sustainability

Review

Aquatic Plants and Aquatic Animals in the Context of Sustainability: Cultivation Techniques, Integration, and Blue Revolution

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Abstract: The aquaculture industry has rapidly increased in response to the increasing world population, with the appreciation that aquaculture products are beneficial for human health and nutrition. Globally, aquaculture organisms are mainly divided into two divisions, aquatic animals (finfish, crustaceans, and molluscs) and aquatic plants (microalgae and seaweed). Worldwide aquaculture production has reached more than 82 million tonnes (MTs) in 2018 with more than 450 cultured species. The development of economical, environmentally friendly, and large-scale feasible technologies to produce aquaculture organisms (even aquatic animals and/or aquatic plants) is an essential need of the world. Some aquaculture technologies are related to aquatic animals or aquatic plants, as well as some technologies have an integrated system. This integration between aquatic plants and aquatic animals could be performed during early larvae rearing, on-growing and/or mass production. In the context of the blue revolution, the current review focuses on the generations of integration between aquatic plants and aquatic animals, such as live feeds, biomass concentrates, water conditioners "green water technique", aqua-feed additives, co-culturing technologies, and integrated multi-trophic aquaculture (IMTA). This review could shed light on the benefit of aquatic animals and plant integration, which could lead future low-cost, highly efficient, and sustainable aquaculture industry projects.

Keywords: integrated aquaculture; IMTA; aquatic animals; microalgae; seaweeds; feed additive; microalgae biomass concentrates

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1. Introduction

As our understanding of aquatic ecosystems has paralleled dramatic growth in aquaculture, we have recognized that utilizing plant species with aquatic animals can dramatically improve sustainability in this important field. In the last few years, scientific progress has resulted in a far stronger understanding of how aquatic ecosystems operate, as well as an improved intercultural understanding of the need to sustainably management of these resources [1]. The world has been rapidly changing and both global population and consumption have significantly increased. As a result, many international organizations and governments have recognized that aquatic resources must be developed and sustainably managed [2,3]. Globally, many countries have dealt well with this important issue and implemented many national and/or international projects that supported intelligent integration of aquaculture industries and activities [4,5]. Aquaculture industries have successfully and rapidly increased in response to the increasing world population [6–8]. While aquaculture has developed significantly and can have sustainable aspects, critics have pointed to a number of challenges in the industry. For example, before the last two decades, Naylor et al., 2000 [9] published an interesting review, in Nature, which characterized aquaculture as a potential sustainable solution to repair the global decrease in fisheries stocks. At that time, aquaculture production had increased from 10 million tonnes (MTs) in 1987 to 29 MTs in 1997, and almost 300 species of fish, shellfish, microalgae, and seaweeds were cultured all over the world. Recently, Naylor et al., 2021 [10] published another review, in Nature, describing the development of the aquaculture sector over the last 20 years, from having a comparatively secondary role to playing an essential role in the universal food system. Interestingly, the worldwide aquaculture production has increased from 29 MTs in 1997 to more than 82 MTs in 2018 with more than 450 species of finfish, shellfish, microalgae, and seaweeds [1,10]. Mainly, commercially, aquaculture organisms are divided into two divisions, aquatic animals (finfish, crustaceans, and molluscs) and aquatic plants (microalgae and seaweeds). These aquatic animals and aquatic plants are the most commonly cultured organisms of great commercial and nutritional value [11].

According to FAO [1], in 2018, world aquaculture production comprised 46.0% of global fish production, contributing 114.5 MTs. This total production consisted of 82.1 MTs of aquatic animals (fish and shellfish), 32.4 MTs of aquatic plants (microalgae, and seaweeds), and 26,000 tonnes (Ts) of pearls and ornamental seashells. Aquatic animals, which come from freshwater and/or marine water, are one of the main animal-protein sources for humans, which include finfish, crustaceans, and molluscs. In 2018, finfish (54.3 MTs) was the most dominant aquatic animal produced from inland aquaculture (47 MTs), marine, and coastal aquaculture (7.3 MTs), followed by molluscs mostly bivalves (17.7 MTs), crustaceans (9.4 MTs), marine invertebrates (435,400 Ts), aquatic turtles (370,000 Ts), and frogs (131,300 Ts) [1,10].

Aquatic plants are photosynthetic organisms that utilize carbon, nutrients, and solar energy to produce organic compounds, such as lipids, carbohydrates, protein, and pigments [11–13]. Because of their advantages over terrestrial plants, aquatic plants are a viable and competitive source of biomass [14]. Aquatic plants have high photosynthetic efficiency, can produce biomass quickly, are resistant to a variety of pollutants, and can be cultivated on land that would otherwise be unsuitable for other uses [15–17]. Due to the wide range of their applications, such as aquaculture [18–22], biofuel [19,23,24], cosmetics [11,14,25], functional foods [11,15,26], and pharmaceuticals [27,28], aquatic plants gained more and more attention at industrial and academic scale, over the world [11,29]. On the other hand, bioremediation is a global concern [17,30–34], and in this regard, aquatic plants are one of the most promising solutions [18,19,35–37]. In terms of environmental aspects, algal cells (microalgae and/or macroalgae) can safely treat wide ranges of many types of polluted waters, including agriculture [26,38–41], industrial, and aquaculture wastewater via bioremediation process [18,19], which means that algal cells can convert and transform highly toxic compounds into less biologically toxic chemicals, as well as at the same time producing a variety high-valuable compounds [42,43].

Globally, the concept of aquatic plants (microalgae and seaweeds) production is a separate concept from aquatic animals' cultivation. In 2018, the seaweed aquaculture produced was approximately 31.04 MTs [1]. For microalgae, the total recorded production was 87,000 tonnes. However, the microalgae production is not correctly estimated as the statistics provided by the important global producers are sometimes incorrect and confidential; FAO statistics underestimate the true scale of microalgae cultivation globally [1,44,45]. Recently, extensive studies have been conducted to develop the technologies used to enhance algal biomass. Despite the problems faced by the production of microalgal biomass, the projected rise in the global population will result in an increasing dependence on natural resources, favouring relying on sustainable bio-resources, which does not bring microalgal biomass under high consumption stress [44,46]. In the context of the blue revolution, the current review focuses on the generations of integration between aquatic plants and aquatic animals, which can drive low-cost, highly efficient, and sustainable aquaculture industry projects in the future (Figure 1).

