) methods and ecosystem-based approaches (e.g., integrated multi-trophic aquaculture (IMTA)). This review article will examine the potential negative impacts of monocultural saltwater aquaculture operations and review established (RAS) and novel (IMTA; constructed wetlands; saltwater aquaponics) saltwater-based food production systems and discuss their (potential) contribution to the development of sustainable and environmentally-friendly systems.

Keywords: aquaculture; constructed wetlands (CWs); recirculating aquaculture systems (RAS); integrated multi-trophic aquaculture (IMTA); hydroponics; saltwater aquaponics

1. Introduction

The human population is rising at a dramatic rate, doubling from 3 billion in the early 1960s to 6.5 billion in 2008, and currently standing at approximately 7.34 billion. It is expected to reach 9.7 billion by 2050 [1–3]. Global demand for fish (i.e., finfish, crustaceans, molluscs, and other aquatic animals) has increased significantly in recent decades, per capita consumption increasing from 9.9 kg in 1960 to 19.7 kg in 2013 [2,3]. Fish are considered an important source of essential micronutrients (i.e., vitamins and minerals), proteins, and polyunsaturated omega-3 fatty acids and has been shown to have positive effects in relation to heart disease, stroke, high blood pressure, muscular degeneration, some cancers, inflammatory disease to name but a few [4,5]. Over 3 billion people worldwide now obtain approximately 17%–20% of their animal protein (6.5% of total protein) from fish [6].

Capture fisheries have grown from a production of c.20 million metric tons (Mt) in the early 1950s to c.90 million Mt (70 million Mt for food use) in the late 1980s, providing the vast majority of global fish supplies during this period (e.g., 91% in 1980). Capture fisheries' production levels have remained stable since the late 1980s. In contrast, aquaculture has seen an annual worldwide production growth rate of 6.3%–7.8% between 1990 and 2010 and is now the fastest growing food production sector [3,4,6,7]. This rapid expansion of the aquaculture industry resulted from: wild fisheries reaching or exceeding their sustainable limit; a high level of global investment; a lack of fishery policies that promote efficiency; improvements in aquaculture technology and management; and innovative techniques/technologies (e.g., RAS) [6,8,9]. It was estimated that, in 2011, 61.3% of marine fish stocks were fully exploited, 28.8% were overexploited, and only 9.9% were underexploited. Also, 13 of the world's 15 major oceanic fishing areas are now fished at or beyond capacity [4,8].

In 2014, a landmark was reached when, for the first time, the contribution to the global supply of fish for human consumption from aquaculture (c.74 million Mt) if the space between c. and number necessary exceeded that from capture fisheries (c.70 million Mt). This is in stark contrast to 1950, when only 1 million Mt of finfish, crustaceans, and molluscs were cultivated from aquaculture [2,3]. The majority of aquaculture today (by tonnage) takes place in freshwater (c.60%), with the remaining taking place in seawater (c.32.3%) and brackish water (c.7.75%). Most aquaculture operations take place in the Asia-Pacific region (88%–89% of volume), with the vast majority occurring in China (60%–62% by volume & 51% by global value) [2,4,6]. Aquaculture production is composed mainly of freshwater finfish (c.55%) and marine/brackish molluscs (c.25%), finfish (c.10%), and crustaceans (9.5%) [2,10]. However, saltwater aquaculture will most likely increase over the coming decades, as global supplies of freshwater continues to decrease [3]. In this article, saltwater aquaculture refers to offshore and on-land (e.g., coastal) marine aquaculture and on-land aquaculture which utilizes non-coastal saline water (e.g., groundwater and artificial saltwater).

As the human population continues to expand and the capture fisheries industry stagnates, the reliance on farmed fish as a fundamental source of protein will also increase. Aquaculture has a number of potential positive impacts such as: reducing the pressure on wild stocks; rebuilding depleted wild stocks through stock enhancement; bioremediation and wastewater treatment (e.g., in RAS); providing a vital source of affordable fish-based protein and income; and in some locations effluent discharge can sometimes increase local abundance and diversity of species [2,7,11–16]. However, there are also potential negative environmental, social, economic, and health concerns resulting from aquaculture (predominantly monoculture operations). Some of the main concerns include: environmentally damaging levels of effluent discharge; water consumption; farmed fish escapes; transmission of parasites and disease; presence of contaminants; reliance on wild fish for fishmeal & oil addition to aquaculture feed; and negative employment and income effects [2,4,6–8,17–19]. To ensure the sustainable development of the aquaculture industry it is of paramount importance to develop technologies and production systems that mitigate these impacts.

This paper will examine the potential negative impacts of monocultural saltwater aquaculture operations and review established (i.e., recirculating aquaculture systems (RAS)) and novel (i.e., Integrated Multi-trophic aquaculture (IMTA); constructed wetlands; saltwater aquaponics) saltwater-based food production systems and discuss their contribution (or potential contribution) to the development of sustainable and environmentally-friendly systems.

2. Potential Negative Aquacultural Impacts

Although aquaculture has become one of the most promising avenues for increasing fish production against a backdrop of continued human pressure on marine fisheries and ocean resources, extensive research has identified a number of potential ecological, social, and health impacts resulting from the aquaculture industry. The main impacts identified in the literature are discussed in this section.

2.1. Effluent Discharge and Contaminants

The discharge of effluent from aquaculture to the aquatic environment falls under three main categories: (1) continuous from aquaculture production; (2) periodic from farm activities; and (3) periodic discharges of chemicals [4,20]. Discharged aquacultural effluent contains metabolic waste products such as feces, pseudofeces, excreta, and uneaten feed, major contributors to organic and nutrient loading in the vicinities of aquaculture farms [4,21,22]. The scale of uneaten feed is dependent upon: farm operator's personal experience and qualifications; feeding management (automated or manual); and feed ingredients [4,22]. It is estimated that 52%–95% of the nitrogen and 85% of the phosphorus input to marine aquaculture systems through feed may be lost to the environment through fish excretion, feces production, and feed wastage. The resulting organic enrichment causes environmental damage to receiving water bodies and sediments [23,24].

Chemical inputs to aquaculture, such as prescribed compounds (e.g., pesticides and pharmaceuticals), antifoulants, anaesthetics, and disinfectants, are an environmental concern when released in effluent water. The use of antibiotics is of particular concern as it may affect non-target species resulting in antibiotic resistance and other toxic effects. The prophylactic use of therapeutants is also a great concern due to their persistency in the environment [18,20,25]. It has been shown that levels of copper and zinc are significantly elevated close to aquaculture sites, in particular, areas where intensive cage aquaculture takes place. Antifoulant paints applied to cages and nets to prevent the attachment of epibiota often contain copper. Unfortunately, copper has low solubility in water and accumulates in sediments. Studies have shown that high concentrations of copper can inhibit the reproduction of some phytoplankton species, subsequently impacting species diversity and can have a negative impact on their diversity. Algae, crustaceans, and molluscs are also very sensitive to copper [4,25–28]. Zinc, like copper, binds to fine particles and sulphides in sediments. It is used as an additive to aquafeed, sometimes in excess of the species' dietary requirement. Fortunately, a number of feeds use zinc methionine, which is a more available source of zinc, resulting in a feed with extremely low levels of required zinc. Elevated levels of zinc have been shown to cause lethal and sublethal responses in invertebrates. Marine algae are also very sensitive to zinc [4,25,29]. Several natural and man-made contaminants are found in higher concentrations in farmed than wild fish. Such contaminants include polyaromatic hydrocarbons (PAH), dioxin, organophosphates (OP), polybrominated diphenyl ethers (PBDE), and polychlorinated biphenyl (PCB). Antibiotic contamination was only found to occur in farmed fish. Exposure to these contaminants can have a number of associated risks such as antibiotic resistance, memory impairment, cancer, and neurocognitive, endocrine, hormonal, immune, and cardiovascular abnormalities [18,30–40]. Although mercury contamination levels were found to be no higher in farmed fish than in wild fish, the interactive toxic effects of mercury with co-existing man-made contaminants are unknown. Mercury contamination of fish has been linked to neurocognitive abnormalities in populations with a high level of fish consumption and to the occurrence of Minamata disease [30,41–43].

Sources of these contaminates include fish feed and the inappropriate location of aquaculture farms in areas of high naturally occurring contaminants [18,30,31,35,37]. A number of approaches can be taken to reduce the potential for contamination of farmed fish meat. Firstly, locating farms in areas with low levels of naturally occurring contaminants [18]. Secondly, dioxins and PCD-like contaminants should be removed from fish feed through partitioning and decontamination processes [44]. Alternatively, a contamination-free feed (potentially of a higher cost than standard feeds) could be used towards the end of the culturing cycle prior to harvesting, allowing for the natural clearance of toxic chemicals [45]. Thirdly, advisory bodies can recommend fish consumption limits, especially for susceptible people (e.g., pregnant women) [18,46].

The most commonly practiced waste management solution for cage aquaculture is "dilution is the solution" and untreated effluent is released to the surrounding waters. In locations that have little flushing by tides and currents, this type of philosophy is problematic as cage aquaculture effluent can have an enormous impact on the ocean floor extending from 100 to 500 feet in diameter. However, for areas that are well flushed, water quality problems and benthic impacts should be minimal. In closed systems (e.g., onshore RAS), waste management technology is utilized to minimize harmful effluent discharge into surrounding waters [8,21,47,48].

2.2. Water Consumption

One of the most common solutions for excess nitrogen removal from on-land aquaculture farms is the frequent exchange and replacement of water, however, this method has a number of restrictions. Many nations have governmental regulations that limit the release of nutrient-rich water to the environment and there is an enormous cost associated with the pumping of large volumes of water [4,49]. Depending upon local conditions, grow-out stage, and feeding cycle, the daily water exchange rate of pond aquaculture systems, for example, can range from 3% to 30% of the pond's volume [50,51]. A reduction in effluent volume would considerably decrease the volume of water that would need to be exchanged or replaced while also limiting the potential polluting impacts of on-land aquaculture [4,52].

2.3. Farmed Fish Escapes

Accidental release of farmed fish into natural waters can lead to a number of ecological risks, including: increased competition for space, prey, and/or mates; pathogen, disease, and parasite transmission; interbreeding between farmed and wild fish resulting in reduced fitness of wild cousins or wild stock enhancement resulting in genetically distinct fish from their wild cousins; habitat damage; and water quality alterations [4,7,8,53–59]. Many of the general features of successful invasive species (i.e., rapid growth, early sexual maturity, high genetic variability, broad environmental range, and a short generation time) are also common features of aquaculture species [4,7]. The escape of farmed salmon through sporadic and mass events is well recorded [39,60–63]. In the early 1990s, a study conducted by Hansen et al. (1993) found that up to 40% of Atlantic salmon caught by fishermen in oceanic waters north of the Faroe Islands were of farmed origin [61]. Since the 1980s, over 255,000 farmed Atlantic salmon have escaped and been caught by fishermen from Washington to Alaska [62]. Various studies have provided evidence that farmed Atlantic salmon (*Salmo salar*) escapees may hybridize and alter the genetic composition of wild populations, potentially exacerbating the decline of local endangered populations of wild Atlantic salmon [56,63,64]. Naylor et al. (2005) showed that farmed Atlantic salmon introduced to their native range are more likely to hybridize with local populations than, for example, farmed Atlantic salmon escaping into non-native regions (e.g., the Pacific) [60].

2.4. Parasite and Disease Transmission

There are a number of diseases and parasites that have the capability to spread between farmed and wild fish and their transmission can occur when infected farmed fish come in contact with wild host species (e.g., infected farmed escapees) or when wild fish migrate or move through plumes of an infected cage or disease outbreak [8,60]. In a lot of cases, pathogens originate from wild populations, but reach epidemic proportions in intensive cage aquaculture operations, risking further, more intensified infection of wild stocks [8]. A number of studies have provided modelled and empirical evidence indicating that sea lice do transmit from farmed to wild salmon and this transmission causes massive mortalities or collapse of infected wild stock [65–67]. The movement of aquaculture stock can increase the risk spreading pathogens to wild species. For example, in Europe, serious epidemics of *Gyrodactylus salaris* in wild Atlantic salmon stocks have been linked to the movement of fish for aquaculture and re-stocking [17,68]. Studies have also indicated that the movement of aquafeed around the world can be a vector for disease transmission [8,69].

2.5. Fishmeal and Oil

Most carnivorous, diadromous fish and marine finfish farm operations require an input of wild fish (i.e., live pelagic fish or low value "trash fish") or feed containing components of wild fish origin (i.e., fishmeal or fish oil) [8,70]. The proportion of farmed aquatic species raised on supplementary feed inputs continues to rise, reaching almost 70% of total aquaculture production in 2012. Mollusc species (e.g., mussels and oysters) account for approximately 23% of global farmed seafood production and do not need to be fed, instead taking their nutrition from the surrounding environment (e.g., plankton & detritus), resources that are otherwise not directly exploitable by humans [6,71]. The efficiency in which the farmed fish utilize the feed (known as feed conversion ratio (FCR)) the quantities of fishmeal and fish oil contained in the feed, and the amount of wild fish used to produce the feed, are important factors determining the economic profitability and environmental impacts of aquaculture [2,8,17,19,72–75]. For example, fishmeal and fish oil generally constitute 50%–75% by weight of carnivorous marine farmed finfish aquafeeds. For salmon, feeds typically contain 35%–40% fishmeal and 25% fish oil, however, some diets containing less than 20% fish oil exist [8,70,76].

Overall, the aquaculture industry has made significant strides in feed efficiency and feed inputs over recent decades. The ratio of wild fish input to farmed fish have fallen to 0.63 for aquaculture overall. However, it is important to note that this figure remains as high as 5.0 for Atlantic salmon. Improvements in FCR ratios and reductions in fishmeal and fish oil inclusion rates in aquaculture feeds have also been made [2,19,74,77]. Despite these improvements, the continued growth of feed-reliant aquaculture has resulted, within the last decade, in the doubling of aquaculture's share of global fishmeal and fish oil consumption to 68% and 88%, respectively [19,77]. An estimated 20–30 million Mt of reduction fish are fished from the oceans each year to produce fishmeal and fish oil. These fish tend to be low on the marine food chain and include small pelagic fish species such as Peruvian and Japanese anchovy, blue whiting, Atlantic herring, and chub and Chilean jack mackerel. Additionally, an estimated 5–9 million Mt of "trash fish" and other small pelagic fish are used in non-pelleted, farm-made feeds [2,78,79]. Most forage fish are either fully exploited, overexploited, or in the process of recovery from overexploitation. These forage fish play an essential role in converting plankton into food for higher trophic level species such as: humans, larger fish, marine mammals, and seabirds [2,19,80]. A number of alternatives to fishmeal and fish oil from forage fish are possible and are currently being researched, including: terrestrial plant alternatives; vegetable proteins and oils; terrestrial animal byproducts (e.g., rendered animal products); fish/seafood processing waste; new genetic and metabolic engineering techniques to produce long-chain omega 3 fatty acids; development of single-cell organisms; microbial (e.g., bacterial) and algal proteins; oils produced by industrial fermentation technology; and the use of (lower trophic level organisms) less-common feed inputs such as krill, polychaetes, insects, and macroalgae [2,6,17,19,81].

2.6. Social Welfare

Aquaculture can generate a large amount of employment for communities. In some coastal regions of Scotland and Norway, for example, the salmon farming industry is the largest private-sector employer. Also, in Maine, where communities once relied on now-collapsed wild fisheries, the benefits from employment in the salmon aquaculture industry have been significant [8].

However, in a broader context, experiences from the growth of the salmon farming industry has shown us that the employment and income losses in the fish capture industry may be as large, or larger, than the employment and income generated for coastal communities through aquaculture [21,60,82]. There is also no guarantee that those fishermen who have lost their jobs due to overfishing and/or as a direct or indirect result of aquaculture growth will find employment in the aquaculture industry or that local communities will benefit from this growth. In Canada, most of the employment gains resulting from the aquaculture industry were limited to areas where hatcheries and processing facilities are located [21]. Grow-out operations can often lack community roots, depending upon a supply of feed, larvae, supplies, equipment, and a skilled workforce from areas distant from the production site. This type of situation rarely has a noteworthy income multiplier effect for local communities [83,84]. Finally, if large multinational companies control a vast majority of the aquaculture industry, as is the case for salmon aquaculture, a large share of the sector's income gains are secured by these companies and the benefits to local communities become limited [21].

The aquacultural production of high trophic level fish species often relies on fishmeal and fish oil from pelagic fish for the production of aquafeeds. These high trophic level fish are mainly aimed towards the markets of developed countries and has negative implications for developing countries that depend on pelagic fish, or fish that feed upon pelagic fish, as a direct source of protein. This demand for pelagic fish for direct consumption will most likely rise as the population grows in developing countries [8,17].

Other potential social conflicts and impacts on other users of water-bodies that can arise from the development of the aquaculture industry, include: blocked access to water-body resources by pond or cage structures; navigational hazards; privatization of public waterways and lands; and the conversion of agricultural (e.g., rice paddies, pastures), residential, and common waterways and land [85–87].

3. Recirculating Aquaculture Systems (On-Land)

A lack of space for expansion, competition with other users for sites, concerns over pollution, and the high costs associated with pumping large volumes of water (e.g., with flow-through on-land aquaculture farms) are major obstacles to the sustainable expansion of the saltwater aquaculture industry [52,88]. One effective solution is the rearing of fish in recirculating aquaculture systems (RASs); defined in a paper by Zhang et al. (2011) as "land-based aquatic systems where the water is (partially) re-used after mechanical and biological treatment in an attempt to reduce the consumption of water and energy and the release of nutrients into the environment" [89,90]. In general, with RASs, large solid particles of uneaten feed, feces, and bacteria are concentrated and removed by settling or mechanical filtration and fine particles (<100 microns) are removed by ozone treatment and/or foam fractionation [2,91]. Some forms of dissolved nitrogenous wastes (i.e., ammonia and nitrite) are toxic to fish and are removed from the wastewater in biofilters containing denitrifying bacteria (e.g., biofilm filtration). In the biofilter, *Nitrosomonas* sp. and *Nitrosococcus* sp. oxidize ammonia into nitrite and then *Nitrospira* sp. oxidize nitrite into nitrate [92–94]. Although high levels of nitrate are tolerable to fish [92], long-term exposure can be harmful to some species (e.g., Turbot (*Psetta maxima*)) [92,95]. To combat this, many RASs will use anaerobic ammonium oxidation (anammox) to convert ammonia and nitrite directly into nitrogen gas [94–97]. Fish and bacterial metabolism strips water of dissolved oxygen while increasing concentrations of carbon dioxide (CO_2). Therefore, many operators will run air through the CO_2 rich wastewater to degas the CO_2 and increase the oxygen concentration [91]. Ozone gas and ultraviolet lamps are also often used to kill fungal, viral, bacterial, and protozoan pathogens in the water prior to its re-entry to the culture tanks or being discharged [98,99].

RASs have a number of advantages over conventional aquaculture systems. They vastly reduce water consumption. RASs enable up to 90%–99% of the water to be recycled and water use in saltwater RASs can be as low as 16 L/kg of fish. This is in stark contrast to conventional aquaculture systems that use 3000–45,000 L of water/kg of seafood produce [88,100,101]. RAS are flexible. Due to this low water requirement, RASs can be located on land unsuitable for other food production methods (e.g., deserts, post-mining lands, urban areas) and/or close to markets, which results in local employment and revenue opportunities and reduced shipping and transportation costs [2,102–104]. They improve opportunities for waste management, nutrient recycling, and biological pollution control. The majority of excess nutrients and waste material (uneaten feed, feces, dead bacteria) are removed before water is released to the environment, subsequently, RASs reduce potential negative impacts on marine and saline environments and ecosystems [2,88,89]. RASs improve conditions for cultured fish by having greater control over environmental and water quality parameters and enhancement of feeding efficiency. Subsequently, RASs can allow for higher stocking densities than most aquacultural systems [91,100,104–110] by sterilizing the water prior to (re)entry to the fish tanks, pathogens and contaminants are removed, reducing the risk of disease outbreaks and contaminant uptake by the fish [18,104,111]. Due to the on-land and recirculatory nature of RASs, the potential for fish escapes is greatly reduced [2,104]. Ultimately the wastes removed from RAS water must be dealt with. The solid wastes removed from a RAS are rich in nitrogen and phosphorus and can be used in methane production, polychaete culture, vermicomposting, and as an agricultural fertilizer. Therefore, the byproducts of RASs can be sold to other industries. Also, the higher stocking densities, year-round production, and reduced water costs are an economic advantage [2,110].

Despite having a number of advantages over conventional aquaculture systems, RASs also have a number of constraints, namely, high capital and operational costs, a requirement for extremely careful management, and difficulties in treating disease [2,88]. The cost of setting up a RAS is very high, therefore, future profitability is uncertain, discouraging many from investing [91,104]. A high level of electricity is required to run recirculating systems that function on a continuous basis, subsequently, RASs consume far more energy than most other types of aquaculture [112,113]. The total energy consumption (including feed) of carnivorous finfish RAS facilities is estimated to range from 16 to 98 kilowatt hours per kilogram (kWh/kg) of fish produced. In comparison, net pen aquaculture consumes approximately 7.4 kWh/kg and flow-through farms approximately 27.2 kWh/kg for similar species of fish [113,114]. Surveys of RAS operators conducted by Badiola et al. (2012) identified the following barriers to the successful operation of RASs: poor system design, poor management (mainly due to unskilled laborers taking responsibility of water quality and mechanical problems), a lack of communication between parties (e.g., between different operators or suppliers), and a disincentive to share information and knowledge within the industry. Badiola et al. (2012) identified two key priorities necessary to improve RAS operations: (1) Improvement of equipment performance. This can be achieved through commercial-scale research to try and identify the best combination of devices on a site-specific basis; (2) the development of a specialized RAS platform for the sharing of knowledge amongst the relevant personnel [88]. If recirculated water is not properly sterilized, the reuse of water in RASs can lead to contaminants from feed and system components and diseases/pathogens accumulating in the system [18,104,111]. However, two studies by Tal et al. (2009) and Martins et al. (2011) found that contaminants in RASs were either below harmful levels or undetectable [90,100]. The use of denitrifying bacteria in RAS biofilm filtration systems has three possible constraints that may negatively impact survival, growth, and reproduction of the cultured organism. Firstly, nitrifying bacteria compete with the cultured organism for oxygen. Secondly, nitrate can be converted into the toxic nitrite under anaerobic conditions. Thirdly, RASs using biofilm filtration tend to acidify over time due to the respiration of the biofilm and the cultured organisms [115–118]. Although RASs improve feed efficiency, the high cost of setting up and running a RAS means that most operators will choose to cultivate high value carnivorous fish, which consume relatively high levels of fishmeal and fish oil [91,104]. To improve upon some of these constraints, feed inputs need to be altered, energy efficiency needs to be improved, and the conditions for bacterial growth need to be optimized [104]. Novel solutions include: bio-floc technology, which greatly reduces the flow rate and suspended communities of microbes (i.e., flocs) convert toxic nutrients into biomass that can be consumed directly by fish or shrimp [119] and periphyton-based systems whereby artificial substrates (e.g., poles, bamboo) are added to the culture system to attract organisms which remove nutrients and provided (additional) food for the cultured animals [120].

4. Integrated Multi-Trophic Aquaculture (Offshore and On-Land)

Another approach to tackling the negative impacts of aquaculture is an ecosystem-based approach to aquaculture management. To be considered an ecologically sound system, these "ecological aquaculture" systems should be designed under the following criteria: preservation of natural ecosystems; environmentally friendly nutrient management; significant reduction or absence of harmful chemicals and antibiotics; trophic level efficiency; and farmed fish escape prevention. It would also be beneficial if these systems improved the economies and provided employment in the areas in which they are located [8,83]. In the following sections, we will discuss established and novel saltwater food production systems that most closely follow the listed criteria for an ecosystem-based approach to saltwater-based food production.

The concept of integrating aquaculture production is not a new one and has been practiced in Asian countries for centuries through trial, error, and experimentation [121–125]. Integrated farming, predominantly in fresh and brackish water pond systems, is an ancient practice in China and has become more refined since the implementation of agricultural and rural development policies since 1949. These policies were motivated by the high population growth in China and the need to maximize productivity of available land and water. They were also based on a philosophy of diversified self-reliance of food and raw material production and the use of by-products (i.e., wastes) as an input to produce other resources [126,127]. This integrated form of farming is often referred to as polyculture, "the (usually) simultaneous cultivation or growth of two or more compatible plants or organisms (especially crops or fish) in a single area" [128]. In contrast, the western world tends to focus on high value, intensive monoculture, which has many potential negative outcomes. Unfortunately, many newcomers to the industry from Asia are following this trend, due to the temptation of expeditious financial gains that result from the monocultural production of fish or shrimp [126].

Integrated Multi-trophic Aquaculture (IMTA) combines, in the appropriate proportions, the cultivation of fed aquaculture species (e.g., finfish/shrimp) with organic (e.g., bivalve molluscs) and/or inorganic extractive species (e.g., seaweed). It is a practice in which the wastes from one species are recycled and become the inputs (e.g., fertilizer, food and energy) for another [126,129,130]. IMTA differs from the traditional practice of aquatic-polyculture in that it incorporates species from different trophic levels, whereas with polyculture, the species tend to be from the same or similar trophic levels, and therefore share the same biological and chemical processes, providing few synergistic benefits [4,130]. The principles of IMTA can be applied to saltwater and freshwater operations on land, near the coast or offshore [2,129]. To function well in open-water IMTA systems, the culture of organic extractive species (e.g., shellfish or deposit-feeding invertebrate) and/or inorganic extractive species (e.g., macroalgae) should take place in close-proximity to the cages, usually somewhat downstream to ensure effective uptake of nutrients [131,132]. Offshore IMTA relies on currents to move nutrient-rich water from fed to extractive species. Coastal and pelagic currents can be difficult to predict and are location and seasonally dependent. Correct positioning of additional crops will require experimental trials and/or modelling [2]. The organic extractive species consume particulate organic matter (i.e., uneaten feed/food and feces) and the inorganic extractive species uptake ammonia, nitrate, phosphorus, and carbon dioxide and release oxygen [2,131,132]. On land, IMTA setups usually take place in tanks, ponds, or as a wetland addition for wastewater treatment. Within the literature on-land IMTA has been broken down into two additional sub-groups (halophyte wetlands and saltwater aquaponics), both of which include an inorganic extractive species as a component of their integrated, multi-trophic system. These will be discussed in more detail in Sections 4.1 and 4.2. It is important to note, that an on-land IMTA system that does not contain an inorganic extractive species would not fall into these two sub-groups and is simply referred to as an on-land IMTA or integrated system. A number of potential candidate species have been identified for their inclusion in offshore and on-land IMTA operations, a number of which are detailed as follows.

Inorganic Extractive Species (i.e., Seaweeds & Aquatic Plants)

Seaweeds are very effective and efficient at taking up nutrients (i.e., nitrogen and phosphorus), making them an ideal bioremediation tool for aquaculture. Studies have shown that seaweeds can remove up to 60% of dissolved inorganic nitrogen and phosphorus [24,133,134]. Intensive seaweed production requires a constant nutrient supply, especially in the summer when warm waters are generally nutrient depleted. Integrating seaweed into fish aquaculture in coastal waters can alleviate the seasonal nutrient depletion by using constant nutrient supply from fish farms [23,126]. Seaweeds have a high market value and are sold worldwide for human consumption, phycocolloids, feed supplements, agrichemicals, neutrachemicals, and pharmaceuticals. In 2014 alone, the global culture of algae reached approximately 27–28 million tons at an estimated value of US$5–6 billion [3,4,131].

Gracilaria is one of the most exploited seaweed genera worldwide [133] and therefore, one of the most commonly studied candidate species for integration into offshore IMTA systems. A number of at sea trials integrating seaweed with monocultural mariculture operations are detailed below, however, a comprehensive list of references is available in Troell et al. (2003), Neori et al. (2004), and Granada et al. (2015) [4,131,135].

Candidate inorganic extractive species for on-land IMTA include seaweeds, halophytes, and low-moderately saline tolerant glycophytes. These will be discussed in more detail in Sections 4.1 and 4.2.

Studies by Fei et al. (2000; 2002) found that when the economically important *Gracilaria lemaneiformis* was grown near fish net pens on 5 km of rope, they achieved extremely high levels of growth. The density increased from 11.6 to 2025 g·m^{-1} over a 3 month growth period and when they enlarged the culture density to 80 km of rope, they achieved 4250 g·m^{-1} over the following 4 months. They achieved a final biomass of 240 metric tons (fresh weight (FW)) and attributed this success to its culture in close proximity to the fish cages [136,137]. Zhou et al. (2006a) co-cultivated longlines of *G. lemaneiformis* c.12 m from black snapper (*Sebastodes fuscescens*) cages and results indicated that this seaweed is a good candidate for seaweed/fish integrated mariculture for bioremediation and economic diversification. *G. lemaneiformis* achieved a maximum growth rate of 11.03%·day^{-1} and mean N and P uptake rates of the thalli were estimated at 10.64 and 0.38 μmol·g^{-1}·dry weight (DW)·h^{-1}. When Zhou et al. (2006a) extrapolated these results, they calculated that 1 Ha of *G. lemaneiformis* cultivation in coastal fish farming waters would give an annual harvest of over 70 tons FW (9 tons DW) and 0.22 tons N and 0.03 tons P would be sequestered from the seawater [23]. Buschmann et al. (2008) installed a 100 m seaweed longline approximately 100 m from a salmon farm that produces 2500–3000 tons of biomass of fish per annum. The longline was positioned in the main water flow that had an average current speed of 7.6 cm^{-1} and 2.6 cm^{-1} during the flood and ebb period respectively. This 100 m longline contained *G. chilensis* and *M. pyrifera* at depths of 1 m, 3 m, and 6 m. The growth rate reached an average of 6%·day^{-1} and 4%·day^{-1} for *M. pyrifera* and *G. chilensis* respectively, equating to an annual production of over 25 kg·m^{-1} of *M. pyrifera* during a 9 month production period and an average of 2.8 kg·m^{-1}·month^{-1} during the spring for *G. chilensis*. Optimal growing conditions occurred in the spring for both species and at a depth of 3 m for *M. pyrifera* and 1 m for *G. chilensis*. The nitrate uptake rate was higher for *M. pyrifera* than *G. chilensis* in the spring at 11.8 ± 4.5 μM·g(DW)$^{-1}$·h^{-1} compared to 4.9 ± 2.3 μM·g(DW)$^{-1}$·h^{-1}. However, the annual range is higher for *G. chilensis* at 1.2–35.6·μM·g(DW)$^{-1}$·h^{-1} in comparison to 3.7–16.9 μM·g(DW)$^{-1}$·h^{-1} for *M. pyrifera*. The incorporation of seaweed species with different light requirements to an IMTA system allows for the utilization of different water column depths and subsequently increases their efficiency and effectiveness as biofilters [138].

Abreu et al. (2009) deployed 3 × 100 m longlines (1 m depth) of *G. chilensis* at a distance of 100 m (L1), 800 m (L2), and 7 km (L3) from salmon cages (production capacity of 1500 tons) in order to receive the main flow of nutrients discharged from the salmon farm during flood tides (average currents: 7.6 cm·s^{-1} and 2.4 cm·s^{-1} during the flood and ebb periods respectively). A fourth longline cultivation unit (L4) was also set up as a traditional bottom culture in a separate location not impacted by the salmon farm. The two longlines positioned closest to the salmon farm (L1 and L2) performed best in terms of productivity and nitrogen removal. Although the L1 and L2 longlines both had a relative growth rate (RGR) of approximately 4%·day^{-1} in the summer and 2%·day^{-1} in the autumn, the L2 longline had stronger productivity at c.1.7 kg·m^{-1}·month^{-1} in comparison to c.1.48 m^{-1}·month^{-1} for L1. In terms of N removal, L2 removed an average of 9.3 g·m^{-1}·month^{-1}, while L1 removed an average of 7.8 g·m^{-1}·month^{-1}. The lower levels of production 100 m from the cages (L1) could be attributed to the higher occurrence of epiphyte growth on these seaweeds. Abreu et al. 2009 estimated that a 100 Ha *G. chilensis* longline system at a distance of 800 m would effectively remove 100% of the N inputs from a 1500 ton salmon farm [133].

Organic Extractive Species (i.e., Invertebrates)

Filter-feeding invertebrates filter large volumes of water to meet their food requirements and have a high level of efficiency in retaining small particles, including bacteria [4,139]. Several studies have shown that bivalves have enormous potential as biocontrollers of fish farm effluent [140–143]. For example, Reid et al. (2010) measured the absorption efficiency of blue mussels (*Mytilus edulis* and *M. trossulus*) feeding on Atlantic salmon feed and fecal particulates and found removal rates of up to 54% of total particulate matter [143]. Macdonald et al. (2011) found that the oyster, *Saccostrea commercialis*, is effective at reducing total suspended solids, and total N and P released from an Atlantic salmon farm [140]. Studies have also shown significant growth increases in oysters and mussels have been achieved when co-cultured with salmon [140–142]. Some studies have suggested that bivalves have the potential to act as a reservoir for finfish pathogens. For example, Pietrak et al. (2012) demonstrated the capability of *M. edulis* to bioaccumulate *Vibrio anguillarum* in the digestive gland at twice the magnitude found in the water column. If *V. anguillarum* can persist in mussel fecal pellets, it is possible that mussels could generate *Vibrio* reservoirs in sediments and/or fecal matter [4,144]. Other studies, however, have demonstrated that bivalves are not hosts, instead consuming parasites or inactivating pathogens [145,146]. More research into bivalves' ability to act as pathogen reservoirs is required, however, steps can be taken to minimize the risk of transmission. Farms should be positioned in locations with sufficient water depth between the bottom of the cage and the benthos at low tide [4]. Nevertheless, it has been shown that bivalves have the capability to reduce the environmental and ecological impacts of aquaculture while at the same time providing a valuable crop for the farmer. Bivalves are therefore ideal candidates for IMTA systems [4,140].

In the natural environment, sea cucumbers are detritus feeders that ingest sediment containing animal and plant organic matter and are therefore considered important processors of surface sediment, making them ideal bioremediation candidates for coculture in an IMTA system [147,148]. MacDonald et al. (2013) conducted land-based tank trials and found that the cotton-spinner (*Holothuria forskali*) readily consumed European seabass (*Dicentrarchus labrax*) waste diets at a level that was suitable to process biodeposition beneath commercial sea-bass cages. The grazing by *H. forskali* also reduced the total N content of *D. labrax* waste in a short-term controlled feeding experiment and suppressed total carbon (C) content in a long-term controlled feeding experiment [149]. *H. forskali* has not yet been utilized on a commercial scale, however, it is a high quality protein source that also has a number of biological features that have potential applications in biotechnology and pharmaceuticals [150–153]. The Japanese common sea cucumber (*Apostichopus japonicus*) is a valuable species across Asia and studies have demonstrated its potential for integration into an IMTA system. Yokoyama (2013) showed that *A. japonicus* cultured under fish cages exhibited enhanced growth and survival and showed evidence of fish feces and organic settling matter ingestion [147]. Kang et al. (2003) cocultured *A. japonicus* and charm abalone (*Haliotis discus hannai*) in tanks and found the levels of ammonium nitrogen and nitrite in the water of cocultured groups were lower than the control group (abalone only). Also, the abalone growing in the coculture had significantly better growth and survival, highlighting *A. japonicus*' ability to reduce the levels of inorganic N in the water [154]. Zhou et al. (2006b) showed that Chinese scallop (*Chlamys farreri*) lantern nets provide a good habitat for *A. japonicus* and they grew well when in close proximity to these nets [155]. The California sea cucumber (*Parastichopus californicus*) has demonstrated its ability to consume fouling debris such as detritus from shellfish (e.g., oysters), fish feces, excess fish feed, and algae [4,156,157]. Other species of sea cucumber that have been assessed for their potential role in IMTA systems are the orange-footed sea cucumber (*Cucumaria frondosa*) and the Australian brown sea cucumber (*Australostichopus mollis*). *C. frondosa* has demonstrated high absorption efficiency (>80%) of salmon feed and feces [158] and

A. mollis cultured below mussel farms grow rapidly and significantly reduce the accumulation of organic carbon and phytopigments associated with biodeposition from these farms [141,159–161].

Other novel potential additions to IMTA systems include polychaetes and sponges. Polychaetes are highly efficient at filtering, accumulating, and removing waste bacterial groups such as vibrios and potential human pathogens with high levels of efficiency [162,163]. They can also ingest and assimilate fecal waste from aquaculture farms. One study found that the polychaete *Perinereis nuntia vallata* converted approximately 50% of the nitrogen ingested from Japanese flounder (*Paralichthys olivaceus*) wastewater into body tissue [164]. Another study involving two species of intertidal polychaetes (*Perinereis helleri* & *Perinereis nuntia*) cultured in sand-beds to remediate wastewater from a prawn farm revealed that the polychaete filtration process significantly reduced chlorophyll a and suspended solids [165]. Polychaetes have commercial value in the saltwater aquarium industry and a number of species have been shown to have antibacterial properties that have applications in the biotechnology industry [4,166]. Like polychaetes, sponges have the ability to utilize bacteria [166] and filter organic particles [139,167,168]. Stabili et al. (2006) showed that Demospongiae (Porifera) unselectively filter organic particles of 0.1 mm–50 mm in size, retaining up to 80% of suspended solids after processing the water column within 24 h. Organic particles that fall within this size range include: heterotrophic eukaryotes and bacteria, phytoplankton, and detritus [139]. Other studies conducted on Mediterranean sponges (*Dysidea avara*, *Chondrosia reniformis*, *Chondrilla nucula*, and *Spongia officinalis* var. *adriatica*) have shown great filtering efficiency and improved growth when cultured in close proximity to aquaculture farms [167–169]. Sponges have enormous commercial potential in the areas of biotechnology, pharmaceuticals, and cosmetics [169–172].

The majority of recent studies on marine or saltwater IMTA systems in industrialized nations have been conducted on an experimental, small-operation scale, and it can be difficult to extrapolate these results to an industrialized scale [4,135]. However, on the east coast of Canada, in the Bay of Fundy, a commercial scale IMTA operation has been on-going since 2001. This IMTA system consists of blue mussels (*Mytilus edulis*) and kelps (*Saccharina latissima* & *Alaria esculenta*) in close proximity to salmon cages (*Salmo salar*). An increased growth rate of kelps (46%) and mussels (50%) were seen when cultured in proximity to the fish farms in comparison to reference sites [173–175]. Over the course of these commercial-scale trials none of the therapeutants used in salmon aquaculture have been detected in kelps and mussels collected from the IMTA sites and levels of heavy metals, arsenic, PCBs, and pesticides have always been below regulatory limits. A taste test of the IMTA mussels in comparison to reference mussels was conducted and showed no discernable difference [130,175]. Two attitudinal studies on salmon farming in the area were conducted. The first one found that the general public were more negative towards current monoculture practices, but feel positive that IMTA would be successful. The second survey found that 65% of participants felt that IMTA had the potential to reduce the environmental impacts of salmon aquaculture, 100% felt it would improve waste management, over 90% believed it would benefit community economics and employment opportunities. All participants felt that seafood produced through IMTA techniques would be safe to eat and 50% were willing to pay 10% more for these products if labelled as such [130,176].

Culturing species from different trophic levels within the same system, in the right proportions, can help farmers achieve environmental sustainability through biomitigation of aquaculture wastes and can also provide the farmer with economic stability through product diversification and risk reduction. Essentially there is the potential to generate revenue from nutrients that would have otherwise been lost [2,129]. Due to filter-feeding organisms' (e.g., bivalves) ability to consume or deactivate potential pathogenic microorganisms and parasites, their inclusion in an IMTA system provides the opportunity to decrease disease outbreaks and control human pathogens. Subsequently the need for antibiotics may be significantly reduced [2,4,129,130,145,146]. It must be noted that there is the possibility that bivalves can act as a vector for fish pathogens, however, studies on this are limited [4,144]. For larger parasites that may not be ingestible by filter-feeders, other species-integration solutions are available. For example, the use of ballen wrasse (*Labrus berggylta*) and lumpfish (*Cyclopterus lumpus*) for the delousing of cage cultured Atlantic salmon has been demonstrated as very effective [177,178]. As IMTA incorporates ecologically based management practices it has the potential to improve the social acceptability of aquaculture. There is a growing interest amongst consumers in sustainably produced seafood and they are willing to pay a premium for them, particularly if the packaging contains eco-labels. Also, if IMTA operators were to incorporate an eco-tourism venture into their farms, there is the opportunity to further the social acceptability of aquaculture, while also educating the community on food production techniques and ecological principles [2,179–181]. As IMTA systems involve a number of different species, farm operators will most likely need to employ more staff due to the increased workload and need for personnel who are experienced with the cultivation of these additional species.