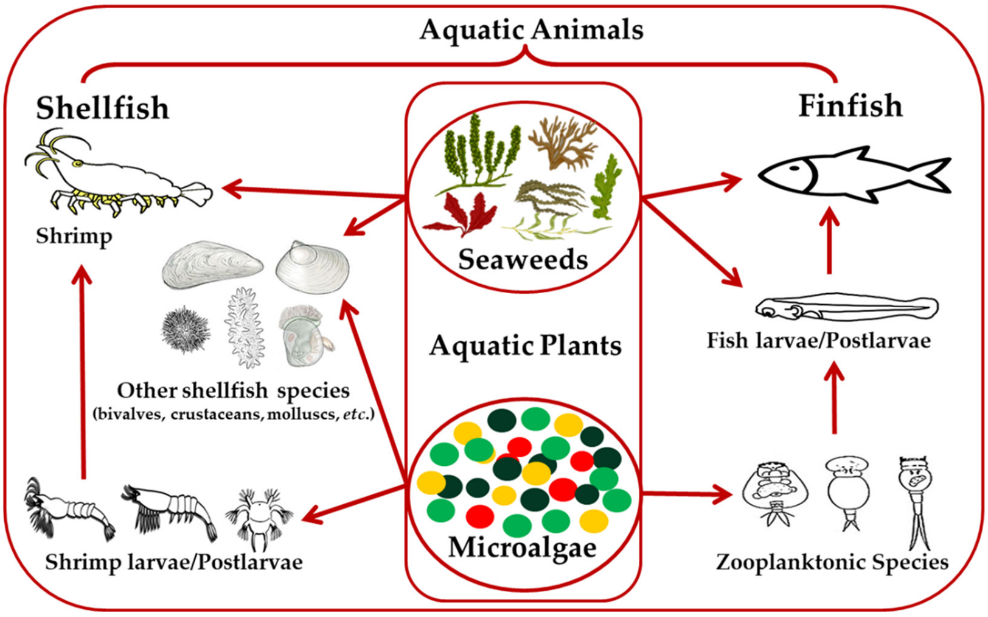

Figure 1. Schematic diagram of the integration between aquatic animals and plants.

2. Cultivation Techniques

On one hand, microalgae and macroalgae cultivation are included in the widely accepted concept of aquaculture. On the other hand, algae production is widely maintained and regulated independently of aquaculture globally [1,25,47]. In the world of aquaculture, several studies have been published acknowledging that microalgae are considered the "super food" for all aquatic animals [48]. In this context, the nutritional profiles (protein, lipid, and carbohydrate) of algae (microalgae and seaweed) in comparison with most commercially available aquafeed components are presented in Table 1.

For all aquatic animals, microalgae are the best source of protein (essential and non-essential amino acids, and peptides), lipid (poly and monounsaturated fatty acids and phospholipids), carbohydrates (mono and polysaccharides), minerals (macro and micronutrients), and vitamins (A, B, C, E, riboflavin, folic acid, nicotinic acid, and biotin). Microalgae also contain pigments (chlorophylls, phycocyanin, xanthophylls, lutein, carotenoids, astaxanthin, phycobiliproteins, and phytol), as well as biologically active molecules (hydrocarbons, alkaloids, terpenoids, and phenol), which have antimicrobial and antioxidant activities [5,49,50].

In general, algal cells could be utilized during all stages of aquaculture activities, which mainly consist of three phases: (1) hatchery seeds and/or incubations; (2) early rearing and/or nurseries, and (3) on-growing and/or mass production. Microalgae were fed to the larvae, post-larvae, and juveniles of most aquatic animals, as well as adults of bivalve, mollusc, and crustacean species, and early developmental stages of some fish species, in hatcheries. Besides, it is the main feed for different zooplankton [5].

There are many forms of microalgae utilization in different aquaculture activities, such as fresh form (live food), concentrated biomass (pastes), dried biomass, spry-dried, freeze-dried, flakes, defatted biomass (biodiesel-by product), and the residuals (wastes) of bioindustries-based-microalgae. Because of their unique biochemical composition, aquatic plants in the aquafeed industry are used as dietary supplements or as substitutes for dietary ingredients, which are mainly fishmeal or fish oil [51,52]. On the other hand, regarding the growing of aquatic animals, seaweed can be incorporated into the culture with different aquatic animals, which leads to positive sustainable, environmental, and economic aspects [53].

Table 1. The typical nutritional profiles (protein, lipid, and carbohydrate, based on % of dry matter DW) of the most commercially aquafeed components, compared to microalgae and seaweed species.

Item	Biochemical Composition (%, Dry Weight Bases)			References
	Protein	Carbohydrate	Lipid	
The most Commercially Aquafeed Ingredients				
Fish meal	63.00	11.00	12.5	[54]
Soybean	44.00	2.20	39.00	[55]
Corn-gluten meal	62.00	5.00	18.50	[56]
Wheat meal	12.20	2.90	69.00	[57]
Yeast (*Saccharomyces cerevisiae*)	50.10	1.80	4.6	[58]
Hydrolyzed feather meal	84.00	10.40	-	[59]
Amphipod meal (*Gammarus pulex*)	40.00	27.40	5.5.0	[60]
Microalgae Species				
Arthrospira platensis	50–65	8–14	4–9	[61,62]
Nannochloropsis	18–34	27–36	24–28	[61,63,64]
Chlorella vulgaris	51–58	2–17	14–22	[65]
Tetraselmis chuii	25	25	12	[63,66]
T. suecica	38.73	44.29	12.38	[21]
Isochrysis galbana	27	34	11	[67]
Botryococcus braunii	39–40	19–31	25–34	[63]
Pavlova sp.	24–29	6–9	9–14	[65,66]
Dunaliella salina	11–34	14–32	6–14	[65,67,68]
Scenedesmus obliquus	48–56	10–17	12–14	[66,69]
Phaeodactylum tricornutum	34–38	11–17	13–20	[61,63]
Chlamydomonas reinhardtii	48	17	21	[66]
Haematococcus pluvialis	17–45	20–37	15–40	[70]
Skeletonema costatum	25	4–6	10	[66]
Chaetoceros muelleri	59.00	10.00	31.00	[71]
C. calcitrans	40.00	37.00	3.00	[71]
Chaetoceros sp.	12–59	4–37	7–31	[66]
Thalassiosira pseudonana	34.00	9.00	19.00	[66]
T. weissflogii	13.2	10.00	20.00	[72]
Porphyridium cruentum	28–39	40–57	9–14	[65]
Macroalgae Species				
Eucheuma sp.	9.8–5.5	26.5–63	1–5	[73,74]
Kappaphycus sp.	3.4–6.2	65.2–55.7	1.1–1.5	[75,76]
Sargassum sp.	7.5–5.5	28–30	1.5–0.4	[74,77,78]
Gracilaria sp.	11–21	19–27	0.5–2.8	[74,79]
Pterocladia capillacea	17–20	47–51	1.7–2.5	[80]
Jania rubens	9–23	34–50	1–2.5	[80]
Ulva lactuca	12–20	42–46	2–4	[80]
Dictyota dichotoma	7–7.5	24–26	7–7.5	[27]
Turbinaria decurrens	32–33	2.5	5	[27]
Laurencia obtusa	21	4	3	[81]
Porphyra sp.	25–42	36	0.5	[82,83]

2.1. Microalgae as Livefeeds in Aquaculture Hatcheries

In the aquatic environment, microalgae are at the base of the food chain. As a result, microalgae are critical for the commercial rearing of various types of aquatic animals as a food source for all growth stages of bivalve, molluscs, sea cucumbers, seahorses, larval stages of some crustacean species, and very early developmental stages of some fish species [84,85]. Several species of microalgae have been tried as live food in marine hatcheries, but only around ten species have become widely used in aquaculture. To be useful in aquaculture, suitable microalgae species must possess several important characteristics. These keys are (1) an acceptable ingestion size (from 1 to 15 µm for filter feeders and 10 to 100 µm for grazers), (2) high digestibility, (3) fast growth rate, (4) easy for mass production, (5) adapted to environmental conditions, (6) cultivable under nutrient limitation, and (7) good nutritional content [5,86].

In aquatic habitats, as presented in Table 2, phytoplankton organisms (microalgae) are the basic food in the aquatic food chain [87] that provides all nutritional requirements to the wild zooplankton species, such as rotifers, copepods, amphipods, and daphnia, which are sequentially utilized as live feeds for crustaceans, fish, and fish larvae [88–90]. In marine hatcheries, microalgae (phytoplankton) are utilized and cultured to nourish zooplankton (rotifers, copepods, and artemia), which in turn are used as feed for fish and shellfish [5].

The most important zooplankton live-feed species used in marine hatcheries are rotifers, artemia, and copepods [91,92]. The two global species of rotifer are *Brachionus plicatilis* and *B. rotundiformis* [93]. For the rearing of marine larvae, two species of artemia (*Artemia franciscana* and *A. salina*) are more widely and commercially used in marine hatcheries [94]. As well, several copepod species were commercially produced, such as *Oithona nana*, *Acartia* spp., *O. rigida*, *Bestiolina* sp., *Temora stylifera*, *Nannocalanus minor*, *Paracalanus pas*, Table 2, [95–101]. In general, all unicellular microalgae species are stable for the production and rearing of rotifers, artemia, and copepods, while the microalgae species differ in their importance for rotifers due to several characteristics, such as their morphological states, cell wall, cell volume, digestibility, form, and their nutritional values [102]. On the other hand, there are several feeding protocols to enrich the biochemical composition (such as enhancing the content of PUFAs, HUFAs, EPA, and DHA) of zooplankton by the microalgae, before using these zooplankton species as prey [93,103,104].

Recently, the demand for shrimp has been globally increasing due to their nutritional value [105]. Pacific white leg shrimp, *Litopenaeus vannamei*, has been extensively hatched and cultivated worldwide (the production in 2018 is about 52.91 × 1000 Ts), due to their disease tolerance, rapid metamorphoses, high growth, and survival rate of larvae and post larvae, and ease of culture in several systems. The Pacific white leg shrimp followed by the Giant Black Tiger shrimp, *Penaeus monodon* (the production in 2018 is about 7.99 × 1000 Ts) [1]. Until now, all shrimp species still depend on live diatoms and microalgae as essential live feeds during larval stages (Nauplius, Zoea, Mysis, and early postlarval stages) [106]. Among all the microalgae classes, the diatoms (Class: Bacillariophyceae) are among the best suitable microalgae for marine shrimp larval rearing in naupulius (N_5 and N_6), zoea (Z_1 to Z_3), mysis (M_1 to M_3), and postlarval (PLs) stages, due to their physiological (like small cell volume size, fast growth, and easy to culture) and nutritional aspects (especially high content of EPA, DHA, and PUFA) [107], such as *Chaetoceros* [108], *Skeletonema*, *Detonula* [109], *T. weissflogii* [72], *Phaeodactylum*, *Nitzschia*, and *Navicula* [106]. Besides diatom species, some genera have been extensively utilized in shrimp larval due to their high nutritional aspects, such as *Isochrysis* [108], *Tetraselmis*, *Tisochrysis*, *Dunaleilla* [110], *Chlorella* [111], and *Nannochloropsis* [112], (Table 2). Rohani-Ghadikolaei et al. [108] concluded that *P. indicus* larvae fed on a mixture of *I. galbana* and *C. muelleri* showed higher significant survival, growth, and development than larvae fed on single species. In this study, six species of macroalgae (*U. lactuca*, *Enteromorpha intestinalis*, *Colpomenia sinuosa*, *S. ilicifolium*, *G. corticata*, and *Hypnea valentiae*) were used in the form of liquid seaweed extract (SWE) as supplementation to F/2 medium. However, the results found that *I. galbana and C. muelleri* cultured with the SWE supplementation can be widely utilized, as an alternative low-cost method for F/2 media preparation, in the production of livefoods to produce shrimp larvae in the marine hatcheries.

In all bivalves' life cycle, microalgae are the main food source. According to the literature, the microalgae genera of *Tetraselmis*, *Chaetoceros*, *Skeletonema*, *Isochrysis*, *Pavlova*, *Schizochytrium*, *Cyclotella*, *Hematococcus*, *Phaeodactylum*, *Tisochrysis*, *Arthrospira*, and *Thalassiosira* are the most recommended live feed species for several commercial bivalves (Table 2), such as Pacific oyster, *C. gigas*, juvenile of scallop, *Pecten fumatus*, larvae and juvenile of Sydney rock oyster, *S. glomerata*, larvae of Manila clam, *T. Philippinarum*, larvae of grooved carpet shell *Ruditapes decussatus*, juveniles of Pacific geoduck clam, *Panopea generosa*, larvae of giant clam, *Tridacna noae* [113–124]. Microalgal species of *Isochrysis*, *Pavlova salina*, *C. simplex*, *Micromonas* sp., *Chaetoceros* sp., and *S. costatum* as live feeds for significantly enhanced the nutritional value and increased the growth performances and survival rate of larvae of the black-lip pearl oyster (*Pinctada margaritifera*) [125,126].