Unfortunately, there are constraints to the development of IMTA. The economic viability of offshore or on-land IMTA is uncertain. Although IMTA has the potential to provide economic stability through product diversification, the co-culturing of various species from different trophic levels is very complex and the development of a successful IMTA system that produces marketable and profitable biomass of additional crops might be a lengthy process, resulting in economic risk and uncertainty of production [2,129,182]. Some consumers might be reluctant to purchase seafood cultured in the waste-streams of finfish aquaculture. Therefore, marketing and educational initiatives may need to be developed in order to address or alleviate these concerns. Encouragingly, surveys conducted in the Bay of Fundy, Canada, found that the majority of the general public believes IMTA products are safe to eat [176,182,183]. IMTA systems include finfish or shrimp that require aquafeed. To make IMTA truly ecosystem-based, aquafeed producers need to reduce their dependence on fishmeal and fish oil, and consider alternative ingredients that can replace or reduce their need for forage fish (see Section 2.5 for list of alternatives) [2,6,17,19,81]. For at-sea IMTA, farmed fish escapes are still a concern. Solutions include the use of stronger net materials, tauter nets that deter sea-mammals (e.g., seals) from grabbing fish, and covers on boat propellers to avoid tears [60]. The most secure method however, would be to isolate fish farms from the natural environment in land-based tanks or close-wall sea pens [21,60].

4.1. Halophyte Wetlands (On-Land)

Natural wetlands are an important part of marine, saline, and freshwater ecosystems; holding and recycling nutrients, controlling and buffering natural floods, and providing habitats and breeding and nursery grounds for many wildlife species. Additionally, wetlands can also efficiently remove organic matter, suspended solids and nutrients (N, C, P) through sedimentation, filtration, assimilation, and biological and microbiological absorption [184].

The use of man-made constructed wetlands (CWs) began in the 1970s as a means to provide a habitat for a variety of organisms and to improve water quality. Since then, CWs have been set up to provide flood control, to offset the decline in natural wetlands resulting from agriculture and urban development, to improve water quality, and for food production [184,185]. In relation to aquaculture, CWs to date have been mainly used for the rearing of shrimp, crayfish, and commercial fish species and for the treatment of freshwater aquaculture effluent [186–191]. Two basic flow regimes have been devised for CWs, free surface flow (SF) and subsurface flow (SSF). In a SF CW, the water flows above ground and plants are rooted in the sediment layer at the base of the basin or floating in the water. In this system the water is exposed to the atmosphere and direct sunlight. A SSF CW, on the other hand, consists of a basin filled with an appropriate medium (e.g., coarse rock, gravel, sand, other soils) that is planted with wetland vegetation. A SSF CW is designed so that the water surface remains below the top surface of the medium, preventing odors and insect infestations. These systems are commonly utilized for secondary or tertiary treatment of wastewater [185,189]. The concept of applying CWs to mariculture systems for wastewater remediation is relatively new, however, a number of trials have already studied the utilization of halophytes for aquaculture wastewater bioremediation in CWs.

A halophyte is a naturally evolved salt-resistant plant that has adapted to grow in saline environments and in some cases they require this exposure to salinity to survive [192,193]. Operating halophytes as a plant biofilter of saltwater aquaculture effluent is a low cost opportunity to mitigate potential negative impacts on the environment [194]. A recent study by Diaz et al. (2013) found that a number of halophytic species (*Salicornia bigelovii*, *Atriplex lentiformis*, *Distichlis spicata*, *Spartina gracilis*, *Allenrolfea occidentalis*, and *Bassia hyssopifolia*) grown under field conditions and irrigated with saline drainage water over a 4 year–6 year period in the San Joaquin Valley of California grew very successfully and can effectively reduce saline drainage effluent [195]. Lymbery et al. (2006) constructed 16 2.5 m × 0.4 m × 0.3 m SSF wetlands incorporating the estuarine sedge, salt marsh rush (*Juncus kraussii*), and assessed its ability to treat inland saline aquacultural wastewater. After a 38 day trial, it was found that this CW removed up to 88% of the total phosphorous load and 69% of the total nitrogen load. Although nutrient concentration didn't have a significant effect on the growth of *J. kraussii* (i.e., plant length and frond number), it was found that higher salinities adversely impacted both growth parameters. Subsequently, it was suggest that *J. kraussii* would be more suited to salinities of up to 20,000 mg/L^{-1} and may not be effective in the treatment of inland, highly saline aquaculture waste, instead, being better suited to the treatment of waste from, for example, low salinity shrimp aquaculture [196]. *J. kraussii* is commonly harvested in South Africa as a source of fiber for craft works and is of significant cultural importance to many Zulu households. For example, for the production of bridal sleeping mats no alternative wetland plant species is acceptable. *J. kraussii* is of significant economic importance to the region, with 97% of *J. kraussii* related income being generated through the sale of craft products and 3% through raw material sales [197]. Shpigel et al. (2013) demonstrated that a CW planted with *Salicornia persica* was effective in the removal of N, P, and total suspended solids (TSS) from a 1000 m^3 commercial, intensive, semi-recirculated aquaculture system growing 100 tons of gilt-head seabream (1 g–500 g in size). It was estimated that approximately 10,000 m^2 of wetland planted with *S. persica* would be required to remove nitrogen and TSS in wastewater during one year. This study also found that an average yield of 10,000 m^2 of *S. persica* would be expected to produce about 28.8 tons (2.88 $kg \cdot m^{-2} \cdot year^{-1}$). The upper (edible) part constitutes approximately 80% of the yield, therefore, the marketable yield would be about 23 tons of fresh produce. Both SF and SFF CWs were trialed in this study, and it was found that a SF regime with *S. persica* would likely be more efficient for facilities with low nutrient loads (NL) (e.g., fish hatcheries) and a SFF regime would be more efficient at high NL facilities (e.g., intensive fish farms) [184]. Although using CWs for effluent treatment requires a relatively extensive area, a cost-effective analysis conducted by Cardoch et al. (2000) found that treatment by wetland costs approximately 75% less to the farmer than conventional onsite treatment [198]. The use of a CW to treat aquaculture wastewater can be even more cost effective if the wetland is planted with a crop that has market demand or potential market demand [184]. The commercial application cost of CWs is estimated to be €0.20 per kg of fish produced. Therefore, the cost of the construction and operation of a CW for, for example, 500 tons of fish would be €100,000. With a conservative price of €6 kg^{-1} (FW) the income from 23 tons of *S. persica* is expected to be €138,000 based on gross calculations [184,199]. Marsh samphire (*S. europaea*) has also been shown to have significant potential in the treatment of aquaculture effluent. Webb et al. (2012) constructed a SFF wetland filter bed planted with marsh samphire to evaluate its ability to treat the wastewater from a commercially operated marine fish and shrimp farm. The results demonstrated the effectiveness of a marsh samphire wetland in removing N and P from the wastewater, with 91%–99% of influent dissolved inorganic nitrogen and 41%–88% of influent dissolved inorganic phosphorus removed [200]. A number of species from the genus *Salicornia* have demonstrated a number of commercial applications and potential in the areas of nutrition, medicine, forage crops, and oilseed production [201–208]. For example, *S. persica* and *S. europaea* contain compounds with antioxidative properties, such as polyphenols, superoxide dismutases, and peroxidases [209].

Providing inexpensive land is available, the integration of CWs into on-land aquaculture can be very cost-effective as they only require moderate capital investment and have low energy consumption and maintenance expenses [210–212]. However, CWs require relatively extensive areas of land, and would not be suitable in locations where land prices are high. The cost of CW operations could, however, be offset by exploiting them as a natural park or tourist attraction (eco-tourism) [184,198,199]. As the maintenance of the CW is low, the farm may not need to employ many (or any) additional staff, however, the construction of the wetland and harvesting of the halophyte crops may provide additional, short-term employment.

4.2. Saltwater Aquaponics (On-Land)

For onshore saltwater aquaculture, an integrated solution to the potential negative impacts of aquaculture may lie in a novel concept known as saltwater aquaponics (SA). To be able to explain the concept of SA, we need to first discuss the freshwater origins of this seafood production technique; hydroponics and aquaponics.

4.2.1. Hydroponics

Hydroponics is the technique of growing plants in a nutrient solution (e.g., water containing fertilizers such as chemical salts) with or without the use of an inorganic/inert (e.g., sand, gravel, coir, perlite) or organic (e.g., peat moss, coconut coir, vermiculture) medium for mechanical support [213,214]. When a hydroponic system contains no medium, it is often referred to as a liquid (non-aggregate) hydroponic system, when it does contain a medium, it is often referred to as an aggregate hydroponic system [213–215]. The concept of growing plants in nutrient rich water is centuries old. For example, the Babylonian hanging gardens and the floating gardens of the Aztecs in Mexico were hydroponic in nature [214,216]. The basic concept of hydroponics was established in the 1800s by investigators of plant growth [213,214]. A number of publications by the Californian scientist, Gericke, popularized the soilless culture of plants in the 1930s [217–219]. However, it wasn't until the 1980s that hydroponics became a profitable commercial vegetable and flower production method [214]. The operation of hydroponic systems in controlled facilities (e.g., greenhouses) was developed by the US army after World War II as an industrial approach to crop production intensification [214,220]. Virtually all hydroponic systems in temperate regions operate in greenhouses to: control temperature, reduce evaporative water loss, control disease and pests, and protect against adverse weather conditions (e.g., wind and rain) [215]. Some common hydroponic systems are detailed below (for information on other hydroponic techniques (e.g., standing aerated nutrient solution and ebb-and-flow nutrient solution) [214]).

Deep Flow Technique

The deep flow technique (DFT), for growing leafy vegetables (e.g., heads of lettuce), was developed independently by Jensen, at the University of Arizona, USA, and Massantini, at the University of Pisa Italy, in 1976 [217,221]. The production system consists of horizontal, rectangular-shaped tanks lined with plastic. The nutrient water in the tanks are aerated and recirculated. It is monitored regularly and replenished when required. The plants are placed in floating rafts of expanded plastic (e.g., Styrofoam), which are spread in a single horizontal plane for maximum sunlight interception. The nutrient pools within the rectangle tanks act as a frictionless conveyor belt for planting and harvesting the movable floats. It is also relatively easy to control root temperature by heating or cooling the nutrient water. For example, the roots may need to be cooled in order to reduce bolting. This is especially important if the production system is located in tropical or desert regions [215,222]. However, one must factor in the costs associated with heating or cooling the nutrient water.

Many of the results from trials establishing the DFT were never reported. Nevertheless, this method of hydroponics is becoming increasingly popular due to the systems' ability to control temperature, maximize sunlight exposure, and ease of planting and harvesting [215,222]. For example, in 2008, Hu et al. (2008) treated eutrophic water using *Ipomoea aquatica* Forsskal (swamp cabbage) in a DFT. After 48 h exposure to the plants, the chemical oxygen demand, biochemical oxygen demand, total suspended solids, and chlorophyll *a* were reduced in the effluent by 84.5%, 88.5%, 91.1% and

68.8% respectively. The concentrations of cadmium, copper, lead, and zinc in the plants all fell within Food and Agriculture Organisation (FAO) and World Health Organisation (WHO) permissible levels. Hu et al. (2008) found that cultivating *I. aquatica* in nutrient-rich, eutrophic water, in a DFT system is an effective, low-cost phytoremediation technology to treat water and undesirable levels of phosphorus and/or nitrogen [223]. Park and Kurata (2009) introduced a novel aeration technique, microbubbles, to a DFT system growing leaf lettuce (*Lactuca sativa*) and found that the fresh and dry weight of lettuce treated with microbubbles was 2.1 times and 1.7 times higher than those treated with standard, macrobubble aeration [224].

Nutrient Film Technique

The nutrient film technique (NFT) was developed by Dr. Allan Cooper in the late 1960s and refined throughout the 1970s and early 1980s, at the Glasshouse Crops Research Institute, Littlehampton, England. In an NFT system, the plant roots are suspended in a channel, trough, or gully (the term "channel" will be used for the remainder of this NFT section) through which a nutrient solution passes [214,215,225]. The channel containing the plant roots is usually set on a slope (approximately 1%) to allow the nutrient solution added at the top of the channel to flow from the top to the lower end by gravity at a flow rate of approximately 1 L per minute. One potential pitfall to the NFT method is that as the root mat increases in size, the plants at the beginning of the channel restrict the flow of nutrients to those at the further end of the channel. The flowing nutrient solution also tends to move over the top and down the outer edge of the root mat, reducing its contact within the root mass, resulting in poor mixing of the nutrient solution. One solution to these issues is to reduce the length of the channel and make it wider to accommodate longer-term crops [214]. A principle advantage of NFT over other hydroponic systems is that it requires much less nutrient solution. Subsequently, it is easier to heat the solution during winter months, to maintain optimum conditions for the roots, and to cool it during hot summers, particularly necessary for arid or tropical regions. The lower volume of water makes disease control more manageable [215]. Another advantage of NFT systems is the ease of establishment and relative low cost of construction materials [214]. Detailed construction information for NFT systems can be found in literature produced by Morgan (1999) and Smith (2004) [226,227]. In most cases, a NFT system is a closed system; the nutrient solution that exits the channel is recovered for reuse. If the system is closed, there is a requirement for the addition of top-up water to replace water lost to evaporation and uptake by the plants and the need to establish procedures for filtering, sterilization, and reconstitution of the pH and nutrient element content of the water [214]. In an open system, the nutrient solution exiting the channels is discarded, which is costly in terms of water usage, and requires careful disposal of nutrient-rich water [214,228]. Recently, the NFT system has been used for purposes other than the growth of vegetable. Ignatius et al. (2014) used an NFT system cultivating *Plectranthus amboinicus*, an aromatic medicinal plant, to treat lead contaminated wastewater. They found that *P. amboinicus* accumulated considerable amounts of lead in the roots and translocation to the leaves and stems was limited to the extent that they could still be used for medicinal purposes [229].

Aeroponics

In 1942, Carter designed a method of growing plants in water vapor to facilitate the examination of roots and subsequently began to research air culture growing [230]. Today, aeroponics is defined as a technique in which the plant's roots are suspended in mid-air and water and essential nutrients are supplied by means of an aerosol mist or water sprinkler bathing the roots, often without the use of soil or an aggregate medium; however, the addition of an organic medium can sometimes be beneficial [213–215,231–235]. Oxygen and water are quite often a limiting factor in conventional soil and water media systems, however, as nutrients and water are applied directly to the roots in an aeroponic system, they are in adequate supply [235]. The plants are positioned in the holes of a panel, with the roots suspended in mid-air beneath the panel and enclosed in a spray-box. This ensures that algal growth is prohibited and that the roots are in a humid environment [215]. Although Jensen (1997) suggests that the system being turned on for a few seconds every 2–3 min is sufficient to keep the roots moist and the nutrient solution aerated, Jones (2005) suggests that continuous exposure of the roots to a fine mist gives better results than intermittent spraying or misting [214,215]. With an aeroponic system, the spray-box contains the mister or sprinkler and a reservoir of the nutrient water. When the roots are long enough, a portion of the roots can gain access to this reservoir and therefore have a continuous supply of water [216,232]. Although the use of aeroponic techniques is not common in the commercial production of crops, it has considerable potential. As the plants can be cultivated very close to each other, this system is ideal for locations with extreme space and/or weight restrictions. It is also ideal for locations where the water supply is scare and/or of poor quality, as aeroponic systems reuses the nutrient solution (the length of time that the nutrient solution can be reused will be dependent on a number of factors, such as: the quantity of nutrients present in the solution, the biomass and type of plants present, temperature) [235]. Aeroponics also has potential in the rooting of foliage plant cuttings, as some exporting regulations require that the roots of cuttings be soil-free and the cuttings do not require overhead misting. Aeroponics can also reduce the problems of fungal diseases and the leaching of nutrients from the foliage of the cuttings [179]. Aeroponics has also shown the ability to achieve higher yields than conventional production techniques and only requires minimal training for the grower [235,236]. Movahedi et al. (2012) conducted a study comparing aeroponic and conventional soil systems for potato minituber production. The plantlets were grown in both aeroponic and conventional soil systems at a density of 100 plants per m^{-2}. It was found that growing the minitubers with an aeroponic system led to an increase in stem length, root length, stem diameter, and yield. The end product was also of better quality when grown in an aeroponic system [236]. These systems can also be run on a continuous basis, apart from some downtime for cleaning or changing the plants [235]. Aeroponics can be utilized for both crop production and plant research. For example, Christie and Nichols, (2004) from Massey University (New Zealand) have developed aeroponic systems for growing vegetable crops (e.g., tomatoes, cucumbers, potatoes, and herbs) and flower crops (e.g., *Zantedeschia* and *Lisianthus*) and for researching crop nutrition, growth analysis, and the gas levels in the root zone [233].

Hydroponic systems have a number of advantages and disadvantages over traditional crop cultivation methods. Crops can be grown in areas where there is no soil or unsuitable soil (e.g., contaminated with a disease), the labor-intensity of traditional crop production methods (e.g., tilling and watering) is either greatly reduced or eliminated, water and nutrients are conserved, plant diseases are more easily eradicated in closed systems (most hydroponic systems are closed), there is better control over environmental conditions (e.g., root environment, nutrient feeding, irrigation), they are suitable systems for "at-home" vegetable production, and if run successfully, hydroponic systems can operate continuously at maximum yields, making the system feasible in high density and expensive land areas [214]. However, hydroponics requires expensive nutrients to feed the plants, initial construction costs are high, even for closed systems, periodic flushing is required which may lead to waste disposal issues, there is a limited availability of plant varieties suitable for controlled growth condition and more research and development is required, as plants react to suitable/unsuitable nutrient conditions quickly, hydroponic systems require constant and careful management, introduced diseases can spread more quickly in a closed system, and the technical aspect to the construction and operation of hydroponic systems requires highly trained staff [214,237].

4.2.2. Aquaponics

Aquaponics is an on-land freshwater IMTA system combining the aquacultural production of fish (e.g., fish, crayfish, molluscs, etc.) with the hydroponic production of aquatic plants (e.g., vegetables, herbs, fruits, medicinal plants, etc.). The waste produced by the fish provides the nutrients required for plant growth, while the plants remove toxic compounds (e.g., nitrate and phosphorus) resulting from fish excretion [220,238–242]. In the majority of cases, aquaponic systems are closed, recirculating systems, which allows for nutrients to be maintained at concentrations sufficient for hydroponic plant production [243–247]. Like hydroponics, aquaponic operations commonly take place in a controlled environment (e.g., greenhouses) in an effort to increase crop production yields [220]. Aquaponics was also influenced by RAS work conducted in the early 1970s. A major challenge for RASs is the accumulation of nitrogen compounds, which are potentially toxic to fish. A number of investigators experimented with the soilless culture of plants as a fish waste treatment solution for the removal of nitrogen compounds, marking the beginning of aquaponics as we recognize it today [248–253]. Since this research was conducted, engineers have developed biofilters that do not rely on plants, however, aquaponic systems improve water quality while producing an additional, potentially profitable crop, distinguishing it from other forms of RAS [91,220]. The development of aquaponics was also influenced by research being conducted on sustainable agriculture (e.g., permaculture) in the 1970s and 1980s. Researchers at the New Alchemy Institute were applying permaculture methods to aquaculture and experimented with the integration of hydroponics and aquaculture [220,254,255].

Fish in aquaponic systems are usually raised in ponds, tanks, or other forms of containers, while the plants are grown separately in hydroponic tanks. The roots are either submerged in water or, in the case of an aeroponic-style system, exposed to a mist or sprinkling of water. The plants are suspended in gravel, sand, perlite, porous plastic films, or on floating rafts (see Section 4.2.1 for more detail on hydroponic plant production) [2,244].

All aquaponic systems share the same basic key functions: aquatic animal and plant production, bacterial nitrification, and suspended solid removal [256]. Suspended solids are removed from aquaponic systems in a similar manner to RASs, by passing the wastewater through mechanical filters or using settling ponds to settle the solids out of suspension. They can also use organic extractive species in combination with or as a replacement to mechanical methods (see Section 4). Again, like in RASs, ammonia is oxidized to nitrite, and then to nitrate by denitrifying bacteria (see Section 3 for more detail) [244]. The nitrate and phosphorous rich water is transferred to the hydroponic tanks for absorption by the plants. This nutrient-reduced water is then reused in the fish tanks/ponds. Due to aquaponics' ability to treat fish wastewater for reuse in the system, aquaponic operations can achieve fish production densities similar to those achieved in RASs [247,257].