Sea cucumbers are one of the most profitable aquatic animal species worldwide, attributed to their nutritional and pharmacological applications [127]. Developing appropriate feeding protocols that improve the growth, enhance metamorphosis and settlement, increase the survival rate, and improve the nutritional value of larvae, juveniles, and even adults of several commercial sea cucumber species (Table 2) have received global attention. The live feed diets of *C. calcitrans*, *C. muelleri*, *C. gracilis*, *I. galbana*, *Isochrysis* sp., *T. chuii*, *T. suecica*, *T. tetrathele*, *D. tertiolecta*, *P. lutheri*, *P. tricornutum*, *T. pseudonana*, *A. platensis*, *Dicrateria inornata*, *Rhodomonas* sp., *Cylindrotheca fusiformis*, and *Nitzschia closterium* were utilized in the commercial production of several sea cucumber species. The using of these species significantly increased the survival rate, enhanced metamorphosis, and improved the nutritional value and energy contents of larval and juvenile stages of several sea cucumber species, such as sandfish, *Holothuria scabra*, Selenka, *Apostichopus japonicus*, red sea cucumber, *Parastichopus tremulus* and California sea cucumber, *P. californicus* [128–131]. Among all the examined microalgae species, the marine diatom species *C. calcitrans* was the only specie that achieved significant larval survival, growth, development, and metamorphosis [130–132].

Sea urchins and seahorses are valuable food products and have many nutritional, pharmacological, and therapeutic properties, besides their positive impacts on environmental ecosystems. Globally, these valuable aquatic animals are facing overfishing and their fisheries are in decline. On the other hand, the hatching, larval rearing, and aquaculture trails of these important aquatic animals are a positive point for their future [133,134]. According to the previous literature, many microalgal species such as *Isochrysis* sp., *C. gracilis*, *C. muelleri*, *S. pseudocostatum*, *P. lutheri*, *P. viridis*, *T. suecica*, *D. tertiolecta*, *Cricosphaera elongata*, *Pleurochrysis carterae*, *C. vulgaris*, *Platymonas subcordiformis*, and *D. zhanjiangensis* were reported as recommended live feeds for larvae stages of several sea urchin species, such as *Tripneustes gratilla*, *Paracentrotus lividus*, and *Anthocidaris crassispina*, as presented in Table 2 [135–137]. Many studies, on the other hand, reported that feeding *N. oculata* or *I. galbana* to longsnout seahorse (*Hippocampus reidi*) juveniles resulted in significantly higher survival, ingestion rate, and growth performances [78,134,138–140].

2.2. Microalgae Biomass

Microalgae have traditionally been used as live feeds for a wide range of aquatic animal organisms, and it is essential to increase the nutritional value (quality) and mass production (quantity) of cultured zooplankton species. Microalgae production is the critical point in marine hatcheries because it involves many risk factors that make it un-vaccinable. Live feeds produced in marine hatcheries represent more than 50% of the total production costs for marine larvae production [141]. Previously, these problems have prompted many researchers to seek forage sources other than live microalgae, such as yeasts [142], microparticulate diets [143], micro-encapsulated, and inert food [144] microalgae paste [145], and microalgae past in the form of free lipid biomass, as a biodiesel by-product [62,64]. The microalgae biomass concentrate has many forms, such as dried biomass, freeze-dried, pastes, flakes, defatted (biodiesel by-product), and microalgae by-products of bioindustries-based-microalgae [145].

Microalgae concentrates are preserved using a variety of techniques [86]. When fresh live microalgae are well harvested, treated, protected, and appropriately stored, they can significantly replace live microalgae as diets utilized to raise marine larval and juvenile stages, adults of bivalves, molluscs, and abalone, as well as shrimp larvae, and different zooplankton species in marine hatcheries [62,64,101]. Microalgae concentrates have achieved the most promising results in total or partial (mixed diet) substitution of the traditional live feed supply in marine hatcheries [62,64,114,146].

Due to many reasons, aquatic organisms (animals and plants) are the richest in their valuable bioactive compounds contents on the planet [27,147,148]. Microalgae (live feeds) provide all aquatic animals with their necessary bioactive compounds, besides the bioactive mass molecules (proteins, lipids, and carbohydrates) that are needed for their growth and metamorphosis. On the other hand, the transformation of microalgae from live feeds to microalgae biomass concentrates renders them free from ciliated protozoa, which act as a contamination source and the main fierce enemy for different marine larvae [145].

Recently, potential applications of different forms (live, dried biomass, freeze-dried biomass, defatted biomass, dried biomass loaded with NH_4 or toxic dye of aquaculture effluent or industrial wastewater treatment, respectively) of several microalgal species (*Arthrospira platensis* NIOF17/003, *Nannochloropsis oceanica* NIOF15/001, *N. oculata*, *I. lutea*, *Rhodomonas* sp., *Cryptomonad* sp., and *P. salina*) were positively applied for zooplankton species, such as rotifer, *B. plicatilis* [18,19,62,142], artemia, *A. franciscana* [64], and several copepods species, such as *O.* nana [101], *Acartia sinjiensis* [149], *Pseudodiaptomus euryhalinus* [150], or *Cyclopina kasignete* [151].

The harvesting process is the separation of microalgal biomass from the culture medium using several techniques, including centrifugation, filtration, sedimentation, flotation, chemical and biological flocculation [11]. Harvesting (dewatering) of microalgae is a challenging process, which is attributed to many factors [13]. Several studies have been conducted to investigate the potential of harvested microalgae (even sun-dried form, paste form, or freeze-dried) as a substitution and/or a complete alteration of shrimp larvae live feeds; however, the life form of microalgae is still the best nutritional and optimal feeds for shrimp larvae [152–156].

Microalgal species of *P. lutheri*, *I. galbana; Tetraselmis* sp.; *C. calcitrans; C. muelleri*, which were harvested and stored for six to eight weeks, achieved adequate survival and growth of the larvae and the juvenile of Sydney rock oyster (*S. glomerata*) similar to the live feeds form of the same algal species [116]. Ponis et al. [157] found that no significant differences in growth or survival were obtained when the larvae of Pacific oyster (*C. gigas*) reared on fresh or the preserved biomass of *P. lutheri*. The commercial products of dried microalgal species of *Isochrysis* sp. (*Isochrysis* 1800®), and *T. pseudonana*, *Tetraselmis* sp., *Pavlova* sp., *T. weissflogii*, and *C. calcitrans* (Shellfish Diet 1800®) confirmed comparable results to those of the same live feeds that traditionally used in the commercial production of sea cucumber *H. scabra* (sand fish) larvae and juveniles in marine hatcheries [158]. Recently, Yu et al. [159] studied the potential of Shellfish Diet 1800® and the dried powder of seaweed *Saccharina latissima* and *Ascophyllum nodosum* as dried feed for the adult individuals of the orange-footed sea cucumber (*Cucumaria frondosa*). The results obtained from this study found that the physiological characteristics of adult *C. frondosa* are similar in both of those fed dried microalgae and seaweeds, and they concluded that the powdered seaweed diet is a promising feed source for intensive aquaculture of adult individuals of *C. frondosa*.