The nutrient removal and water reuse ability fluctuates amongst different aquaponic systems due to a number of variables such as flow rates, the type of plant used, the medium (or lack of) used to grow the plant, and the ratio of plants to fish [246,257,258]. For example, nitrate and phosphorus removal rates range from 9%–93% to 0%–53% respectively, while water reuse can reach over 98% [246,256–260]. Al-Hafedh et al. (2008) compared their recirculating aquaponic system to semi-intensive aquaculture in Saudi Arabia, and found that their system recycled more than 98% of its water and produced more than 40 kg fish/m^3 of water every 6 months, whereas the semi-intensive system exchanged 20%–30% of its water daily and only produced 8–15 kg fish/m^3 over a 6 month period [260]. The most common species of fish currently used in aquaponics include tilapia, perch, carp, barramundi, cod, and trout [247]. Research has found that plants with low-medium nutrient requirements (e.g., lettuce, herbs, spinach, watercress) perform better in aquaponic systems than more nutrient-demanding species (e.g., cauliflower, tomatoes). Lettuce co-cultured with tilapia is the most common aquaponic pairing [243,258]. The relative proportions of soluble nutrients that the hydroponically grown plants are able to obtain from the fish waste does not mirror the proportion of nutrients normally assimilated by plants growing in a normal manner. A solution to this issue would be to manipulate the nutrient content of the fish diet in such a way that the relative proportions of nutrients excreted by the fish are more similar to the relative proportion of nutrients assimilated by plants, while maintaining optimal nutrition for the fish [243,258]. Another option, which is commonly practiced, is to top-up the water supplying the hydroponic plants with required nutrients that are in limited supply or are not present in the wastewater [261,262]. Another challenge with an aquaponic system is the dichotomy that exists between the optimum pH for plant nutrient availability in hydroponics (pH 5.5–6.5) and the optimum for nitrifying bacteria in biofilters (pH 7.5–9.0). The recommended pH range for the nutrient solution irrigation water in hydroponics tends to be slightly acidic to avoid precipitation of Fe, Mn, P, Ca, and Mg to insoluble and unavailable salts when the pH is >7. If aquaponic recirculating water pH is maintained at levels more optimum for nitrifying bacteria, plant uptake of certain nutrients may become restricted, reducing plant yield [247]. However, work conducted by Tyson et al. (2008) suggests that total yields may be maintained at pH levels above those recommended for the production of plants, even with reduced nutrients in recirculating solutions, when the nutrients constantly bathe the roots [263,264].

4.2.3. Saltwater Aquaponics

Although freshwater aquaponics is the most widely described and practiced aquaponic technique, resources of freshwater for food production (agriculture and aquaculture) are becoming increasingly limited and soil salinity is progressively increasing in many parts of the world [265,266]. This has led to an increased interest and/or move towards alternative water sources (e.g., brackish to highly saline water) and the use of euryhaline or saltwater fish, halophytic plants, seaweed, and low salt tolerant glycophytes [267,268]. Saltwater aquaponics (SA) is an on-land IMTA system combining the aquacultural production of fish (e.g., fish, crustaceans, molluscs, etc.) with the hydroponic production of aquatic plants (e.g., seaweeds, algae, halophytes, salt-tolerant glycophytes etc.) in a range of salinities from low (e.g., brackish water) to high (e.g., seawater) [265,269–271]. The term maraponics (i.e., marine aquaponics) has also been coined for SA systems that utilize seawater. These are mainly located on-land, in coastal locations close to a seawater source [265,272–274].

As can be seen in Section 4.1, a number of CW studies have shown that halophytes can be successfully irrigated with saltwater aquacultural wastewater [195–215]. The concept of growing halophytes through hydroponic techniques or as part of a SA system is very new. Waller et al. (2015) investigated the feasibility of nutrient recycling from a saltwater (16 psu salinity) RAS for European sea bass (*D. labrax*) through the hydroponic production of three halophyte plants; *Tripolium pannonicum*, *Plantago coronopus*, and *Salicornia dolichostachya*. The hydroponic setup consisted of hydroponic tanks being fed RAS process water at a flow rate of 0.15 $m^3 \cdot h^{-1}$ from 8 a.m. to 8 p.m. (1.8 $m^3 \cdot day^{-1}$). This flow rate is significantly less than the flow that would occur through a nitrifying biofilter (15 $m^3 \cdot h^{-1}$ 24 h a day or 360 $m^3 \cdot day^{-1}$). Each plant species grew at a similar specific growth rate (SGR) of 9%–9.9%$\cdot day^{-1}$. After the 35 day experimental period, both *T. pannonicum* and *S. dolichostachya* had reached marketable size with average shoot weights of 25 g and 60 g. High air temperatures in the greenhouse at the beginning of the experiment may have limited the growth of *P. coronopus* plants (average shoot weights of 17 g). The total production of plant material over the course of the experiment amounted to 6 kg, 4 kg, and 13 kg for *T. pannonicum*, *P. coronopus*, and *S. dolichostachya*, respectively. The plants incorporated a total of 46 g N and 7 g P during the 35 day trial, equivalent to 9% N and 10% P that was introduced with the fish feed. For this system, it was estimated that 189 g of N resulted from fish excretion and if only the best performing halophyte (*S. dolichostachya*) was included, 1128 plants would be needed in a 14.4 m^2 hydroponic area to remove all of this excreted N. During the 35-day trial, the sea bass grew from 32 g to 54 g on average, at a SGR of 1.5%$\cdot day^{-1}$ and exhibited an FCR of 0.93. The edible part of the harvested plant material was tested and found to be microbial safe and approved for human consumption [275]. Boxman et al. (2016) evaluated the capacity for water treatment and production requirements of two halophytes, sea purslane (*Sesuvium portulacastrum*) and saltwort (*Batis maritima*), when grown in an indoor, bench-scale recirculatory SA system with platy fish (*Xiphophorus* sp.). Two thirty-day trials were carried out at a minimum to maximum salinity of 13.1‰ to 17.1‰. The first trial assessed nitrate removal rates with the sea purslane present and no plants present and the performance of two different medium types, coconut fiber and expanded clay. They found that the presence of plants significantly contributed to nitrate removal, such that mean nitrate concentrations were 10.1 ± 5.4 mg/L in planted treatments in comparison to 12.1 ± 6.1 mg/L in the unplanted treatments. The use of coconut fiber as a medium for the plants resulted in a significantly lower mean level of nitrate in the water (9.78 ± 5.4 mg/L) in comparison to when expanded clay was used (12.4 ± 6 mg/L). The second trial assessed the impact of flow rate, plant species, and plant density on nitrogen uptake from the fish tank water. The nitrogen uptake rate was monitored for both sea purslane and saltwort (separately) under the following treatments: high flow rate (1 L·min^{-1}) and high density (24 plants); high flow rate and low density (12 plants); low flow rate (0.5 L·min^{-1}) and high density; low flow rate and low density. It was found that the low flow rate/low density treatment with saltwort had the greatest nitrogen removal rate, ranging from 25% to 172%. However, the mean yield of 0.53 ± 0.09 kg·m^{-2} and 0.32 ± 0.06 kg·m^{-2} for sea purslane and saltwort, respectively, were low and further research into the use of these species in bench-scale units is required [276]. Kong and Zheng (2008) successfully grew *Salicornia bigelovii* hydroponically (in Styrofoam disks floating on nutrient solution) and found that a marketable yield of 1.69 ± 0.21 kg·m^{-2} achieved when grown at high salinities (200 mM NaCl) was significantly higher than the yield achieved at moderate salinities (6, 8, and 10 mM NaCl) [277]. Gunning (2016) showed that *S. europaea* cultivated in an aeroponic unit with oyster farm wastewater grew very successfully at low to moderate salinities (i.e., a freshwater/seawater mix containing 33%–66% seawater) and reduced the levels of ammonia, nitrite, nitrate, and phosphate in the wastewater [232]. Work conducted by Buhmann et al. (2015) on the use of halophytes (9 different species) as a biofilter for nutrient-rich saline water found that the use of a hydroponic culture system is more suitable than sand or clay culture if controlled conditions and nutrient cycling are desired. After a 5 week trial, it was shown that at least 10 mg·L^{-1} of nitrate was necessary for reasonable biomass production and 0.3 mg·L^{-1} of phosphate is sufficient, but higher concentration promote the uptake of phosphate. The addition of iron in chelated form was also required for the growth of healthy plant biomass, whereas, the addition of manganese is beneficial but not implicitly necessary. Buhmann et al. (2015) found that all tested species have the potential to serve as a biofilter, are a source of valuable co-product, and have potential for integration into a SA systems (species studied in this trial were: *T. pannonicum*; *Atriplex portulacoides*; *S. dolichostachya*; *Plantago coronopus*; *Lepidium latifolium*; and *A. halimus*) [194]. As many halophytes have reduced levels of growth at higher salinities the integration of algae cultivation into SA is a potential solution for systems that are using seawater levels of salinity (i.e., c.35 ppt) [196,232,271,278].

Although the concept of "saltwater aquaponics (SA)" is very new, an interest in on-land seaweed-based integrated mariculture began to appear in the 1970s, starting from a laboratory-scale and then expanding to outdoor pilot-scale trials. In some of the earliest quantitative studies, Haines (1976) and Langton et al. (1977) studied the growth of the red seaweed, *Hypnea musciformis*, cultured in tanks with shellfish culture effluent [279,280]. Haines (1976) found that *H. musciformis* grown with the effluent from clam mariculture grew approximately 5 times faster than growth in unaltered deep water and about three times faster than in surface water [279]. Langton et al. (1977) also grew *H. musciformis* with clam wastewater and found that it had an ammonia-N uptake rate of up to 70% [280]. From the 1980s, the number of studies reporting on the use of algae for integration into on-land aquaculture increased, with *Ulva* spp. and *Gracilaria* spp. being the most frequently studied species. Troell et al. (2003), Neori et al. (2004), and Granada et al. (2015) have a comprehensive list of references for these studies, a few examples of which will be discussed below [4,131,135].

Vandermeulen and Gordin (1990) found that *Ulva lactuca* cultured with intensive fishpond wastewater grew very strongly, with a growth rate of over 55 g·dry weight (DW)/day^{-1} per 600 L and efficiently removed up to 85% of the ammonium from the wastewater [281]. Neori et al. (1991) cultured *U. lactuca* in effluent from intensive fishponds and found that the specific growth rate and yield were higher than *U. lactuca* grown in enriched fresh seawater. Under wastewater culture conditions, the maximum yield (DW) achieved was 55 g·m^{-2}·day^{-1} and maximum specific growth rate was 18%·day^{-1}. Yields achieved through wastewater cultivation were up to 38% higher than the enriched fresh seawater. Through conducting this research, Neori et al. (1991) suggested that, for high yield and nitrogen content, *U. lactuca* should be kept at a density of 1–2 kg·m^{-2} and at ammonia fluxes of approximately 0.5 moles·m^{-2}·day^{-1} [282]. Jimenez del Río et al. (1996) cultivated *Ulva rigida* in 750 L tanks being fed wastewater from a commercial marine fishpond rearing 40 metric tonnes (Mt) of Gilt-head bream (*Sparus aurata*), and determined that maximum yields of *U. rigida* (40 g·DW·m^{-2}·day^{-1}) were obtained at a seaweed density of 2.5 g·FW·L^{-1} and a dissolved inorganic nitrogen (DIN) inflow rate of 1.77 g·DIN·m^{-2}. The average annual DIN removal efficiency under these parameters was 2 g·DIN·m^{-2}·day^{-1} and it was calculated that 153 m^2 of *U. rigida* tank surface would be needed to recover 100% of the DIN produced by 1 Mt of fish [283]. Buschmann et al. (1996) cultivated *Gracilaria chilensis* in four 2500 L raceways that received wastewater from the tank cultivation of coho salmon (*Oncorhynchus kisutch*) and rainbow trout (*O. mykiss*). At its highest, *G. chilensis* production can reach up to 48.9 kg·m^{-2}·year^{-1} and can remove 50% of dissolved ammonium in winter, increasing to 90%–95% in spring. Buschmann et al. (1996) also performed an income-analysis model and calculated that the harvesting of *G. chilensis* can provide additional total revenue of over $60,000, representing approximately 10% of the total income [284]. Chow et al. (2001) utilised *G. chilensis* as a biofilter in the depuration of effluents from tank cultures of Cabinza grunt (*Isacia conceptionis*), oysters (*Crassostrea gigas*), and sea urchins (*Loxechinus albus*) and compared its productivity and relative growth rate (RGR) to *G. chilensis* cultivated with seawater. *G. chilensis* was cultivated in 200 L tanks (0.5 m^2 surface area). It was found that productivity was highest in the *G. chilensis* tanks fed with the fish effluent, with a FW of 51.2 g·m^{-2}·day^{-1}, in comparison to 23.9, 16.2, and 18.6 g·m^{-2}·day^{-1} for *G. chilensis* tanks fed with oyster effluent, urchin effluent, and control seawater, respectively. [285]. Abreu et al. (2011) established 12, 1200 L (total footprint of 18 m^2) *G. vermiculophylla* tanks at a commercial, land-based intensive aquaculture farm producing 40 tonnes of turbot (*Scophthalmus rhombus*), 5 tons of sea bass (*D. labrax*), and 500,000 Senegalese sole juveniles (*Solea sengalensis*). *G.vermiculophylla* grew best at a stocking density of 3 kg·WW·m^{-2} and water exchange rate of 200 L·h^{-1}, producing 0.7 $\pm$ 0.05 kg·DW·m^{-2}·month^{-1}, while removing 40.54 $\pm$ 2.02 g·m^{-1}·month^{-1} of N. They calculated that in one year, this system could produce approximately 156 kg (DW) of seaweed and this biomass level would remove 8.8 kg of N. To attain 100% N removal efficacy, it was calculated that the tank area would need to be increased to 0.36 ha, considering the cultivation conditions are kept the same (i.e., stocking density of 3 kg·WW·m^{-2}, 1200 L tanks with a footprint of 1.5 m^{-2}, and a water exchange rate of 200 L·h^{-1}) [286]. As can be seen from some of the above studies, seaweeds not only grow well when cultivated with effluent water from mariculture, but can grow better than seaweed cultivated with seawater or fertilizer-enriched seawater.

Alternatively, crops that would usually be classed as glycophytes, such as the common tomato (*Lycopersycon esculentum*), the cherry tomato (*Lycopersycon esculentum* var. *Cerasiformee*), and basil (*Ocimum basilicum*) can achieve remarkably successful production levels at up to 4 g/L salinity and are often referred to as having low-moderate levels of salt tolerance (not to be confused with halophytes, which are resistant of high salinities). Other crops that are tolerant of low-moderate salinities include: turnip, radish, lettuce, sweet potato, broad bean, corn, cabbage, spinach, asparagus, beets, squash, broccoli, and cucumber [265,287–289]. Dufault et al. (2001) and Dufault and Korkmaz (2000) experimented with shrimp biosolids (SB) (shrimp fecal matter and decomposed feed) as a fertilizer for broccoli (*Brassica oleracea italica*) and bell pepper (*Capsicum annuum*) production respectively. In both trials, they fertilized the crops with just SB, combined with Oscomote fertiliser (OSM), and just OSM and found that SB does not maximize yields when used alone. For the broccoli trial, the culture system that enhanced yield combined nine MT SB/ha with 75 kg OSM/ha, delivering a combined total of 263, 116, 99, and 99 kg/Ha of N, P, K, and Na respectively. For the bell pepper trial, the culture system that enhanced yield included the highest rates of both SB and OSM, which delivered a total of 633, 253, and 303 kg/Ha of N, P, and K respectively. N–253 P–303 K kg/ha. In both trials, however, it was noted that SB contains a high level of sodium and an increase in soil salt concentration could suppress the growth of some crops, especially those that are salt sensitive (e.g., carrots, strawberries, and onions). For this reason, Dufault and Korkmaz (2000) recommend a number of cultural steps when using SB, to reduce the risk of salinity damage. They advise to modify the salinity of the SB by: dilution, blending with other organic matter, leaching SB with irrigation water, or by using SB in soils with high buffering capacity [288,289]. Although the above studies did not use SA techniques, they involved plants that are commonly grown using aquaponic (freshwater) techniques. Therefore, due to their salinity tolerance levels, they have enormous potential as candidate species for use in SA systems using low to medium salinities.

A majority of the SA work conducted so far involves the integration of two trophic levels. An example of a SA system incorporating more than two trophic levels can be seen in an experiment conducted by Neori et al. (2000), who designed a 3.3 m^2 system for the intensive land-based culture of Japanese abalone (*Haliotis discus hannai*), seaweeds (*Ulva lactuca* & *Gracilaria conferta*), and pellet-fed Gilt-head bream (*Sparus aurata*). The system design consisted of unfiltered seawater (2400 $L \cdot day^{-1}$) pumped to two abalone tanks, drained through a fish tank, and finally through a seaweed filtration/production unit before being discharged to the sea. The abalone unit consists of two 120 L rectangular bottom drained tanks, which were elevated to allow effluents to drain into the fish tank. A removable screen (1 cm mesh) covered the whole area 10 cm above the flat bottom, to retain the abalone while allowing feces and detritus to drain. The first tank was stocked with 1200 juveniles (mean: 0.23 ± 0.04 g) and the second tank had 251 adults (mean: 15.7 ± 4.6 g). Three hundred sea bream with an average weight of 40 g were stocked in a 600 L (1 m^2 surface area) rectangular aerated tank and fed a 45% protein pellet diet. Stocking density was maintained below 15 $kg \cdot m^3$. *U. lactuca* and *G. conferta* were grown in two 600 L (1 m^2 surface area) tanks. The algae were suspended in the water column by air diffusers situated at the bottom. Total seaweed biomass was kept at approximately 1.5 kg of *U. lactuca* and 5–13 kg of *G. conferta* (excess seaweed was harvested twice a week and fed to the abalone). The fish grew at $0.67\% \cdot day^{-1}$, yielding 28 $kg \cdot m^{-2} \cdot year^{-1}$. The nutrients excreted by the fish supported high yields of *U. lactuca* (78 $kg \cdot m^{-2} \cdot year^{-1}$) and efficient ammonia filtration (80%), however, *G. conferta* functioned poorly. The *Ulva* supported an abalone growth rate of $0.9\% \cdot day^{-1}$ and a length increase of 40–66 $\mu m \cdot day^{-1}$ in juveniles and $0.34\% \cdot day^{-1}$ and 59 $\mu m \cdot day^{-1}$ in young adults. The total abalone yield was 9.4 $kg \cdot year^{-1}$. Ammonia as a fraction of total feed-N was reduced from 45% in the fish effluents to 10% in the post-seaweed discharge. A surplus of seaweed was created in the system and based on this trials results, a doubling of the abalone:fish ratio form 0.3 to 0.6 is feasible [290].

SA offers a number of advantages over traditional crop and fish production methods. As SA systems use saline water (brackish to saline) there is a reduced dependence on freshwater, which has become a very limited resource. It is typically practiced in a controlled environment (e.g., a greenhouse; controlled flow-rate tanks) giving a better opportunity for intensive production. Many SA systems are closed RASs with organic and/or mechanical biofilters, subsequently, water reuse is high, wastewater pollution is vastly reduced or eliminated, and contaminants are removed or treated. SA systems that are not RASs significantly reduce the excess nutrients in the wastewater prior to discharge. Also, the occurrence of contaminants in non-RAS SA systems can be reduced or eliminated through the use of water containing low levels of naturally occurring contaminants and the use of alternatives aquafeeds that do not contain dioxins or PCDs (e.g., novel feeds made from macroalgae). This improvement in water quality reduces the potential for disease occurrence and the need for antibiotic use is therefore vastly reduced [2,18,265,269,271,290,291]. Due to SA's versatile configuration and low water requirements, it can be successfully implemented in a wide-variety of settings, from fertile coastal areas to arid deserts, as well as in urban or peri-urban settlements [273]. Another potential benefit of SA is that many of the species that are suitable for these systems, have a high commercial value. For example, the euryhaline European sea bass (*Dicentrarchus labrax*) and gilthead sea bream (*Sparus aurata*) can fetch a market price of €9/kg and €6/kg respectively. Additionally, edible halophytes tend to have a high market price; with sea-agretto (*Salsola soda*), for example, having a market price of €4/kg–€4.5/kg [265,270]. SA is a dynamic and rapidly growing field that has the potential to provide a number of services to communities. Love et al. (2014) conducted an international survey of aquaponic practitioners and found that most were hobbyists, however, a significant proportion of respondents were educators, non-profit organizations (NGOs), and commercial producers. The main reasons cited for being involved in aquaponics were to grow their own food, to advance environmental sustainability, and improve personal health. As SA shares many of the principles and methodologies of aquaponics, it also has many potential applications for local communities [220]. For example, due to the interdisciplinary nature and technological skills required to set-up and run a SA system, they are ideal systems for use as an educational tool. Aquaponic systems, for example, are already in a number of schools across America, allowing students to conduct activities involving chemistry, physics, biology, and sustainability. Also, small to medium scale systems require very little space and can be located in schoolyards, basements, balcony spaces, classrooms, rooftops etc. SA systems could be utilized in the same manner to teach students about these aspects, from a marine/saltwater biology perspective [292]. The ideal pH range for the growth of saltwater fish, halophytes, and saline nitrifying bacteria is approximately 7.5–8.5. Therefore, the issue of a dichotomy between the optimum pH for plant nutrient availability and for nitrifying bacteria that occurs in aquaponics should not be an issue for SA, apart from, perhaps, when salt-tolerant glycophytes are chosen as the plant component [278,293].