As well, the dried microalgae product, Shellfish Diet 1800®, has been reported as a good feed for larvae of sea urchin (*P. lividus*) [133]. The juveniles of white sea urchin (*T. gratilla*) fed and reared for 20 days on *U. pertusa*, *Gloiopeltis furcata*, *Undaria pinnatifida*, and mixtures of them (1:1:1) showed different specific growth rates, fatty acid profiles, and feed conversion efficiencies, which were attributed to the different fatty acid (FAs) profiles of selected seaweeds [160]. Lyons and Scheibling [161] found that the mixed diet of seaweed species (*Laminaria longicruris* and *Codium fragile*) may be the best feeding strategy for food preference and feeding rate of the green sea urchin (*Strongylocentrotus droebachiensis*).

2.3. Algae as Aqua-Feed Additives and/or Replacement of Diet Ingredient

Fish nutritionist needs to develop and improve nutritionally balanced diets using commonly available raw ingredients. The disadvantages of fishmeal and fish oil have motivated aquatic feed producers to reduce their use of forage fish by partially substituting terrestrial plant ingredients. Furthermore, due to competition for aquafeed ingredients from producers of other animal feed and human nutritional supplements, aquafeed manufacturers are also seeing actual increases in fishmeal prices [162,163]. In general, the most limiting factors that influence the inclusion of aquatic plants (microalgae and/or seaweeds) in the diets of aquatic animals are (1) the form of inclusion, and (2) the level of inclusion [21,22,24,39].

Microalgae have greater potential for aquaculture than macroalgae or other plant sources due to their higher nutritional value, high growth rate, and availability of several species that have wide ranges of culture conditions, simpler production processes, and have high levels of antioxidants, probiotics, antimicrobial, and colouring compounds, all of which are important variables in fish and invertebrate aquaculture [61,164]. The use of microalgae as feed additives and/or fishmeal replacement is limited by several factors, such as availability, ease of digestion, high production cost, the potential of mass production, and overall high value. However, not all microalgal species are compatible in supporting the survival and growth of aquatic animals [164,165].

Many studies have reported that the inclusion of microalgae in different aquatic animals increased survival, growth performance, feed utilization, enhanced health status, improved gut health, coloration, and stimulated immune response [164]. The 1.2% inclusion of *Schizochytrium* sp. meal in the diet of Nile tilapia (*Oreochromis niloticus*) positively influenced the gut microbiota and improved the overall health of the Nile tilapia, *O. niloticus* [166].

A diet of white leg shrimp, *L. vannamei*, supplemented with 1–2% of *D. salina* significantly increased their survival rate [167]. The weight gain of the post-larvae of *L. vannamei* was increased by 30% when a diet contained 7.5 g kg^{-1} of microalga *T. suecica*, compared to the control diet [21]. Replacement of fish meal with 6–8% *C. vulgaris* improved the immune response of post-larvae of the *Macrobrachium rosenbergii*, along with improved survival against the infection of *Aeromonas hydrophila* [168]. The inclusion of *N. gaditana*, *T. chuii*, and *P. tricornutum* improved growth performance and enhanced the immune activity of gilthead seabream, *Sparus aurata* [169]. Rohu fish, *Labeo rohita*, achieved increased immunostimulatory effects when fed the biomass of *Euglena viridis* besides improving survival against *A. hydrophila* [170]. According to the literature, aqua-diets supplemented with *Arthrospira* have significantly improved the coloration of different aquatic animals such as Koi, Red tilapia, Striped jack, Yellow catfish, and Black tiger prawn [171–173]. Sun et al. [174] cited that the pigmentation of koi fish was positively enhanced by the inclusion rate of 7.5% *A. platensis.* Ribeiro et al. [175] reported that a diet supplemented with 2.5% of a diatom, containing a high level of fucoxanthin, *P. tricornutum*, improved the bright yellow pigmentation of gilthead seabream. Liu et al. [173] cited that 0.4% *Spirulina*-lipid-extract and 4% defatted-*Spirulina* had significantly improved skin coloration of the yellow catfish *Pelteobagrus fulvidraco*.

On the other hand, macroalgae (seaweeds), either in the form of whole dry weight and/or their extracts, has recently shown excellent potential as feed additives, attributed to their high levels of pigments, antioxidants and antimicrobial compounds, and secondary metabolites, and cell walls like the saccharides (mono, poly, oligo, and lipo), which support the immunity of aquatic animals [24,39,164]. Interestingly, previous research concluded that using a commercial seaweed liquid extract (TrueAlgaeMax, TAM®) as aqua-feed additive significantly promoted growth performance, improved zooplankton community, enhanced non-specific immune responses of Nile tilapia *O. niloticus* challenged with *A. hydrophila* [24]. Meanwhile, the utilization of high levels of seaweeds as feed additives lead to low digestibility, due to their high excess of heavy metals content and the existence of anti-nutritional factors like amylase and trypsin inhibitors, lectins, phlorotannins, and phytic acids [164].

In another study, seaweed species of *Ecklonia radiata*, *S. linearifolium*, *Gracilaria* sp., *Lophocladia kuetzingii*, and *U. lactuca* have been successfully utilized as stimulant dry feed additives for the regime of the sea urchin *T. gratilla*. These selected macroalgae-dry-additives significantly increased the growth performance, feed intake, energy, and protein consumption of *T. gratilla* [176]. At different protein and lipid levels, the dried seaweed (*Sargassum* spp., *Solieria robusta*, and *U. lactuca*) were used, as a single or multiple, as a feed additive to the diet of sea urchin (*Heliocidaris erythrogramma*), which improved gonad indices [177].

2.4. Algae as a Water Conditioner

Algae as water conditioner is a technology that uses microalgae, macroalgae, or their extracts and phytochemical compounds, as water optimizers, which leads to improved growth performances, control of pathogenic bacteria, increased disease resistance, improved feed efficiency, and stimulation of the immunity of cultured aquatic animals [39]. The technique of rearing aquatic animals/larvae in the presence of microalgae called "green water technology" is common and usually connected with higher survival and growth rates than larvae reared in clear water [93,178]. Green water technology is to manage the rearing environment in aquaculture [53]. In this technology, microalgae, microbes, and zooplankton were abundant in rearing ponds where fish larvae were kept. This technology can be based on natural microalgal populations that are stimulated to flourish with the addition of fertilizer, or cultured microalgae strains can be inoculated to culture tanks if the system water has been pre-treated to exclude competing bacteria [48].