Despite these benefits, there are a number of constraints. The hydroponic aspect of SA systems in particular can require a relatively large area of land. For example, Rakocy et al. (2006) estimated that, on average, a square meter of plant growth area is required to treat the water for every 60–100 g of fish feed used [244]. There is an increased risk of cross contamination of pathogens (e.g., of the bacteria *Salmonella* and *Escherichia coli*) when growing animals (e.g., fish) near plant produce. However, a number of steps can be taken to prevent any food-safety risks associated with the SA production of food products (refer to reference 295 for more information on on-site freshwater and saltwater aquaponic food safety procedures) [2,294]. Consumers may be wary of consuming produce that was grown with water containing fish feces. Educational initiatives and careful marketing may help alleviate these concerns. Also, if SA develops a strong community-based interest similar to aquaponics, this concern may be reduced further [2,220]. As SA is a relatively new concept, there is a lack of large-scale models to base designs off and a lack of trained or experienced personnel capable of commercial SA management. The development of SA has also been constrained by limited land-based production of saltwater fish species and a limited selection of appropriate edible species that grow in saltwater. Further research is required to identify compatible species of fish and aquatic plants that will thrive in an on-land SA system [2,269].

5. Conclusions

In 2014, for the first time in history, aquaculture's contribution to the global supply of fish for human consumption exceeded that from capture fisheries. This was as a result of wild fisheries reaching or exceeding their sustainable limit, a lack of fishery policy that promotes efficiency, and an aquaculture industry that is becoming increasingly innovative and making enormous strides in technology and management [3,6,8,9]. Although the majority of aquaculture currently takes place in freshwater (c.60%), it is likely that saltwater aquaculture will close this gap as global freshwater shortages reduce the ability to conduct on-land freshwater aquaculture [3]. Saltwater aquaculture has become one of the most promising avenues for increasing the production of seafood against a backdrop of exploited or over-exploited fisheries, however, it does come with a number of potential negative impacts (i.e., effluent discharge; presence of contaminants; water consumption; farmed fish escapes; parasite and disease transmission; reliance on fishmeal and oil for addition to feeds).

RAS operations offer a number of solutions to these concerns. Due to the on-land and recirculatory nature of RAS, the potential for fish escapes is extremely low and 90%–99% of water is recycled. They can be located on land unsuitable for other food production methods, in urban areas or close to markets Contaminants, parasites, and diseases can be removed or treated effectively through sterilization of the reused water and all wastes can be concentrated and treated or used as an input to other production systems (e.g., agricultural fertilizer or methane generation) [2,88,89,100–104]. RASs can also be located away from water bodies, further reducing the potential for fish escapes to the environment, and allowing for the culture of faster-growing fish that have been selectively bred or genetically modified without the worry of potential biological invasion [2]. Despite these advantages, RASs have a significant drawback; the high cost of infrastructure, labor, management, and energy. For this reason RASs show most promise for the production of high valued species such as salmonids, which have a high reliance of fishmeal and fish oil rich aquafeeds and will not be affordable for developing nations who rely mainly on lower trophic level fish for their fish protein intake [91,104].

The concept of integrated multi-trophic aquaculture (IMTA) aims to address the negative impacts of saltwater aquaculture through an ecosystem-based approach, where species from different trophic levels utilize the wastes from fed aquaculture (e.g., finfish and shrimp). Inorganic extractive species (e.g., seaweeds) uptake excess nutrients such as nitrogen and phosphorus, while organic extractive species (i.e., invertebrates) uptake detritus and organic matter [126,129,130]. Organic extractive species (e.g., mussels) have also demonstrated their ability to consume parasites and inactivate pathogens. The novel use of cleaner-fish is also being trialed and has shown promise in, for example, the removal of sea-lice from Atlantic salmon [145,146,177,178]. Culturing species form different trophic levels can achieve environmental stability through the biomitigation of aquaculture wastes, while at the same time providing the farmer economic stability through product diversification [2,129].

For offshore aquaculture and non-RASs on-land systems, the issue of natural and man-made contaminants accumulating in farmed crops and/or negatively impacting their health may not be solved through IMTA techniques. However, solutions include locating farms in areas with low levels of naturally occurring contaminates and the use of PCD and dioxin free fish feeds [18]. The concept of IMTA itself will also not solve the potential for fish escapes in offshore IMTA systems, however, the risk can be reduced through the use of stronger net materials and covers on boat propellers to avoid tearing of nets. Like RASs, on-land IMTA systems isolated from the natural environment will provide a more secure method for fish escape mitigation [21,60]. Aquaculture's high reliance of fishmeal and fish oil for the production of aquafeeds will also need to be addressed for IMTA systems to be truly environmentally sustainable. Fishmeal and fish oil is generally obtained from fish low down on the food chain (i.e., small pelagic fish). These fish provide an essential food source for large fish, marine mammals, seabirds, and humans (particularly those from developing countries) [2,19,78–80]. This will require further research and development into alternative feed ingredients (e.g., terrestrial plant alternatives, macroalgae) and the further improvement of fed fish FCRs [2,6,17,19,74,77,81].

For on-land saltwater aquaculture, there are a number of IMTA options currently being researched and developed. For farms that are located in areas where a large quantity of low cost land is available, halophyte constructed wetlands (CWs) provide an IMTA approach that is cost-effective, requires moderate capital investment, and has low energy consumption and maintenance expenses [210–212]. A number of studies have demonstrated the effectiveness of halophyte CWs in the removal of nitrogen, phosphorus, and suspended solids, while providing a crop that has a number of commercial applications [185,196–210]. However, halophyte CWs require an extensive area and would not be suitable in locations with a high land price. Also, the variety of crops you can grow in constructed wetlands is quite limited [184,198].

SA is an on-land IMTA concept that combines saltwater aquaculture with the hydroponic cultivation of saltwater or salt resistant/tolerant aquatic plants. These systems are typically practiced in a controlled manner (e.g., controlled flow rates; located in greenhouses), are often recirculatory in nature, and have organic and/or mechanical biofilters, providing a better opportunity for intensive cultivation, water reuse, and reduced wastewater production when compared with traditional crop and fish production methods. Improvements to the water quality also reduce the potential for disease occurrence and subsequently the need for antibiotic use [265,269,291]. Due to SA's versatile configuration options and low water requirements they can be located in a variety of settings from arid deserts to urban settlements [270] and can be utilized by a wide range of user-groups such as hobbyists, NGOs, educators, and commercial producers [220]. However, as SA is a relatively new concept, there is a lack of models (especially on a commercial-scale) to base designs off and there is a lack of trained or experienced personnel capable of running SA systems. In contrast to freshwater systems, there is also a limited selection of suitable, edible species that grow in saltwater [2,269].

IMTA as a concept is still in its infancy and a large amount of research and development is still required to identify a suitable combination of species, in the correct proportions, that will operate effectively on a site-specific basis. Nevertheless, rethinking aquaculture production with an integrated mind-set will be needed to tackle the simultaneous challenges of feed and energy demands, containment of wastes, control of pathogens and disease, escaped fish, land and water requirements, and consumers' increasing preference for sustainably produced food products. Also, as profit margins in aquaculture continue to become smaller, the attractiveness of using wastes as inputs to other profitable crops will continue to grow, as long as food safety issues and the public perception of food produced with water containing fish feces is effectively dealt with.

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References

1. United States Census Bureau. U.S. and World Population Clock. Available online: http://www.census.gov/popclock/ (accessed on 11 August 2016).
2. Klinger, D.; Naylor, R. Searching for solutions in aquaculture: Charting a sustainable course. *Annu. Rev. Environ. Resour.* **2012**, *37*, 247–276. [CrossRef]
3. Food and Agriculture Organization of the United Nations. *The State of World Fisheries and Aquaculture 2016: Contributing to Food Security and Nutrition for All*; FAO: Rome, Italy, 2016; p. 200.
4. Granada, L.; Sousa, N.; Lopes, S.; Lemos, M.F.L. Is integrated multitrophic aquaculture the solution to the sectors' major challenges?—A review. *Rev. Aquac.* **2016**, *8*, 283–300. [CrossRef]
5. Lund, E.K. Health benefits of seafood; is it just the fatty acids? *Food Chem.* **2013**, *140*, 413–420. [CrossRef] [PubMed]
6. Troell, M.; Naylor, R.L.; Metian, M.; Beveridge, M.; Tyedmers, P.H.; Folke, C.; Arrow, K.J.; Barrett, S.; Crépin, A.; Ehrlich, P.R.; et al. Does Aquaculture add resilience to the global food system? *Proc. Natl. Acad. Sci. USA* **2014**, *111*, 13257–13263. [CrossRef] [PubMed]
7. Diana, J.S. Aquaculture production and biodiversity conservation. *BioScience* **2009**, *59*, 27–38. [CrossRef]
8. Naylor, R.; Burke, M. Aquaculture and ocean resources: Raising tigers of the sea. *Annu. Rev. Environ. Resour.* **2005**, *30*, 185–218. [CrossRef]
9. Eagle, J.; Naylor, R.; Smith, W. Why farm salmon outcompete fishery salmon. *Mar. Policy* **2004**, *28*, 259–270. [CrossRef]
10. Food and Agriculture Organisation of the United Nations. *The State of World Fisheries and Aquaculture 2010*; FAO: Rome, Italy, 2010; p. 197.
11. Bell, J.D.; Bartley, D.M.; Lorenzen, K.; Loneragan, N.R. Restocking and stock enhancement of coastal fisheries: Potential, problems and progress. *Fish. Res.* **2006**, *80*, 1–8. [CrossRef]
12. Gifford, S.; Dunstan, R.H.; O'Connor, W.; Koller, C.E.; MacFarlane, G.R. Aquatic zooremediation: Deploying animals to remediate contaminated aquatic environments. *Trends Biotechnol.* **2007**, *25*, 60–65. [CrossRef] [PubMed]
13. Bunting, S.W. Wastewater aquaculture: Perpetuating vulnerability or opportunity to enhance poor livelihoods? *Aquat. Resour. Cult. Dev.* **2004**, *1*, 51–57.
14. Kawarazuka, N.; Béné, C. Linking small-scale fisheries and aquaculture to household nutritional security: An overview. *Food Secur.* **2010**, *2*, 343–357. [CrossRef]
15. Subasinghe, R.; Soto, D.; Jia, J. Global aquaculture and its role in sustainable development. *Rev. Aquac.* **2009**, *1*, 2–9. [CrossRef]

16. Smith, M.D.; Roheim, C.A.; Crowder, L.B.; Halpern, B.S.; Turnipseed, M.; Anderson, J.L.; Asche, F.; Bourillón, L.; Guttormsen, A.G.; Khan, A.; et al. Sustainability and global seafood. *Science* **2010**, *327*, 784–786. [CrossRef] [PubMed]
17. Naylor, R.L.; Goldburg, R.J.; Primavera, J.H.; Kautsky, N.; Beveridge, M.C.M.; Clay, J.; Folke, C.; Lubchenco, J.; Mooney, H.; Troell, M. Effect of aquaculture on world fish supplies. *Nature* **2000**, *405*, 1017–1024. [CrossRef] [PubMed]
18. Cole, D.W.; Cole, R.; Gaydos, S.J.; Gray, J.; Hyland, G.; Jacques, M.L.; Powell-Dunford, N.; Sawhney, C.; Au, W.W. Aquaculture: Environmental, toxicological, and health issues. *Int. J. Hyg. Environ. Health* **2009**, *212*, 369–377. [CrossRef] [PubMed]
19. Naylor, R.L.; Hardy, R.W.; Bureau, P.D.; Chiu, A.; Elliott, M.; Farrell, A.P.; Forster, I.; Gatlin, D.M.; Goldburg, R.J.; Hua, K.; et al. Feeding aquaculture in an era of finite resources. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 15103–15110. [CrossRef] [PubMed]
20. Read, P.; Fernandes, T. Management of environmental impacts of marine aquaculture in Europe. *Aquaculture* **2003**, *226*, 139–163. [CrossRef]
21. Naylor, R.; Eagle, J.; Smith, W. Salmon aquaculture in the Pacific North-west: A global industry with local impacts. *Environment* **2003**, *45*, 18–39. [CrossRef]
22. Grigorakis, K.; Rigos, G. Aquaculture effects on the environmental and public welfare—The case of Mediterranean Mariculture. *Chemosphere* **2011**, *855*, 899–919. [CrossRef] [PubMed]
23. Zhou, Y.; Yang, H.; Hu, H.; Liu, Y.; Mao, Y.; Zhou, H. Bioremediation potential of the macroalga *Gracilaria lemaneiformis* (Rhodophyta) integrated into fed fish culture in coastal waters of north China. *Aquaculture* **2006**, *252*, 264–276. [CrossRef]
24. Marinho-Soriano, E.; Azevedo, C.A.A.; Trigueiro, T.G.; Pereira, D.C.; Carneiro, M.A.A.; Camara, M.R. Bioremediation of aquaculture wastewater using macroalgae and Artemia. *Int. Biodeterior. Biodegrad.* **2011**, *65*, 253–257. [CrossRef]
25. Burridge, L.; Weis, J.S.; Cabello, F.; Pizarro, J.; Bostick, K. Chemical use in salmon aquaculture: A review of current practices and possible environmental effects. *Aquaculture* **2010**, *306*, 7–23. [CrossRef]
26. Brand, L.E.; Sunda, W.G.; Guillard, R.R.L. Reduction of marine phytoplankton reproduction rates by copper and cadmium. *J. Exp. Biol. Ecol.* **1986**, *96*, 225–250. [CrossRef]
27. Le Jeune, A.H.; Charpin, M.; Deluchat, V.; Briand, J.F.; Lenain, J.F.; Baudu, M.; Amblard, C. Effect of copper sulphate treatment on natural phytoplanktonic communities. *Aquat. Toxicol.* **2006**, *80*, 267–280. [CrossRef] [PubMed]
28. Winner, R.W.; Owen, H.A. Seasonal variability in the sensitivity of freshwater phytoplankton communities to a chronic copper stress. *Aquat. Toxicol.* **1991**, *19*, 73–88. [CrossRef]
29. Russell, M.; Robinson, C.D.; Walsham, P.; Webster, L.; Moffat, C.F. Persistent organic pollutants and trace metals in sediments close to Scottish marine fish farms. *Aquaculture* **2011**, *319*, 262–271. [CrossRef]
30. Hites, R.A.; Foran, J.A.; Carpenter, D.O.; Hamilton, M.C.; Knuth, B.A.; Schwager, S.J. Global assessment of organic contaminants in farmed salmon. *Science* **2004**, *303*, 226–229. [CrossRef] [PubMed]
31. Hites, R.A.; Foran, J.A.; Schwager, S.J.; Knuth, B.A.; Hamilton, M.C.; Carpenter, D.O. Global assessment of polybrominated diphenyl ethers in farmed and wild salmon. *Environ. Sci. Technol.* **2004**, *38*, 4945–4949. [CrossRef] [PubMed]
32. Montory, M.; Barra, R. Preliminary data on poly-brominated dephenyl ethers (PBDE) in farmed fish tissues (*Salmo salar*) and fish feed in Southern Chile. *Chemosphere* **2006**, *63*, 1252–1260. [CrossRef] [PubMed]
33. Hayward, D.; Wong, J.; Krynitsky, A.J. Polybrominated diphenyl ethers and polychlorinated biphenyls in commercially wild caught and farm-raised fish fillets in the United States. *Environ. Res.* **2007**, *103*, 46–54. [CrossRef] [PubMed]
34. Minh, N.H.; Minh, T.B.; Kajiwara, N.; Kunisue, T.; Iwata, H.; Viet, P.H.; Tu, N.P.; Tuyen, B.C.; Tanabe, S. Contamination by polybrominated diphenyl ethers and persistent organochlorides in catfish and feed from Mekong River Delta, Vietnam. *Environ. Toxicol. Chem.* **2006**, *25*, 2700–2708. [CrossRef] [PubMed]
35. Blanco, S.L.; Sobrado, C.; Quintela, C.; Cabaleiro, S.; Gonzalez, J.C.; Vietites, J.M. Dietary uptake of dioxin (PCDD/PCDFs) and dioxin-like PCBs in Spanish aquacultured turbot (*Psetta maxima*). *Food Addit. Contam.* **2007**, *24*, 421–428. [CrossRef] [PubMed]

36. Carubelli, G.; Fanelli, R.; Mariani, G.; Nichetti, S.; Crosa, G.; Calamari, D.; Fattore, E. PCB contamination in farmed and wild sea bass (*Dicentrarchus labrax* L.) from a coastal wetland area in central Italy. *Chemosphere* **2007**, *68*, 1630–1635. [CrossRef] [PubMed]
37. Pinto, B.; Garritano, S.L.; Cristofani, R.; Ortaggi, G.; Giuliano, A.; Amodio-Cocchierri, R.; Cirillo, R.; DeGiusti, M.; Boccia, A.; Reali, D. Monitoring of polychlorinated biphenyl contamination and estrogenic activity in water, commercial feed, and farmed seafood. *Environ. Monit. Assess.* **2008**, *144*, 445–453. [CrossRef] [PubMed]
38. Dewailly, E.; Ayotte, P.; Lucas, M.; Blanchet, C. Risk and benefits from consuming salmon and trout: A Canadian perspective. *Food Chem. Toxicol.* **2007**, *45*, 1345–1349.
39. Foran, J.A.; Carpenter, D.O.; Hamilton, M.C.; Knuth, B.A.; Schwager, S.J. Risk-based consumption advice for farmed Atlantic and wild pacific salmon contaminated with dioxins and dioxin-like compounds. *Environ. Health Perspect.* **2005**, *113*, 552–555. [PubMed]
40. Hastein, T.; Hjeltnes, B.; Lillehaugh, A.; Utne Skare, J.; Berntssen, M.; Lundebye, A.K. Food safety hazards that occur during the production stage: Challenges for fish farming and the fishing industry. *Rev. Sci. Technol.* **2006**, *25*, 607–625.
41. Easton, M.D.L.; Luszniak, D.; Von der Geest, E. Preliminary examination of contaminant loadings in farm salmon, wild salmon, and commercial salmon feed. *Chemosphere* **2002**, *46*, 1053–1074. [CrossRef]
42. Davidson, P.; Myers, G.J.; Weiss, B.; Shamlaye, C.F.; Cox, C. Commentary: Prenatal methyl mercury exposure from fish consumption and child development: A review of evidence and perspectives from the Seychelles child development study. *Neuro Toxicol.* **2006**, *27*, 1106–1109.
43. Axelad, D.A.; Bellinger, D.C.; Ryan, L.M.; Woodruff, T.J. Dose-response relationship of prenatal mercury exposure and IQ: An integrative analysis of epidemiologic data. *Environ. Health Perspect.* **2007**, *115*, 609–615. [CrossRef] [PubMed]
44. Oterhals, A.; Nygard, E. Reduction of persistent organic pollutants in fishmeal: A feasibility study. *J. Agric. Food Chem.* **2008**, *56*, 2012–2020. [CrossRef] [PubMed]
45. Brambilla, G.; Dellatte, E.; Fochi, I.; Iacovella, N.; Miiero, R.; diDomenico, A. Depletion of selected polychlorinated biphenyl, dibenzodioxin, and debenzofuran congeners in farmed rainbow trout (*Oncorhynchus mykiss*): A hint for safer fish farming. *Chemosphere* **2007**, *20*, 34–43.
46. Kiljunen, M.; Vanhatalo, M.; Mantyniemi, S.; Peltonen, H.; Kuikka, S.; Kiviranta, H.; Parmanne, R.; Tuomisto, J.T.; Vuorinen, P.J.; Hallikainen, A.; et al. Human dietary intake of organochlorines from Baltic herring: Implications of individual fish variability and fisheries management. *Ambio* **2007**, *36*, 257–264. [CrossRef]
47. Bridger, C.J.; Garber, A. Aquaculture escapement, implications, and mitigation: The salmonid case study. In *Ecological Aquaculture: The Evolution of the Blue Revolution*; Costa-Pierce, B.A., Ed.; Blackwell Science: Malden, MA, USA, 2002; pp. 77–102.
48. Brown, N. Flatfish farming systems in the Atlantic region. *Rev. Fish. Sci.* **2002**, *10*, 403–419. [CrossRef]
49. Avnimelech, Y. Carbon/nitrogen ratio as a control element in aquaculture systems. *Aquaculture* **1999**, *176*, 227–235. [CrossRef]
50. Páez-Osuna, F. The environmental impact of shrimp aquaculture: A global perspective. *Environ. Pollut.* **2001**, *112*, 229–231. [CrossRef]
51. Páez-Osuna, F.; Guerrero-Galván, S.R.; Ruiz-Fernández, A.C. The environmental impact of shrimp aquaculture and the coastal pollution in Mexico. *Mar. Pollut. Bull.* **1998**, *36*, 65–75. [CrossRef]
52. Boyd, C.E.; Gross, A. Water use and conservation for inland aquaculture ponds. *Fish. Manag. Ecol.* **2000**, *7*, 55–63. [CrossRef]
53. Arthur, R.I.; Lorenzen, K.; Homekingkeo, P.; Sidavong, K.; Sengvilaikham, B.; Garaway, C.J. Assessing impacts of introduced aquaculture species on native fish communities: Nile tilapia and major carps in SE Asian freshwaters. *Aquaculture* **2010**, *299*, 81–88. [CrossRef]
54. Fleming, I.A.; Hindar, K.; Mjolnerod, I.; Jonsson, B.; Balstad, T.; Lamberg, A. Lifetime success and interactions of farm salmon invading a natural population. *Proc. R. Soc. Lond. Ser. B* **2000**, *267*, 1517–1523. [CrossRef] [PubMed]

55. McGinnity, P.; Prodohl, P.; Ferguson, A.; Hynes, R.; Maoileidigh, N.O.; Baker, N.; Cotter, D.; O'Hea, B.; Cooke, D.; Rogan, G.; et al. Fitness reduction and potential extinction of wild populations of Atlantic salmon, *Salo salar*, as a result of interactions with escaped farmed salmon. *Proc. R. Soc. Lond. Ser. B* **2003**, *270*, 2443–2450. [CrossRef] [PubMed]
56. McGinnity, P.; Stone, C.; Taggart, J.; Cooke, D.; Cotter, D.; Hynes, R.; McCamley, C.; Cross, T.; Ferguson, A. Genetic impact of escaped farmed Atlantic salmon (*Salmo salar* L.) on native populations: Use of DNA profiling to assess freshwater performance of wild, farmed, and hybrid progeny in a natural river environment. *ICES J. Mar. Sci.* **1997**, *54*, 998–1008. [CrossRef]
57. Volpe, J.; Taylor, E.; Rimmer, D.; Glickman, B. Evidence of natural reproduction of aquaculture-escaped Atlantic salmon in a coastal British Columbia river. *Conserv. Biol.* **2000**, *14*, 899–903. [CrossRef]
58. Kolmes, S.A. Salmon farms and hatcheries. *Environment* **2004**, *46*, 40–43.
59. Levin, P.S.; Zabel, R.W.; Williams, J.G. The road to extinction is paved with good intentions: Negative association of fish hatcheries with threatened salmon. *Proc. R. Soc. Lond. Ser. B* **2001**, *268*, 1153–1158. [CrossRef] [PubMed]
60. Naylor, R.; Hindar, K.; Fleming, I.A.; Goldburg, R.; Williams, S.; Volpe, J.; Whoriskey, F.; Eagle, L.; Kelso, D.; Mangel, M. Fugitive salmon: Assessing the risks of escaped fish from net-pen aquaculture. *BioScience* **2005**, *55*, 427–437. [CrossRef]
61. Hansen, P.; Jacobsen, J.A.; Und, R.A. High numbers of farmed Atlantic salmon, *Salmo salar*, observed in oceanic waters north of the Faroe Islands. *Aquac. Fish. Manag.* **1993**, *24*, 777–781. [CrossRef]
62. McKinnell, S.; Thomson, A.J. Recent events concerning Atlantic salmon escapees in the Pacific. *ICES J. Mar. Sci.* **1997**, *54*, 1221–1225. [CrossRef]
63. Gross, M.R. One species with two biologies: Atlantic salmon (*Salmo salar*) in the wild and in aquaculture. *Can. J. Fish. Aquat. Sci.* **1998**, *55*, 1–14. [CrossRef]
64. Slaney, T.L.; Hyatt, K.D.; Northcote, T.G.; Fielden, R.J. Status of anadromous salmon and trout in British Columbia and Yukon fisheries. *Am. Fish. Soc.* **1996**, *21*, 20–35.
65. Krkosek, M.; Lewis, M.A.; Volpe, J.P.; Morton, A. Fish farms and sea lice infestations of wild juvenile salmon in the Broughton Archipelago—A rebuttal to Brooks (2005). *Fish. Sci.* **2006**, *14*, 1–11. [CrossRef]
66. Krkosek, M.; Ford, J.S.; Morton, A.; Lele, S.; Myers, R.A.; Lewis, M. Declining wild salmon populations in realtion to parasites from farm salmon. *Science* **2007**, *318*, 1772–1775. [CrossRef] [PubMed]
67. Ford, J.S.; Myers, R.A. A global assessment of salmon aquaculture impacts on wild salmonids. *PLoS Biol.* **2008**, *6*. [CrossRef] [PubMed]
68. McVicar, A.H. Disease and parasite implications of the coexistence of wild and culture salmon populations. *ICES J. Mar. Sci.* **1997**, *54*, 1093–1103. [CrossRef]
69. Dalton, R. Fishing for trouble. *Nature* **2004**, *431*, 502–504. [CrossRef] [PubMed]
70. Tacon, A.G.J. Selected developments and trends: Aquafeeds and feeding strategies. In *Review of the State of World Aquaculture*; Shehadeh, Z., Ed.; UN Food Agriculture Organization: Rome, Italy, 1997. Available online: http://www.fao.org/docrep/003/W7499E/w7499e16.htm (accessed on 26 August 2016).
71. Food and Agriculture Organisation of the United Nations. *The State of World Fisheries and Aquaculture 2014*; FAO: Rome, Italy, 2014; p. 243.
72. Tacon, A.G.J.; Hasan, M.R.; Subasinghe, R.P. *Use of Fishery Resources as Feed Inputs for Aquaculture Development: Trends and Policy Implications*; FAO Fisheries Circular No. 1018; Food Agriculture Organization: Rome, Italy, 2006; p. 99.
73. Tacon, A.G.J.; Hasan, M.R.; Metian, M. *Demand and Supply of Feed Ingredients for Farmed Fish and Crustaceans*; FAO Fisheries and Aquaculture Technical Paper No. 564; Food Agriculture Organization: Rome, Italy, 2011; p. 87.
74. Hardy, R.W. Utilization of plant proteins in fish diets: Effects of global and supplies of fishmeal. *Aquac. Res.* **2010**, *41*, 770–776. [CrossRef]
75. Boissy, J.; Aubin, J.; Abdeljalil, D.; van der Werf, H.M.G.; Bell, G.J.; Kaushik, S.J. Environmental impacts of plant-based salmonid diets at feed and farm scales. *Aquaculture* **2011**, *321*, 61–71. [CrossRef]
76. Goldburg, R.; Naylor, R. Future seascapes, fishing and fish farming. *Front. Ecol.* **2005**, *3*, 21–28. [CrossRef]
77. Tacon, A.G.J.; Metian, M. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. *Aquaculture* **2008**, *285*, 146–158. [CrossRef]
78. Kaushik, S.; Troell, M. Consumer confusion on seafood's sustainability. *Aquac. Eur.* **2010**, *35*, 15–17.

79. Tacon, A.G.J.; Metian, M.; Turchini, G.M.; De Silva, S.S. Responsible aquaculture and trophic level implications to global fish supply. *Rev. Fish. Sci.* **2010**, *18*, 94–105. [CrossRef]
80. Alder, J.; Campbell, B.; Karpouzi, V.; Kaschner, K.; Pauly, D. Forage fish: From ecosystems to markets. *Annu. Rev. Environ. Resour.* **2008**, *33*, 153–166. [CrossRef]
81. Bendiksen, E.Å.; Johnsen, C.A.; Olsen, H.J.; Jobling, M. Sustainable aquafeeds: Progress towards reduced reliance upon marine ingredients in diets for farmed Atlantic salmon (*Salmo salar* L.). *Aquaculture* **2011**, *314*, 132–139. [CrossRef]
82. Marshall, D. *Fishy Business: The Economics of Salmon Farming in BC*; Canadian Centre for Policy Alternative—BC Office: Vancouver, BC, USA, 2003; p. 45.
83. Costa-Pierce, B.A. Ecology as the paradigm for the future of aquaculture. In *Ecological Aquaculture: The Evolution of the Blue Revolution*; Costa-Pierce, B.A., Ed.; Blackwell Science: Malden, MA, USA, 2002; pp. 339–372.
84. Bailey, C.; Jentoft, S.; Sinclair, P. *Aquacultural Development: Social Dimensions of an Emerging Industry*; Westview Press: Boulder, CO, USA, 1996; p. 300.
85. Primavera, J.H. Overcoming the impacts of aquaculture on the coastal zone. *Ocean Coast. Manag.* **2006**, *49*, 531–545. [CrossRef]
86. Bailey, C.M. The social consequences of tropical shrimp Mariculture development. *Ocean Shorel. Manag.* **1988**, *11*, 31–44. [CrossRef]
87. Primavera, J.H. Socio-economic impacts of shrimp culture. *Aquac. Res.* **1997**, *28*, 815–827. [CrossRef]
88. Badiola, M.; Mendiola, D.; Bostock, J. Recirculating aquaculture systems (RAS) analysis: Main issues on management and future challenges. *Aquac. Eng.* **2012**, *51*, 26–35. [CrossRef]
89. Zhang, S.; Li, G.; Wu, H.; Liu, X.; Yao, Y.; Tao, L.; Liu, H. An integrated recirculating system (RAS) for land-based fish farming: The effect on water quality and fish production. *Aquac. Eng.* **2011**, *45*, 93–102. [CrossRef]
90. Martins, C.I.M.; Eding, E.H.; Verreth, J.A.J. The effect of recirculating aquaculture systems on the concentration of heavy metals in culture water and tissues of Nile tilapia *Oreochromis niloticus*. *Food Chem.* **2011**, *126*, 1001–1005. [CrossRef]
91. Timmons, M.B.; Ebeling, J.M. *Recirculating Aquaculture*; Cayuga Aqua Ventures LLC: Ithaca, NY, USA, 2010; p. 948.
92. Helfman, G.; Collette, B.B.; Facey, D.E.; Bowen, B.W. *The Diversity of Fishes: Biology, Evolution, and Ecology*, 2nd ed.; Wiley-Blackwell: Chichester, UK, 2009; p. 736.
93. Gutierrez-Wing, M.T.; Malone, R.F. Biological filters in aquaculture: Trends and research directions for freshwater and marine applications. *Aquac. Eng.* **2006**, *34*, 163–171. [CrossRef]
94. Schreier, H.J.; Mirzoyan, N.; Saito, K. Microbial diversity of biological filters in recirculating aquaculture systems. *Curr. Opin. Biotechnol.* **2010**, *21*, 318–325. [CrossRef] [PubMed]
95. Van Bussel, C.G.J.; Schroeder, J.P.; Wuertz, S.; Schulz, C. The chronic effect of nitrate on production performance and health status of juvenile turbot (*Psetta maxima*). *Aquaculture* **2012**, *326–329*, 163–167. [CrossRef]
96. Chavez-Crooker, P.; Obreque-Contreras, J. Bioremediation of aquaculture wastes. *Curr. Opin. Biotechnol.* **2010**, *21*, 313–317. [CrossRef] [PubMed]
97. Van Rijn, J.; Tal, Y.; Schreier, H.J. Denitrification in recirculating systems: Theory an applications. *Aquac. Eng.* **2006**, *34*, 364–376. [CrossRef]
98. Schroeder, J.P.; Croot, P.L.; Von Dewitz, B.; Waller, U.; Hanel, R. Potential and limitations of ozone for the removal of ammonia, nitrite, and yellow substances in marine recirculating aquaculture systems. *Aquac. Eng.* **2011**, *45*, 35–41. [CrossRef]
99. Gonçalves, A.A.; Gagnon, G.A. Ozone application in recirculating aquaculture system: An overview. *Ozone Sci. Eng.* **2011**, *33*, 345–367. [CrossRef]
100. Tal, Y.; Schreier, H.J.; Sowers, K.R.; Stubblefield, J.D.; Place, A.R. Environmentally sustainable land-based marine aquaculture. *Aquaculture* **2009**, *286*, 28–35. [CrossRef]
101. Verdegem, M.C.J.; Bosma, R.H.; Verreth, J.A.J. Reducing water use for animal production through aquaculture. *Int. J. Water Resour. Dev.* **2006**, *22*, 101–113. [CrossRef]

102. Singer, A.; Parnes, S.; Gross, A.; Sagi, A.; Brenner, A. A novel approach to denitrification processes in a zero-discharge recirculating system for small-scale urban aquaculture. *Aquac. Eng.* **2008**, *39*, 72–77. [CrossRef]
103. Miller, D. Using aquaculture as a post-mining land use in West Virginia. *Mine Water Environ.* **2008**, *27*, 122–126. [CrossRef]
104. Martins, C.I.M.; Eding, E.H.; Verdegem, M.C.J.; Heinsbroek, L.T.N.; Schneider, O.; Blancheton, J.P.; Roque d'Orbcastel, E.; Verreth, J.A.J. New developments in recirculating aquaculture systems in Europe: A perspective on environmental sustainability. *Aquac. Eng.* **2010**, *43*, 83–93. [CrossRef]
105. Heinen, J.M.; Hankins, J.A.; Adler, P.R. Water quality and waste production in recirculating trout culture system with feeding of a higher energy or a lower energy diet. *Aquaculture* **1996**, *27*, 699–710. [CrossRef]
106. Mirzoyan, N.; Tal, Y.; Gross, A. Anaerobic digestion of sludge from intensive recirculating aquaculture sytems: Review. *Aquaculture* **2010**, *306*, 1–6. [CrossRef]
107. Brown, N.; Eddy, S.; Plaud, S. Utilization of waste from a marine recirculating fish culture system as a feed source for the polychaete worm, *Nereis virens*. *Aquaculture* **2011**, *322–323*, 177–183. [CrossRef]
108. Marsh, L.; Subler, S.; Mishra, S. Suitability of aquaculture effluent solids mixed with cardboard as a feedstock for vermicomposting. *Bioresour. Technol.* **2005**, *96*, 413–418. [CrossRef] [PubMed]
109. Piedrahita, R.H. Reducing the potential environmental impact of tank aquaculture effluents through intensification and recirculation. *Aquaculture* **2003**, *226*, 35–44. [CrossRef]
110. Cripps, S.J.; Bergheim, A. Solids management and removal for intensive land-based aquaculture production systems. *Aquac. Eng.* **2000**, *22*, 33–56. [CrossRef]
111. Jeffery, K.R.; Stone, D.; Feist, S.W.; Verner-Jeffreys, D.W. An outbreak of disease caused by *Francisella* sp. in Nile tilapia *Oreochromis niloticus* at a recirculation fish farm in the UK. *Dis. Aquat. Org.* **2010**, *91*, 161–165. [CrossRef] [PubMed]
112. Pelletier, N.; Audsley, E.; Brodt, S.; Garnett, T.; Henriksson, P.; Kendall, A.; Kramer, K.J.; Murphy, D.; Nemecek, T.; Troell, M. Energy intensity of agriculture and food systems. *Annu. Rev. Environ. Resour.* **2011**, *36*, 223–246. [CrossRef]
113. Ayer, N.W.; Tyedmers, P.H. Assessing alternative aquaculture technologies: Life cycle assessment of salmonid culture systems in Canada. *J. Clean. Prod.* **2009**, *17*, 362–373. [CrossRef]
114. D'Orbcastel, E.R.; Blancheton, J.P.; Aubin, J. Towards environmentally sustainable aquaculture: Comparison between two trout farming systems using life cycle assessment. *Aquac. Eng.* **2009**, *40*, 113–119. [CrossRef]
115. Cahill, P.L.; Hurd, C.L.; Lokman, M. Keeping the water clean—Seaweed biofiltration outperforms traditional bacterial biofilms in recirculating aquaculture. *Aquaculture* **2010**, *306*, 153–159. [CrossRef]
116. Greiner, A.D.; Timmons, M.B. Evaluation of nitrification rates of microbead and trickling filters in an intensive recirculating tilapia production facility. *Aquac. Eng.* **1998**, *18*, 189–200. [CrossRef]
117. Van Rijn, J. The potential for integrated biological treatment systems in recirculating fish culture: A review. *Aquaculture* **1996**, *139*, 181–201. [CrossRef]
118. Watten, B.J.; Sirbrell, P.L. Comparative performance of fixed film biological filters: Application of reactor theory. *Aquac. Eng.* **2006**, *34*, 193–213. [CrossRef]
119. De Schryver, P.; Crab, R.; Defoirdt, T. The basics of bio-flocs technology: The added value for aquaculture. *Aquaculture* **2008**, *277*, 125–137. [CrossRef]
120. Azim, M.E.; Verdegem, M.C.J.; van Dam, A.A.; Beveridge, M.C.M. (Eds.) *Periphyton: Ecology, Exploitation, and Management*; CABI: Oxfordshire, UK, 2006; 319p.
121. Li, S. Energy structure and efficiency of a typical Chinese integrated fish farm. *Aquaculture* **1987**, *65*, 105–118. [CrossRef]
122. Tian, Z.P.; Gao, F.M.; Sun, S.; Liu, S.Q.; Zhang, Y.L.; Li, L.X. Effects of the interculture of *Mytilus edulis* and *Laminaria* on the environment condition. *Trans. Oceanol. Limnol.* **1987**, *2*, 60–66.
123. Wei, S.Q. Study of mixed culture of *Gracilaria tenuistipitata*, *Penaeus penicillatus*, and *Seylla serrata*. *Acta Oceanol. Sin.* **1990**, *12*, 388–394.
124. Chan, G.L. Aquaculture, ecological engineering: Lessons from China. *Ambio* **1993**, *22*, 491–494.
125. Qian, P.Y.; Wu, C.Y.; Wu, M.; Xie, Y.K. Integrated cultivation of the red alga *Kappaphycus alvarezii* and the pearl oyster *Pinctada martensi*. *Aquaculture* **1996**, *147*, 21–35. [CrossRef]