Several authors have indicated that the better growth and survival rates in this technique are mainly attributed to (1) achieving better direct and indirect feeding of larvae, (2) lower stress levels, (3) improving environmental conditions for feeding by increasing turbidity, light, and enhanced visual contrast, (4) increased oxygenation rates, and (5) increased antibacterial properties in rearing ponds [53]. There are various mechanisms associated with the profitable and beneficial effects of green water, such as the production of bioactive compounds by algal cells, which have antibacterial and antioxidant substances that control virulence genes [179,180]. *Chlorella*, *N. gaditana*, *Nannochloropsis* sp., *I. galbana*, *Isochrysis* sp., and *Tetraselmis* sp. are the most common microalgal species used for this purpose [49,181].

Green water is generally a low-cost technique. For example, shrimp grown in "green water" costs US \$1–3 kg^{-1}, while shrimp feed on the traditional diet costs US \$4–8 kg^{-1} [182,183]. In this technology, the survival rates are increased and the fry rearing conditions have improved for several commercial aquatic animal species, such as Nile tilapia (*O. niloticus*) [184], Tilapia (mosambique and Nile hybrid) [185], Pacific white shrimp (*P. vannamei)* [186], Giant Tiger shrimp (*P. monodon*) [187], banana prawn (*Fenneropenaeus merguiensis*) [188], gilthead seabream (*S. aurata*) [93,178], red sea bream (*Pagrus auratus*), Australian bass (*Macquaria novemaculeata*), dusky flathead (*Platycephalus fuscus*), and sand whiting fish (*Sillago ciliata*) [188].

On the other hand, seaweed extract has recently shown excellent potential as a water-conditioner. Few studies have been conducted on this important point. Interestingly, previous studies concluded that the addition of the commercial seaweed liquid extract (TrueAlgaeMax, TAM®, prepared from *U. lactuca*, *J. rubens*, and *P. capillacea*) as an aquaculture water conditioner significantly enhanced the growth performance, improved zooplankton community and abundance, and enhanced non-specific immune responses of *O. niloticus* challenged with *A. hydrophila* [39].

2.5. Seaweed Co-Culture and Integration with Aquatic Animals

The commercial integration of seaweed with aquatic animals has shown various benefits to aquaculturists and allows for large quantities of additional valuable aquaculture products to be produced in the coastal area, in addition to providing many benefits to the aquaculture environment. Combining economic and valuable seaweeds in aquaculture can improve the economic yields of aquatic animals by reducing the environmental consequences without increasing pressure on crowded coastal areas and resources [189]. In all cases, the growth and survival rates for seaweed and co-cultured aquatic animals were positively increased above those reported in commercial monoculture [190]. The use of seaweed in polyculture systems can assist in improving the value of aquaculture products by removing up to 80% or 90% of inorganic wastes and nitrogen, resulting in a positive impact on resource utilization efficiency [190,191]. In this type of culture system, seaweed captures inorganic nutrients in the water and converts them into profitable biomass [192]. Various *Gracilaria* species have shown their great ability to remove nutrients from fish and shrimp effluents, promote growth and survival, and act as a natural food source for many aquatic species [190,193,194]. Moreover, the same positive effects have been demonstrated when using *Ulva* sp. [195–197]. Beltran-Gutierrez et al. [198] concluded that co-cultivation of red seaweed, *Kappaphycus striatum*, and sea cucumber, *H. scabra*, is a highly effective co-culture system of lagoons, lakes, and tropical climates. This type of culture is proposed as a promising alternative to the coastal livelihood alternative for lagoon and lake growers in tropical climates because it makes better use of limited coastal land than monoculture. However, seaweeds are important biological filters, because they can remove soluble inorganic components from aquaculture effluents and are cheap to use, even for beginner farmers [190,191,198].

Besides the simplistic view of seaweed cultivation, as a single product, seaweeds can be incorporated into an integrated multi-trophic aquaculture (IMTA) to solve various environmental problems in aquaculture [199,200]. The IMTA model is recognized by breeding species from various trophic levels close to one other. As a result, the co-products (organic and inorganic wastes) of one cultured species are recycled as food inputs for the others [201]. Because of the integrated aspect of this type of aquaculture, there is no need to use chemical fertilizers to promote seaweed growth, and sustainability and profitability are not affected [202]. IMTA can decrease environmental impacts around aquaculture systems, through product diversity, faster production cycles, and financial advantages to aquaculture operators and enhancing societal views of aquaculture. In the IMTA concept, nutrients produced by aquatic animals, rich in ammonia and phosphate, are dissolved into the water and absorbed, and transformed by other microorganisms into useful biomass while keeping stable levels of oxygen, pH, and CO_2 [203–205]. Some of the advantages of the IMTA system include utilizing the remains of the diet of finfish by shellfish (organic) and seaweeds (inorganic) extractive aquaculture, taking advantage of the enrichment in dissolved inorganic nutrients [206]. The most recent studies reported that the seaweed biomass produced by the IMTA system was higher, compared to wild seaweed as well as monoculture seaweed. In addition, IMTA-based seaweeds are characterized as a source of improved biochemical composition, protein profiles, potent bioactive compounds, and techno-functional components [207]. In conclusion, Table 2 focused on some examples of the application types, generations of integration, and interactions between aquatic plants and aquatic animals in the different phases of aquaculture activities.

Table 2. The applications and the interactions of the generations of integration between aquatic plants and aquatic animals, in the different phases of aquaculture activities.

Integration/Applications Type	Aquatic Animal Species	Aquatic Plant Species	Results/Interactions	References
	Zooplankton			
Live Feeds	Rotifers (*B. plicatilis* and *B. rotundiformis*), artemia (*A. franciscana* and *Artemia* sp.), and copepods (*Bestiolina* sp., *T. stylifera*, *O. rigida*, *N. minor*, *Acartia* spp., *Paracalanus pas*).	*N. salina*, *N. oculata*, *N. gaditana*, *Nannochloropsis* sp., *Nannochloris* sp., *C. salina*, *Chlorella* sp., *Dunaleilla salina*, *C. calcitrans*, *Chaetoceros* sp., *I. galbana; T. chuii*, *T. suecica*, *P. lutheri*, *Coscinodiscus* sp., *S. costatum*, *Pseudo-nitzschia* sp., *Prorocentrum* sp., *Rhodomonas* sp., and *Navicula* sp.	Improved egg production, hatchability, filtration and ingestion rates, productivity, population, sex ratio, growth performance, survival rates, reproductive behaviour. In addition, enhance the biochemical composition; PUFAs; HUFAs; EPA; and DHA contents.	[94–100,102,103]

Table 2. *Cont.*

Integration/Applications Type	Aquatic Animal Species	Aquatic Plant Species	Results/Interactions	References
	Shrimp			
	Larvae of Pacific white leg shrimp, *L. vannamei*, Giant Tiger shrimp, *P. monodon*, and Kuruma shrimp, *Marsupenaeus japonicus*.	*Chaetoceros*, *Skeletonema*, *Thalassiosira*, *Detonula*, *Phaeodactylum*, *Nitzschia*, *Navicula Isochrysis*, *Tetraselmis*, *Nannochloropsis*, *Chlorella*, *Dunaliella*, and *Tisochrysis*	The larvae that fed on different diatom species achieved a higher survival rate, growth, body composition, development, digestive capability, and digestive enzyme activities, than the other microalgae genera.	[106,109,110,112,154,167,208,209]
	Larvae of Giant tiger shrimp, *P. monodon*	*I. galbana* and *C. muelleri* cultured with F/2 media supplemented with seaweed liquid extract (SWE) of *U. lactuca*, *E. intestinalis*, *C. sinuosa*, *S. ilicifolium*, *G. corticata*, and *H. valentiae*.	Microalgae cultured with F/2 media supplemented with SWE can be widely utilized as an alternative low-cost media in the production of live foods for the production of shrimp larvae *P. monodon*.	[108]
	Bivalve			
	Larvae and juvenile of Pacific oyster, *C. gigas*, juvenile of scallop, *Pecten fumatus*, larvae and juvenile of Sydney rock oyster, *S. glomerata*, larvae of Manila clam, *T. philippinarum*, larvae of grooved carpet shell *Ruditapes decussatus*, juveniles of Pacific geoduck clam, *Panopea generosa*, larvae of Giant clam, *Tridacna noae*, larvae and juvenile of some important commercial bivalves of *Ostrea edulis*, *Mercenaria mercenaria*, *T. semidecussata*, and *Mytilus galloprovincialis*	*Tetraselmis*, *Chaetoceros*, *Skeletonema*, *Isochrysis*, *Pavlova*, *Schizochytrium*, *Cyclotella*, *Hematococcus*, *Phaeodactylum*, *Tisochrysis*, *A. platensis*, and *Thalassiosira*	Bivalves larvae and juveniles fed on the live form of microalgae showed increased survival rates, enhanced growth, nutritional value, body composition filtration, ingestion rates, and improved digestibility rates.	[113–124]
	Sea Cucumber			
	Larvae of sandfish *H. scabra*	*C. gracilis*, *I. galbana*, and *T. chuii*, *Rhodomonas* sp., and *T. tetrathele* (single or mixed diets).	Increased the survival rate, enhanced metamorphosis, settlement, and improved the nutritional value of larvae. Improved the larval survival, development, and growth.	[128,131]
	Larvae of California sea cucumber, *P. californicus*	*C. calcitrans*, *C. muelleri*, *D. tertiolecta*, *Isochrysis* sp., *P. lutheri*, *P. tricornutum*, *T. suecica*, and *T. pseudonana* (single or mixed diets).	Among all the examined species, the diatom species *C. calcitrans* was the best species that achieved significant larval survival, growth, and metamorphosis.	[130]
	Juvenile of Selenka, *A. japonicus*	*A. platensis*, *D. inornata*, *Cylindrotheca fusiformis*, and *N. Closterium*.	The juvenile growth, energy contents, and nutritional value were improved.	[129]
	Adults red sea cucumber, *P. tremulus*	*D. tertiolecta*, *I. galbana*, and *T. chuii* (a mixture of them).	Low food availability (10–20 $\times$ 10^3 cell mL^{-1}) resulted in high mortality.	[132]

Table 2. *Cont.*

Integration/Applications Type	Aquatic Animal Species	Aquatic Plant Species	Results/Interactions	References
	Sea Urchin			
	Larvae of white-spined sea urchin, *T. gratilla*	*Isochrysis* sp., *C. muelleri*, *S. pseudocostatum*, *P. lutheri*, and *T. suecica*,	*Isochrysis* sp., *C. muelleri*, *S. pseudocostatum*, and are the best significant species for the rearing of larvae.	[135]
	Larvae of *P. lividus*	*D. tertiolecta*, *T. suecica*, *C. elongata*, and *P. carterae*.	When larvae fed on *C. elongata*, *P. carterae*, and *D. tertiolecta*, the metamorphosis was successfully enhanced. Larvae fed on *C. elongata* had 300% and 20% higher survival and development rates than larvae fed on *P. carterae* and *D. tertiolecta*.	[136]
	Larvae of *A. crassispina*.	*C. gracilis*, *P. viridis*, *C. vulgaris*, *Platymonas subcordiformis*, *D. zhanjiangensis*, and *mixture of C. gracilis*, and *D. zhanjiangensis*.	There were significant differences in the larvae's survival and growth. The highest level was recorded by the larvae fed on *D. zhanjiangensis* followed by *C. gracilis*, *P. viridis*, *C. vulgari*, and, finally, the mixture of *D. zhanjiangensis* and *C. gracilis*.	[137]
	Seahorses			
	Juveniles of longsnout seahorse, *H. reidi*.	*N. oculate*, and *I. galbana*.	The survival, ingestion rate, and growth of the juveniles were significantly higher in the treatment that fed on *N. oculata* or *I.*	[78,134,138–140]
Biomass	**Zooplankton**			
	Rotifers, *B. plicatilis* and *B. rotundiformis*, used in larvae rearing of Gilthead seabream, *S. aurata*.	*N. oculata* (live and freeze-dried forms).	Applications of freeze-dried *N. oculata* can be used successful with 100% survival and without affecting water quality.	[93,178,210]
	Rotifer, *B. plicatilis*.	*I. galbana*, *C. muelleri*, *P. lutheri*, and *Nannochloropsis* sp. (live and frozen-concentrated forms).	All examined species could apply to relative enriched PUFA, EPA, and DHA levels in the rotifer, even in live and/or frozen-concentrated forms.	[104]
	Rotifer, *B. plicatilis*.	*N. oculata* (freeze-dried), *A. platensis* (dried), comparing to baker's yeast *S. cerevisiae* (dried).	Unlive species of freeze-dried *N. oculata* and dried *A. platensis* resulted in an adequate rotifer population and population growth rate, comparing to yeast.	[142]
	Rotifer, *B. plicatilis*.	*A. platensis* NIOF17/003 (defatted, biodiesel by-product).	There was a significant increase in rotifer females carrying eggs and population when fed free lipid *A. platensis* NIOF17/003 at a level of 0.6 g L^{-1}.	[62]