126. Chopin, T.; Buschmann, A.H.; Halling, C.; Troell, M.; Kautsky, N.; Neori, A.; Kraemer, G.P.; Zertuche-González, J.A.; Yarish, C.; Neefus, C. Integrating seaweeds into marine aquaculture systems: A key toward sustainability. *J. Phycol.* **2001**, *37*, 975–986. [CrossRef]
127. Ruddle, K.; Zhong, G. *Integrated Agriculture-Aquaculture in the South of China. The Dike-Pond System in the Zhujiang Delta*; Cambridge University Press: Cambridge, UK, 1988; 173p.
128. Merriam-Webster. Available online: http://www.merriam-webster.com/dictionary/polyculture (accessed on 11 September 2016).
129. Troell, M.; Joyce, A.; Chopin, T.; Neori, A.; Buschmann, A.H.; Fang, J.G. Ecological engineering in aquaculture—Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. *Aquaculture* **2009**, *297*, 1–9. [CrossRef]
130. Barrington, K.; Chopin, T.; Robinson, S. Integrated multi-trophic aquaculture (IMTA) in marine temperate waters. In *Integrated Mariculture: A Global Review*; Soto, D., Ed.; FAO Fisheries and Aquaculture Technical Paper 529; FAO: Rome, Italy, 2009; pp. 7–46.
131. Neori, A.; Chopin, T.; Troell, M. Integrated aquaculture: Rationale, evolution, and state of the art emphasizing seaweed biofiltration in modern Mariculture. *Aquaculture* **2004**, *231*, 361–391. [CrossRef]
132. Sará, G.; Zenone, A.; Tomasello, A. Growth of *Mytilus galloprovincialis* (Mollusca, Bivalva) close to fish farms: A cases of integrated multi-trophic aquaculture within the Tyrrhenian Sea. *Hydrobiologia* **2009**, *636*, 129–136. [CrossRef]
133. Abreu, M.H.; Varela, D.A.; Henríquez, L.; Villarroel, A.; Yarish, C.; Sousa-Pinto, I.; Buschmann, A.H. Traditional vs. integrated multi-trophic aquaculture of *Gracilaria chilensis* C.J. Bird, J. McLachlan & E.C. Oliveira: Productivity and physiological performance. *Aquaculture* **2009**, *293*, 211–220.
134. Huo, Y.; Wu, H.; Chai, Z. Bioremediations efficiency of *Gracilaria verrucosa* for an integrated multi-trophic aquaculture system with *Pseudosciaena crocea* in Xiangshan Harbor, China. *Aquaculture* **2012**, *326–329*, 99–105. [CrossRef]
135. Troell, M.; Halling, C.; Neori, A.; Chopin, T.; Buschmann, A.H.; Kautsky, N.; Yarish, C. Integrated mariculture: Asking the right questions. *Aquaculture* **2003**, *226*, 69–90. [CrossRef]
136. Fei, X.G.; Bao, Y.; Lu, S. Seaweed cultivation-traditional way and its reformation. *Oceanol. Limnol. Sin.* **2000**, *31*, 575–580.
137. Fei, X.G.; Tseng, C.K.; Pang, S.J.; Lian, S.X.; Huang, R.K.; Chen, W.Z. Transplant of *Gracilaria lemaneiformis* by raft culture on the sea along fish cages in southern China. In Proceedings of the World Aquaculture Society, Baton Rouge, LA, USA, 23–27 April 2002; p. 219.
138. Buschmann, A.H.; Varela, D.A.; Hernández-González, M.C.; Huovinen, P. Opportunities and challenges for the development of an integrated seaweed-based aquaculture activity in Chile: Determining the physiological capabilities of *Macrocystis* and *Gracilaria* as biofilters. *J. Appl. Phycol.* **2008**, *20*, 571–577. [CrossRef]
139. Stabili, L.; Licciano, M.; Giangrande, A.; Longo, C.; Mercurio, M.; Marzano, C.N.; Corriero, G. Filtering activity of *Spongia officinalis* var. adriatica (Schmidt) (Porifera, Demospongiae) on bacterioplankton: Implications for bioremediation of polluted seawater. *Water Res.* **2006**, *40*, 3083–3090. [CrossRef] [PubMed]
140. MacDonald, B.A.; Robinson, S.M.C.; Barrington, K.A. Feeding activity of mussels (*Mytilus edulis*) held in the field at an integrated multi-trophic aquaculture (IMTA) site (*Salmo salar*) and exposed to fish food in the laboratory. *Aquaculture* **2011**, *314*, 244–251. [CrossRef]
141. Handå, A.; Ranheim, A.; Olsen, A.J.; Altin, D.; Reitan, K.I.; Olsen, Y.; Altin, D.; Reitan, K.I.; Olsen, Y.; Reinertsen, H. Incorporation of salmon fish feed and feces components in mussels (*Mytilus edulis*): Implications for intergrated multi-trophic aquaculture in cool-temperate North Atlantic waters. *Aquaculture* **2012**, *370–371*, 40–53. [CrossRef]
142. Lander, T.R.; Robinson, S.M.C.; MacDonald, B.A.; Martin, J.D. Characterization of the suspended organic particles released from salmon farms and their potential as a food supply for the suspension feeder, *Mytilus edulis* in integrated multi-trophic aquaculture (IMTA) systems. *Aquaculture* **2013**, *406–407*, 160–170. [CrossRef]
143. Reid, G.K.; Liutkus, M.; Bennett, A. Absorption efficiency of blue mussels (*Mytilus edulis* and *M. trossulus*) feeding on Atlantic salmon (*Salmo salar*) feed and fecal particulates: Implications for integrated mulit-trophic aquaculture. *Aquaculture* **2010**, *299*, 165–169. [CrossRef]

144. Pietrak, M.R.; Molloy, S.D.; Bouchard, D.A.; Singer, J.T.; Bricknell, I. Potential role of *Mytilus edulis* in modulating the infections pressure of *Vibrio anguillarum* 02β on an integrated multi-trophic aquaculture farm. *Aquaculture* **2012**, *326–329*, 36–39. [CrossRef]
145. Molloy, S.D.; Pietrak, M.R.; Bouchard, D.A.; Bricknell, I. Ingestion of *Lepeophtheirus salmonis* by the blue mussel *Mytilus edulis*. *Aquaculture* **2011**, *311*, 61–64. [CrossRef]
146. Skar, C.K.; Mortensen, S. Fate of infectious salmon anaemia virus (ISAV) in experimentally challenged blue mussels (*Mytilus edulis*). *Dis. Aquat. Org.* **2007**, *74*, 1–6. [CrossRef] [PubMed]
147. Yokoyama, H. Growth and food source of the sea cucumber *Apostichopus japonicus* cultured below fish cages—Potential for integrated multi-trophic aquaculture. *Aquaculture* **2013**, *372–375*, 28–38. [CrossRef]
148. Slater, M.J.; Carton, A.G. Effect of sea cucumber (*Australostichopus mollis*) grazing on coastal sediments impacted by mussel farm deposition. *Mar. Pollut. Bull.* **2009**, *58*, 1123–1129. [CrossRef] [PubMed]
149. MacDonald, C.L.E.; Stead, S.M.; Slater, M.J. Consumption and remediation of European seabass (*Dicentrarchus labrax*) waste by the sea cucumber *Holothuria forskali*. *Aquac. Int.* **2013**, *21*, 1279–1290. [CrossRef]
150. Taboada, M.C.; González, M.; Rodríguez, E. Value and effects on digestive enzymes and serum lipids of the marine invertebrate *Holothuria forskali*. *Nutr. Res.* **2003**, *23*, 745–758. [CrossRef]
151. Rodríguez, E.; González, M.; Caride, B.; Lamas, M.A.; Taboada, M.C. Nutritional value of *Holothuria forskali* protein and effects on serum lipid profile in rats. *J. Physiol. Biochem.* **2000**, *56*, 39–44. [CrossRef] [PubMed]
152. Bordbar, S.; Anwar, F.; Saari, N. High-value components and bioactives from sea cucumbers for functional foods—A review. *Mar. Drugs* **2011**, *9*, 1761–1805. [CrossRef] [PubMed]
153. Van Dyck, S.; Gerbaux, P.; Flammang, P. Elucidation of molecular diversity and body distribution of saponins in the sea cucumber *Holothuria forskali* (Echindoermata) by mass spectrometry. *Comp. Biochem. Physiol. B* **2009**, *152*, 124–134. [CrossRef] [PubMed]
154. Kang, K.H.; Kwon, J.Y.; Kim, Y.M. A beneficial co-culture: Charm abalone *Haliotis discus hannai* and sea cucumber *Stichopus japonicus*. *Aquaculture* **2003**, *216*, 87–93. [CrossRef]
155. Zhou, Y.; Yang, H.; Liu, S.; Yuan, X.; Mao, Y.; Liu, Y.; Xu, X.; Zhang, F. Feeding and growth on bivalve biodeposits by the deposit feeder *Stichopus japonicus* Selenka (Echinodermata: Holothuroidea) co-cultured in lantern nets. *Aquaculture* **2006**, *256*, 510–520. [CrossRef]
156. Paltzat, D.L.; Pearce, C.M.; Barnes, P.A.; McKinley, R.S. Growth and production of California sea cucumbers (*Parastichopus californicus* Stimpson) co-cultured with suspended Pacific oysters (*Crossostrea gigas* Thunberg). *Aquaculture* **2008**, *275*, 124–137. [CrossRef]
157. Hannah, L.; Pearce, C.M.; Cross, S.F. Growth and survival of California sea cucumbers (*Parastichopus californicus*) cultivated with sablefish (*Anoplopoma fimbria*) at an integrated multi-trophic aquaculture site. *Aquaculture* **2013**, *406–407*, 34–42. [CrossRef]
158. Nelson, E.J.; MacDonald, B.A.; Robinson, S.M.C. The absorption efficiency of the suspension-feeding sea cucumber, *Cucumaria frondosa*, and its potential as an extractive integrated multi-trophic aquaculture (IMTA) species. *Aquaculture* **2012**, *370–371*, 19–25. [CrossRef]
159. Zamora, L.N.; Jeffs, A.G. Feeding, selection, digestion, and absorption of the organic matter from mussel waste by juveniles of the deposit-feeding sea cucumber, *Australostichopus mollis*. *Aquaculture* **2011**, *317*, 223–228. [CrossRef]
160. Zamora, L.N.; Jeffs, A.G. The ability of the deposit-feeding sea cucumber *Australostichopus mollis* to use natural variation in the biodesposits beneath mussel farms. *Aquaculture* **2012**, *326–329*, 116–122. [CrossRef]
161. Slater, M.J.; Jeffs, A.G.; Carton, A.G. The use of waste from green-lipped mussels as a food source for juvenile sea cucumbers, *Australostichopus mollis*. *Aquaculture* **2009**, *292*, 219–224. [CrossRef]
162. Stabili, L.; Schirosi, R.; Licciano, M.; Mola, E.; Giangrande, A. Bioremediation of bacteria in aquaculture waste using the polychaete *Sabella spallanzanii*. *New Biotechnol.* **2010**, *27*, 774–781. [CrossRef] [PubMed]
163. Licciano, M.; Stabili, L.; Giangrande, A. Clearance rates of *Sabella spallanzanii* and *Branchiomma luctuosum* (Annelida: Polychaeta) on a pure culture of *Vibrio alginolyticus*. *Water Res.* **2005**, *39*, 4375–4384. [CrossRef] [PubMed]
164. Honda, H.; Kikuchi, K. Nitrogen budget of polychaete *Perinereis nuntia vallata* fed on the feces of Japanese flounder. *Fish. Sci.* **2002**, *68*, 1304–1308. [CrossRef]
165. Palmer, P.J. Polychaete-assisted sand filters. *Aquaculture* **2010**, *306*, 369–377. [CrossRef]

166. Stabili, L.; Schirosi, R.; Licciano, M.; Giangrande, A. The mucus of *Sabella spallanzanii* (Annelida, Polychaeta): Its involvement in chemical defence and fertilisation success. *J. Exp. Mar. Biol. Ecol.* **2009**, *374*, 144–149. [CrossRef]
167. Milanese, M.; Chelossi, E.; Manconi, R.; Sará, A.; Sidri, M.; Pronzato, R. The marine sponge *Chondrilla nucla* Schmidt, 1862 as an elective candidate for bioremediation in integrated aquaculture. *Biomol. Eng.* **2003**, *20*, 363–368. [CrossRef]
168. Osinga, R.; Sidri, M.; Cerig, E.; Gokalp, S.Z.; Gokalp, M. Sponge aquaculture trials in the East-Mediterranean Sea: New approaches to earlier ideas. *Open Mar. Biol. J.* **2010**, *4*, 74–81. [CrossRef]
169. Wijffels, R.H. Potential of sponges and mircoalgae for marine biotechnology. *Trends Biotechnol.* **2008**, *26*, 26–31. [CrossRef] [PubMed]
170. Koopmans, M.; Matens, D.; Wijffels, R.H. Towards commercial production of sponge medicines. *Mar. Drugs* **2009**, *7*, 787–802. [CrossRef] [PubMed]
171. Sipkema, D.; Osinga, R.; Schatton, W.; Mendola, D.; Tramper, J.; Wijffels, R.H. Large-scale production of pharmaceuticals by marine sponges: Sea, cell, or synthesis. *Biotechnol. Bioeng.* **2005**, *90*, 201–222. [CrossRef] [PubMed]
172. Webster, N.S.; Taylor, M.W. Marine sponges and their microbial symbionts: Love and other relationships. *Environ. Microbiol.* **2012**, *14*, 335–346. [CrossRef] [PubMed]
173. Chopin, T.; Robinson, S. Defining the appropriate regulatory and policy framework for the development of integrated multi-trophic aquaculture practises: Introduction to the workshop and positing of the issues. *Bull. Aquac. Assoc. Can.* **2004**, *104*, 4–10.
174. Chopin, T.; Robinson, S.; Sawhney, M.; Bastarache, S.; Belyea, S.; Shea, R.; Armstrong, W.; Stewart, I.; Fitzgerald, P. The AquaNet integrated multi-trophic aquaculture project: Rationale of the project and development of kelp cultivation as the inorganic extractive component of the system. *Bull. Aquac. Assoc. Can.* **2004**, *104*, 11–18.
175. Lander, T.R.; Barrington, K.A.; Robinson, S.M.C.; MacDonald, B.A.; Martin, J.D. Dynamic of the blue mussel as an extractive organism in an integrated multi-trophic aquaculture system. *Bull. Aquac. Assoc. Can.* **2004**, *104*, 19–28.
176. Barrington, K.; Ridler, N.; Chopin, T.; Robinson, S.; Robinson, B. Social aspects of the sustainability of integrated multi-trophic aquaculture. *Aquac. Int.* **2010**, *18*, 201–211. [CrossRef]
177. Skiftesvik, A.B.; Bjelland, R.M.; Durif, C.M.F.; Johansen, I.S.; Browman, H.I. Delousing of Atlantic salmon (*Salmo salar*) by cultured vs. wild ballan wrasse (*Labrus bergylta*). *Aquaculture* **2013**, *402–403*, 113–118. [CrossRef]
178. Imsland, A.K.; Reynolds, P.; Eliassen, G.; Hangstad, T.A.; Foss, A.; Vikingstad, E.; Elvegård, T.A. The use of lumpfish (*Cyclopterus lumpus* L.) to control sea lice (*Lepeophtheirus salmonis* Krøyer) infestations in intensively farmed Atlantic salmon (*Salmo salar* L.). *Aquaculture* **2014**, *424–425*, 18–23. [CrossRef]
179. Roheim, C.A.; Asche, F.; Santos, J.I. The elusive price premium for ecolabelled products: Evidence from seafood in the UK market. *J. Agric. Econ.* **2011**, *62*, 655–668. [CrossRef]
180. Ma, C.; Zhang, X.; Chen, W.; Zhang, G.; Duan, H.; Ju, M.; Li, H.; Yang, Z. China's special marine protected area policy: Trade-off between economic development and marine conservation. *Ocean Coast. Manag.* **2013**, *76*, 1–11. [CrossRef]
181. Culver, K.; Castle, D. *Aquaculture, Innovation, and Social Transformation*; Springer Science and Business Media: Berlin, Germany, 2008; Volume 17, p. 344.
182. Chopin, T. Progression of the integrated multi-trophic aquaculture (IMTA) concept and upscaling of IMTA systems towards commercialization. *Aquac. Eur.* **2011**, *36*, 5–12.
183. Bunting, S.W.; Shpigel, M. Evaluating the economic potential of horizontally integrated land-based marine aquaculture. *Aquaculture* **2009**, *294*, 43–51. [CrossRef]
184. Shpigel, M.; Ben-Ezra, D.; Shauli, L.; Sagi, M.; Ventura, Y.; Samocha, T.; Lee, J.J. Constructed wetland with *Salicornia* as a biofilter for Mariculture effluent. *Aquaculture* **2013**, *412–413*, 52–63. [CrossRef]
185. Kadlec, R.H.; Knight, R.L. *Treatment Wetlands*, 2nd ed.; CRS Press: Boca Raton, FL, USA, 2009.
186. Buhmann, A.; Papenbrock, J. Biofiltering of aquaculture effluents by halophytic plants: Basic principles, current uses and future perspectives. *Environ. Exp. Bot.* **2013**, *92*, 122–133. [CrossRef]
187. Lin, Y.F.; Jing, S.R.; Lee, D.Y.; Wang, T.W. Nutrient removal from aquaculture wastewater using a constructed wetland system. *Aquaculture* **2002**, *209*, 169–184. [CrossRef]

188. Lin, Y.F.; Jing, S.R.; Lee, D.Y.; Wang, T.W. Removal of solids and oxygen demand from aquaculture wastewater with a constructed wetland system in the start-up phase. *Water Environ. Res.* **2002**, *74*, 136–141. [CrossRef] [PubMed]
189. Schulz, C.; Gelbrecht, J.; Rennert, B. Treatment of rainbow trout farm effluents in constructed wetland with emergent plants and subsurface horizontal water flow. *Aquaculture* **2003**, *217*, 207–221. [CrossRef]
190. Schwartz, M.F.; Boyd, C.E. Constructed wetlands for treatment of channel catfish pond effluents. *Progress. Fish-Cult.* **1995**, *57*, 255–267. [CrossRef]
191. Tilley, D.R.; Badrinarayanan, H.; Rosati, R.; Son, J. Constructed wetlands as recirculation filters in large-scale shrimp aquaculture. *Aquac. Eng.* **2002**, *26*, 81–109. [CrossRef]
192. Singh, D.; Buhmann, A.K.; Flowers, T.J.; Seal, C.E.; Papenbrock, J. *Salicornia* as a crop plant in temperate regions: Selection of genetically characterised ecotypes and optimisation of their cultivation conditions. *AoB Plants* **2014**, *6*. [CrossRef] [PubMed]
193. Ramani, B.; Reeck, T.; Debez, A.; Stelzer, R.; Huchzermeyer, B.; Schmidt, A.; Papenbrock, J. *Ater tripolium* L. and *Sesuvium portulacastrum* L.: Two halophytes, two strategies to survive in saline habitats. *Plant Physiol. Biochem.* **2006**, *44*, 395–408. [CrossRef] [PubMed]
194. Buhmann, A.K.; Waller, U.; Wecker, B.; Papenbrock, J. Optimisation of culturing conditions and selection of species for the use of halophytes as biofilter for nutrient-rich saline water. *Agric. Water Manag.* **2015**, *149*, 102–114. [CrossRef]
195. Díaz, F.J.; Benes, S.E.; Grattan, S.R. Field performance of halophytic species under irrigation with saline drainage water in the San Joaquin Valley of California. *Agric. Water Manag.* **2013**, *118*, 59–69. [CrossRef]
196. Lymbery, A.J.; Doupe, R.G.; Bennett, T.; Starcevich, M.R. Efficacy of a subsurface-flow wetland using the estuarine sedge *Juncus kraussii* to treat effluent from inland saline aquaculture. *Aquac. Eng.* **2006**, *34*, 1–7. [CrossRef]
197. Traynor, C.H. *Juncus kraussii* harvesting in Umlalazi nature reserve, KwaZulu-Natal, South Africa: Socio-economic aspects and sustainability. *Afr. J. Aquat. Sci.* **2008**, *33*, 27–36. [CrossRef]
198. Cardoch, L.; Day, J.W.; Rybczyk, J.M.; Kemp, G.P. An economic analysis of using wetlands for treatment of shrimp processing wastewater—A case study in Dulac, LA. *Ecol. Econ.* **2000**, *38*, 93–101. [CrossRef]
199. Sindilariu, P.D.; Wolter, C.; Reiter, R. Constructed wetlands as a treatment method for effluents from intensive trout farms. *Aquaculture* **2008**, *277*, 179–184. [CrossRef]
200. Webb, J.M.; Quintã, R.; Papadimitriou, S.; Norman, L.; Rigby, M.; Thoma, D.N.; Le Vay, L. Halophyte filter beds for treatment of saline wastewater from aquaculture. *Water Res.* **2012**, *46*, 5102–5114. [CrossRef] [PubMed]
201. Price, L.L. From pedestrian fare to gourmet trend: The case of *Salicornia europaea* L., a traditional gathered wild seashore vegetable. In *Changing Families and Their Lifestyles*; Moerbeek, H.H., Niehof, A., Eds.; Wageningen Academic Publishers: Wageningen, The Netherlands, 2007; Volume 2, pp. 201–211.
202. Guil, J.L.; Rodriguez-Garcia, I.; Torija, E. Nutritional and toxic factors in selected wild edible plants. *Plant Foods Hum. Nutr.* **1997**, *51*, 99–107. [CrossRef] [PubMed]
203. Rhee, M.H.; Park, H.-J.; Cho, J.Y. *Salicornia herbacea*: Botanical, chemical, and pharmacological review of halophyte marsh plant. *J. Med. Plants Res.* **2009**, *3*, 548–555.
204. Lee, S.; Kong, D.H.; Yun, S.H.; Lee, K.P.; Franzblau, S.G.; Lee, E.Y.; Chang, C.L. Evaluation of a modified antimycobacterial susceptibility test using Middlebrook 7H10 agar containing 2,3-diphenyl-5-thienyl-(2)-tetrazolium chloride. *J. Microbiol. Methods* **2006**, *66*, 548–551. [CrossRef] [PubMed]
205. Glenn, E.P.; Brown, J.; Blumwald, E. Irrigating crops with seawater. *Sci. Am.* **1998**, *279*, 56–61. [CrossRef]
206. Abdal, M.S. *Salicornia* production in Kuwait. *World Appl. Sci. J.* **2009**, *6*, 1033–1038.
207. Liu, X.G.; Xia, Y.G.; Wang, F.; Sun, M.; Jin, Z.J.; Wang, G.T. Analysis of fatty acid composition of *Salicornia europaea* L. seed oil. *Food Sci.* **2005**, *2*, 42.
208. Glenn, E.P.; O'Leary, J.W.; Watson, M.C.; Thompson, T.L.; Kuehl, R.O. *Salicornia bigelovii* Torr.: An oilseed halophyte for seawater irrigation. *Science* **1991**, *251*, 1065–1067. [CrossRef] [PubMed]
209. Aghaleh, M.; Niknam, V.; Ebrahimzadeh, H.; Razavi, K. Antioxidative enzymes in two in vitro cultured *Salicornia* species in response to increasing salinity. *Biol. Plant.* **2014**, *58*, 391–394. [CrossRef]
210. Lin, Y.F.; Jing, S.R.; Lee, D.Y.; Chang, Y.F.; Chen, Y.M.; Shih, K.C. Performance of a constructed wetland treating intensive shrimp aquaculture wastewater under high hydraulic loading rate. *Environ. Pollut.* **2005**, *134*, 411–421. [CrossRef] [PubMed]

211. Sindilariu, P.D.; Reiter, R.; Wedekind, H. Impact of trout aquaculture on water quality and farm effluent treatment options. *Aquat. Living Resour.* **2009**, *22*, 93–103. [CrossRef]
212. Sindilariu, P.D.; Brinker, A.; Reiter, R. Factors influencing the efficiency of constructed wetlands used for the treatment of intensive trout farm effluent. *Ecol. Eng.* **2009**, *35*, 711–722. [CrossRef]
213. Lakkireddy, K.K.R.; Kasturi, K.; Sambasiva Rao, K.R.S. Role of hydroponics and aeroponics in soilless culture in commercial food production. *Res. Rev. J. Agric. Sci. Technol.* **2012**, *1*, 26–35.
214. Jones, J.B., Jr. *Hydroponics—A Practical Guide for the Soilless Grower*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2005; p. 440.
215. Jensen, M.H. Hydroponics worldwide—A technical overview. *Int. Symp. Grow. Med. Hydroponics* **1997**, *481*, 719–730.
216. Steiner, A.A. The history of mineral plant nutrition until about 1860 as a source of the origin of soilless culture methods. *Soil. Cult.* **1985**, *1*, 7–24.
217. Gericke, W.F. Aquaculture: A means of crop production. *Am. J. Bot.* **1929**, *16*, 862.
218. Gericke, W.F. Hydroponics—Crop production in liquid culture media. *Science* **1937**, *85*, 177–178. [CrossRef] [PubMed]
219. Gericke, W.F. *The Complete Guide to Soilless Gardening*; Prentice-Hall: New York, NY, USA, 1940; p. 304.
220. Love, D.C.; Fry, J.P.; Genello, L.; Hill, E.S.; Frederick, J.A.; Li, X.; Semmens, K. An international survey of aquaponics practitioners. *PLoS ONE* **2014**, *9*, e102662. [CrossRef] [PubMed]
221. Jensen, M.H.; Collins, W.L. Hydroponic vegetable production. *Hortic. Rev.* **1985**, *7*, 1–44.
222. Jensen, M.H. Deep flow hydroponics—Past, present and future. In Proceedings of the 30th National Agricultural Plastics Congress, San Diego, CA, USA, 17–19 August 2002; Volume 30, pp. 40–46.
223. Hu, M.H.; Ao, Y.S.; Yang, X.E.; Li, T.Q. Treating eutrophic water for nutrient reduction using an aquatic macrophyte (*Ipomoea aquatica* Forsskal) in a deep flow technique system. *Agric. Water Manag.* **2008**, *95*, 607–615. [CrossRef]
224. Park, J.-S.; Kurata, K. Application of microbubbles to hydroponics solution promotes lettuce growth. *HortTechnology* **2009**, *19*, 212–215.
225. Graves, C.J. The nutrient film technique. *Hortic. Rev.* **1983**, *5*, 1–44.
226. Morgan, L. Introduction to hydroponic gullies and channels. *Grow. Edge* **1999**, *106*, 67–75.
227. Smith, B. A short history of NFT gully design. *Grow. Edge* **2004**, *15*, 79–82.
228. Johnson, B. Greenhouse nutrient management: Regulations and treatment options. *Grow. Edge* **2002**, *13*, 38–43.
229. Ignatius, A.; Arunbabu, V.; Neethu, J.; Ramasamy, E.V. Rhizofiltration of lead using an aromatic medicinal plant *Plectranthus amboinicus* cultured in a hydroponic nutrient film technique (NFT) system. *Environ. Sci. Pollut. Res.* **2014**, *21*, 13007–13016. [CrossRef] [PubMed]
230. Carter, W.A. A method of growing plants in water vapour to facilitate examination of roots. *Phytopathology* **1942**, *32*, 623–625.
231. Nickols, M. Aeroponics: Production systems and research tools. *Grow. Edge* **2002**, *13*, 30–35.
232. Gunning, D. *Cultivating Salicornia europaea (Marsh Samphire)*; Irish Sea Fisheries Board: Dublin, Ireland, 2016; pp. 1–92. Available online: http://www.bim.ie/our-publications/ (accessed on 15 September 2016).
233. Christie, C.B.; Nichols, M.A. Aeroponics—Production system and research tool. *Acta Hortic.* **2004**, *648*, 185–190. [CrossRef]
234. Barak, P.; Smith, J.D.; Kreuger, A.R.; Peterson, L.A. Measurement of short-term nutrient uptake rates in cranberry by aeroponics. *Plant Cell Environ.* **1996**, *19*, 237–242. [CrossRef]
235. Nir, I. Growing plants in aeroponics growth system. *Acta Hortic.* **1982**, *126*, 435–448. [CrossRef]
236. Movahedi, Z.; Moieni, A.; Soroushzadeh, A. Comparison of aeroponics and conventional soil systems for potato minituber production and evaluation of their quality characters. *J. Plant Physiol. Breed.* **2012**, *2*, 13–21.
237. Blidariu, F.; Grozea, A. Increasing the economical efficiency and sustainability of indoor fish farming by means of aquaponics—Review. *Sci. Pap. Anim. Sci. Biotechnol.* **2011**, *44*, 1–8.
238. Love, D.C.; Fry, J.P.; Li, X.; Hill, E.S.; Genello, L.; Semmens, K.; Thompson, R.E. Commercial aquaponics production and profitability: Findings from an international survey. *Aquaculture* **2015**, *435*, 67–74. [CrossRef]
239. Shete, A.P.; Verma, A.K.; Chadha, N.K.; Prakash, C.; Peter, R.M.; Ahmad, I.; Nuwansi, K.K.T. Optimization of hydraulic loading rate in aquaponic system with Common carp (*Cyrinus carpio*) and Mint (*Mentha arvensis*). *Aquac. Eng.* **2016**, *72*, 53–57. [CrossRef]

240. Buzby, K.M.; Lin, L. Scaling aquaponic systems: Balancing plant uptake with fish output. *Aquac. Eng.* **2014**, *63*, 39–44. [CrossRef]
241. Salam, M.A.; Hashem, S.; Asadujjaman, M.; Li, F. Nutrient recovery from in fish farming wastewater: An aquaponic system for plant and fish integration. *World J. Fish Mar. Sci.* **2014**, *6*, 355–360.
242. Goddek, S.; Espinal, C.A.; Delaide, B.; Jijakli, M.H.; Schmautz, Z.; Wuertz, S.; Keesman, K.J. Navigating towards decoupled aquaponic systems: A system dynamics design approach. *Water* **2016**, *8*, 1–29. [CrossRef]
243. Seawright, D.E.; Stickney, R.R.; Walker, R.B. Nutrient dynamics in integrated aquaculture—Hydroponic systems. *Aquaculture* **1998**, *160*, 215–237. [CrossRef]
244. Rakocy, J.; Masser, M.P.; Losordo, T.M. *Recirculating Aquaculture Tank Production Systems: Aquaponics—Integrating Fish and Plant Culture*; SRAC Publication: Stoneville, MS, USA, 2006; No. 454; p. 16.
245. Endut, A.; Jusoh, A.; Ali, N.; Wan Nik, W.N.S.; Hassan, A. Effect of flow rate on water quality parameters and plant growth of water spinach (*Ipomoea aquatica*) in an aquaponic recirculating system. *Desalination Water Treat.* **2009**, *5*, 19–28. [CrossRef]
246. Lennard, W.A.; Leonard, B.V. A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film technique) in an aquaponic test system. *Aquac. Int.* **2006**, *14*, 539–550. [CrossRef]
247. Tyson, R.V.; Treadwell, D.D.; Simonne, E.H. Opportunities and challenges to sustainability in aquaponic systems. *HortTechnology* **2011**, *21*, 6–13.
248. Bohl, M. Some initial aquaculture experiments in recirculating water systems. *Aquaculture* **1977**, *11*, 323–328. [CrossRef]
249. Collins, M.T.; Gratzek, J.B.; Shotts, E.B., Jr.; Dawe, D.L.; Campbell, L.M.; Senn, D.R. Nitrification in an aquatic recirculating system. *J. Fish. Res. Board Can.* **1975**, *32*, 2025–2031. [CrossRef]
250. Naegel, L.C.A. Combined production of fish and plants in recirculating water. *Aquaculture* **1977**, *10*, 17–24. [CrossRef]
251. Lewis, W.M.; Yop, J.H.; Schramm, H.L., Jr.; Brandenburg, A.M. Use of hydroponics to maintain quality of recirculated water in a fish culture system. *Trans. Am. Fish. Soc.* **1978**, *107*, 92–99. [CrossRef]
252. Sneed, K.; Allen, K.; Ellis, J. Fish farming and hydroponics. *Aquac. Fish Farmer* **1975**, *2*, 18–20.
253. Sutton, R.J.; Lewis, W.M. Further observations on a fish production system that incorporates hydroponically grown plants. *Prog. Fish Cult.* **1982**, *44*, 55–59. [CrossRef]
254. Todd, J. Dreaming in my own backyard. *J. New Alchem.* **1980**, *6*, 108–111.
255. Zweig, R.D. An integrated fish culture hydroponic vegetable production systems. *Aquac. Mag.* **1986**, *1*, 34–40.
256. Diver, S.; Rinehart, L. Aquaponics—Integration of hydroponics with agriculture. *ATTRA Natl. Sustain. Agric. Inf. Serv.* **2010**, *28*, 1–28.
257. Graber, A.; Junge, R. Aquaponic systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination* **2009**, *246*, 147–156. [CrossRef]
258. Endut, A.; Jusoh, A.; Ali, N.; Nik, W.B.W.; Hassan, A. A study on the optimal hydraulic loading rate and plant ratios in recirculation aquaponic systems. *Bioresour. Technol.* **2010**, *101*, 1511–1517. [CrossRef] [PubMed]
259. Rupasinghe, J.W.; Kennedy, J.O.S. Economic benefits of integrating a hydroponic-lettuce system into a barramundi fish production system. *Aquac. Econ. Manag.* **2010**, *14*, 81–96. [CrossRef]
260. Al-Hafedh, Y.S.; Alam, A.; Beltagi, M.S. Food production and water conservation in a recirculating aquaponic system in Saudi Arabia at different ratios of fish feed to plants. *J. World Aquac. Soc.* **2008**, *39*, 510–520. [CrossRef]
261. Somerville, C.; Cohen, M.; Pantanella, E.; Stankus, A.; Lovatelli, A. *Small-Scale Aquaponic Food Production. Integrated Fish and Plant Farming*; FAO Fisheries and Aquaculture Technical Paper No. 589; FAO: Rome, Italy, 2014; 262p.
262. University of Hawaii Aquaponics Workforce Development. Available online: http://www.hawaiiaquaponicsworkforce.com/faqs-2.html (accessed on 13 September 2016).
263. Tyson, R.V.; Simonne, E.H.; Treadwell, D.D.; White, J.M.; Simonne, A. Reconciling pH for ammonia biofiltration and cucumber yield in a recirculating aquaponic system with perlite biofilters. *HortScience* **2008**, *43*, 719–724.
264. Tyson, R.V.; Simonne, E.H.; Treadwell, D.D.; Davis, M.; White, J.M. Effect of water pH on yield and nutritional status of cucumber grown in recirculating hydroponics. *J. Plant Nutr.* **2008**, *31*, 2018–2030. [CrossRef]

265. Fronte, B.; Galliano, G.; Bibbiani, C. From freshwater to marine aquaponic: New opportunities for marine fish species production. In Proceedings of the 4th Conference with International Participation Conference VIVUS on Agriculture, Environmentalism, Horticulture and Floristics, Food Production and Processing and Nutrition, Naklo, Slovenia, 20–21 April 2016.
266. Turcios, A.E.; Papenbrock, J. Sustainable treatment of aquaculture effluents—What can we learn for the past for the future? *Sustainability* **2014**, *6*, 836–856. [CrossRef]
267. Joesting, H.M.; Blaylock, R.; Biber, P.; Ray, A. The use of marine aquaculture solid waste for nursery of salt marsh plants *Spartina alterniflora* and *Juncus roemerianus*. *Aquac. Rep.* **2016**, *3*, 108–114. [CrossRef]
268. Buhmann, A.; Papenbrock, J. An economic point of view of secondary compounds in halophytes. *Funct. Plant Biol.* **2013**, *40*, 952–967. [CrossRef]
269. Boxman, S.; Main, K.; Nystrom, M.; Ergas, S.J.; Trotz, M.A. *Aquaponic System Produces Red Drum, Saltwater Vegetable Species*; Global Aquaculture Advocate: Portsmouth, NH, USA, 2015; pp. 58–60.
270. Pantanella, E. *Integrated Marine Aquaculture-Agriculture: Sea Farming out of the Sea*; Global Aquaculture Advocate: Portsmouth, NH, USA, 2012; pp. 70–72.
271. Wilson, G. Seaweed is the common denominator in exciting saltwater aquaponics. *Aquaponics J.* **2005**, *36*, 12–16.
272. Gunning, D.; Harman, L.; Keily, M.; Nunan, R.; Jones, P.; Horgan, B.; Burnell, G. Designing a marine aquaponics (maraponics) system to model IMTA. In Proceedings of the Aquaculture Europe Conference 2014, San Sebastian, Spain, 14–17 October 2014. Available online: https://www.was.org/easonline/documents/MeetingPresentations/AE2014/AE2014_0681.pdf (accessed on 13 September 2016).
273. Gunning, D.; Fernández, T.; Dick, J.; Sprague, M.; Betancor, M.; Burnell, G. Mapping the Production and Recycling of Fatty Acids through Different Trophic Levels in a Marine Aquaponics System (Maraponics). Available online: https://www.was.org/EasOnline/Mobile/Paper.aspx?i=6697 (accessed on 13 September 2016).
274. Maraponics Ireland. Available online: http://www.maraponics.com/ (accessed on 13 September 2016).
275. Waller, U.; Buhmann, A.K.; Ernst, A.; Hanke, V.; Kulakowski, A.; Wecker, B.; Orellana, J.; Papenbrock, J. Integrated multi-trophic aquaculture in a zero-exchange recirculation aquaculture system for marine fish and hydroponic halophyte production. *Aquac. Int.* **2015**, *23*, 1473–1489. [CrossRef]
276. Boxman, S.E.; Nystrom, M.; Capodice, J.C.; Ergas, S.J.; Main, K.L.; Trotz, M.A. Effect of support medium, hydraulic loading rate and plant density on water quality and growth of halophytes in marine aquaponic systems. *Aquac. Res.* **2016**. [CrossRef]
277. Kong, Y.; Zheng, Y. Potential of producing *Salicornia bigelovii* hydroponically as a vegetable at moderate NaCl salinity. *HortScience* **2014**, *4999*, 1154–1157.
278. Reimold, R.J.; Queen, W.H. *Ecology of Halophytes*; Academic Press Inc.: New York, NY, USA; London, UK, 1974; 620p.
279. Haines, K.C. Growth of the carrageenan-producing tropical red seaweed *Hypnea musciformis* in surface water, 870 m deep water, effluent from a clam mariculture system, and in deep water enriched with artificial fertilizers or domestic sewage. In *10th Symposium on Marine Biology*; Persoone, G., Jaspers, E., Eds.; University Press: Wtteren, Belgium, 1976; Volume 1, pp. 207–220.
280. Langton, R.W.; Haines, K.C.; Lyon, R.E. Ammonia nitrogen produced by the bivalve mollusc *Tapes japonica* and its recovery by the red seaweed *Hypnea musciformis* in a tropical mariculture system. *Helgol. Wiss. Meeresunters.* **1977**, *30*, 217–229. [CrossRef]
281. Vandermeulen, H.; Gordin, H. Ammonium uptake using *Ulva* (Chlorophyta) in intensive fishpond systems: Mass culture and treatment of effluent. *J. Appl. Phycol.* **1990**, *2*, 363–374. [CrossRef]
282. Neori, A.; Cohen, I.; Gordin, H. *Ulva lactuca* biofilters for marine fish-pond effluents: II. Growth rate, yield, and C:N ratio. *Bot. Mar.* **1991**, *34*, 483–489. [CrossRef]
283. Jimenez del Río, M.; Ramazanov, Z.; García-Reina, G. *Ulva rigida* (Ulvales, Chlorophyta) tank culture as biofilters for dissolved inorganic nitrogen from fishpond effluents. *Hydrobiologia* **1996**, *326/327*, 61–67. [CrossRef]
284. Buschmann, A.H.; Troell, M.; Kautsky, N.; Kautsky, L. Integrated tank cultivation of salmonids and *Gracilaria chilensis* (Gracilariales, Rhodophyta). *Hydrobiologia* **1996**, *326/327*, 75–82. [CrossRef]

285. Chow, F.; Macciavello, J.; Santa Cruz, S.; Fonck, O. Utilization of *Gracilaria chilensis* (Rhodophyta: Gracilariaccae) as biofilter in the depuration of effluents from tank cultures of fish, oyster, and sea urchins. *J. World Aquac. Soc.* **2001**, *32*, 214–220. [CrossRef]
286. Abreu, M.H.; Pereira, R.; Yarish, C.; Alejandro, H.; Buschmann, A.H.; Sousa-Pinto, I. IMTA with *Gracilaria vermiculophylla*: Productivity and nutrient removal performance of the seaweed in a land-based pilot scale system. *Aquaculture* **2011**, *312*, 77–87. [CrossRef]
287. Pantanella, E.; Bhujel, C.R. *Saline Aquaponics—Potential Player in Food, Energy Production*; Global Aquaculture Advocate: Portsmouth, NH, USA, 2015; pp. 42–43.
288. Dufault, R.J.; Korkmaz, A.; Ward, B. Potential of biosolids from shrimp aquaculture as a fertiliser for broccoli production. *Compost Sci. Util.* **2001**, *9*, 107–114. [CrossRef]
289. Dufault, R.J.; Korkmaz, A. Potential of biosolids from shrimp aquaculture as a fertiliser in bell pepper production. *Compost Sci. Util.* **2000**, *3*, 310–319. [CrossRef]
290. Neori, A.; Shpigel, M.; Ben-Ezra, D. A sustainable integrated system for culture of fish, seaweed, and abalone. *Aquaculture* **2000**, *186*, 279–291. [CrossRef]
291. Pantanella, E.; Colla, G. Saline aquaponics opportunities for integrated marine aquaculture. In Proceedings of the International Aquaponic Conference: Aquaponics and Global Food Security, University of Wisconsin, Stevens Point, WI, USA, 19–21 June 2013.
292. Hart, E.R.; Webb, J.B.; Danylchuk, A.J. Implementation of aquaponics in education: An assessment of challenges and solutions. *Sci. Educ. Int.* **2013**, *24*, 460–480.
293. Nitrifying Bacteria Facts. Available online: http://www.bioconlabs.com/nitribactfacts.html (accessed on 1 September 2016).
294. Hollyer, J.; Tamaru, C.; Riggs, A.; Klinger-Bowen, R.; Howerton, R.; Okimoto, D.; Castro, L.; Ron, T.R.; Fox, K.; Troegner, V.; et al. On-farm food safety: Aquaponics. *Food Saf. Technol.* 2009. Available online: http://www.ctahr.hawaii.edu/oc/freepubs/pdf/FST-38.pdf (accessed on 14 December 2016).