Table 2. *Cont.*

Integration/Applications Type	Aquatic Animal Species	Aquatic Plant Species	Results/Interactions	References
	Rotifer, *B. plicatilis*.	*A. platensis* NIOF17/003 (dried form), loaded with aquaculture effluent based ammonia or toxic dye (Ismate violet 2R, IV2R).	Rotifers are highly sensitive to the dried biomass of *A. platensis* loaded with ammonia levels or toxic dyes. Overall, the dried *A. platensis* loaded with ammonia levels is a potential feed source for rotifers.	[18,19]
	Artemia, *A. franciscana*.	*N. oceanica* NIOF15/001 (Defatted biodiesel by-product).	Applying defatted biomass of *N. oceanica* NIOF15/001 at 0.1 g L^{-1} significantly enhanced growth (40%) and survival (500%) of *A. franciscana.*	[64]
	Copepod, *Cyclopina kasignete*.	*Melosira* sp. and *N. oculata* (dried form), compared to *I. lutea* and *N. oculata* (live form).	The copepod *C. kasignete* that fed *Melosira* sp. (live or dried form) achieved higher EPA, DHA, ARA contents, trypsin, and protease activities than other microalga species.	[151]
	Shrimp			
	Larvae and postlarval of Pacific white leg shrimp, *L. vannamei*.	*Chaetoceros* sp. (freeze-dried).	The survival, growth, and beneficial bacterial count in the gut of marine shrimp, *L. vannamei*, was significantly increased by the addition of freeze-dried *Chaetoceros* sp. directly in the culture water of propped.	[155]
	Larvae of Giant tiger shrimp, *P. Monodon*.	Sun-dried *Chaetoceros* sp., *Isochrysis* sp., and *Tetraselmis*, compared the live form of *Chaetoceros* sp.	Larvae fed the sun-dried *Chaetoceros* sp. and *Tetraselmis* sp. had good survival and growth performance, compared to the sun-dried *Isochrysis* sp. and the live form of *Chaetoceros* sp.	[152]
	Larvae of Giant tiger shrimp, *P. monodon*.	*C. muelleri* and *T. weissflogii* in live form comparing to *Arthrospira* powder.	Larval metamorphosis, survival, beneficial bacterial count and stability, digestive capability, and digestive enzyme activities of larvae fed the microalgae life form were significantly higher than those of the Arthrospira powder.	[154]
	Larvae of brown shrimp, *Farfantepenaeus aztecus*.	Replacement of live *Chaetoceros* sp. in partial or total replacement using their paste form (*Chaetoceros* 1000®, Premium Fresh Instant Algae™ paste) and other inert feeds.	Larvae growth performances were significantly lower than the control "live *Chaetoceros* sp."	[153]

Table 2. *Cont.*

Integration/Applications Type	Aquatic Animal Species	Aquatic Plant Species	Results/Interactions	References
	Larvae of Indian prawn, *P. indicus*.	Partial replacement of *Tetraselmis* and *Skeletonema* with a freeze dried microencapsulated diets.	The microcapsules (application contains the extracts of *Tetraselmis* and *Skeletonema*) improved the survival and growth of the *P. indicus* larval stages, besides reducing their reliance on microalgae life forms.	[156]
	Bivalves			
	Larvae of Pacific oyster, *C. gigas*.	*P. lutheri* (biomass compared to live form).	No significant differences in growth or survival between the larvae reared on the fresh and the preserved biomass.	[86]
	Larvae of Pacific oyster, *C. gigas*.	*P. lutheri* (concentrated as replacing live *C. calcitrans* of 50–80%).	No significant differences in growth or survival compared to the control live form.	[113]
	Larvae of Pacific oyster, *C. gigas*.	*T. suecica* (concentrated compared to live form).	There were no significant differences in larval growth compared to the control live form.	[211]
	Larvae and juvenile of Pacific oyster, *C. gigas*.	*C. calcitrans*, *S. costatum; I. galbana* (concentrates as partial replacement or supplementation, compared to live form).	There were no significant differences in larvae and juvenile growth rates compared to the live forms.	[86]
	Juvenile of Pacific oyster, *C. gigas*	*C. calcitrans*, *S. costatum* (concentrated, compared to live form)	There were no significant differences in juvenile growth compared to the live forms.	[115]
	Juveniles Scallop, *C. gigas*, and *Pecten fumatus*.	*C. muelleri* (concentrated, compared to live form).	Improved the growth performances of juveniles.	[114]
	Larvae and juveniles of Sydney rock oyster, *S. commercialis*	*P. lutheri*, *I. galbana*, *Tetraselmis* sp., *C. calcitrans*, *C. muellei* (concentrated and storage for 6–8 weeks).	The survival rates and growth performance of bivalves (larval and juvenile) are equal to that achieved by the microalgal live forms.	[116]
	Larvae of Sydney rock oyster, *S. commercialis*	*P. lutheri*, *I. galbana*, *C. calcitrans* (mixed concentrated).	Similar and/or higher growth performance than larvae fed the control live forms.	[212]
	Larvae Manila clam, *T. Philippinarum*.	*T. suecica; Nannochloris* sp. (spray-dried)	Larval growth was similar to that of the same live species.	[118]
	Juvenile of five important commercial bivalve species (*C. gigas*, *O. edulis*, *M. mercenaria*, *T. philippinarum*, and *T. decussata*).	*T. suecica* (spray-dried), compared to live *T. suecica; C. calcitrans.*	The juvenile growth was similar to live *Tetraselmis*, while less than *C. calcitrans.*	[117]
	Juveniles *C. gigas* and *T. Semidecussata*.	*Schizochytrium* sp. (spray-dried as a 40% partial replacement of the live form).	Similar juvenile growth compared to the control live form.	[120]
	Juveniles of *C. gigas*, *T. philippinarum*, and *O. edulis*.	*T. suecica; Cyclotella cryptica* (mixed spray-dried, 70:30%).	There were no significant differences in juvenile growth compared to the live form.	[119]

Table 2. *Cont.*

Integration/Applications Type	Aquatic Animal Species	Aquatic Plant Species	Results/Interactions	References
	Juveniles of Mediterranean mussels *M. galloprovincialis*	*Schizochytrium* sp.; *A. Platensis*; *Hematococcus pluvialis* (spray-dried).	Growth performances of juvenile fed spray-dried algae were significantly higher than those of live feeds form.	[121]
	Larvae *Ruditapes decussatus* (Grooved carpet shell).	*I. galbana; T. suecica; P. tricornutum* (freeze-dried).	The growth of larvae fed freeze-dried algal species was significantly lower than that of live feeds.	[122]
	Juveniles of Pacific Geoduck Clam *Panopea generosa*.	*C. muelleri; Tisochrysis lutea; Schizochytrium* sp.; *A. platensis* (spray-dried as a different partial replacement of the live form).	Low significant growth rates of juveniles were obtained when replacing 25–50% of the live forms with spray-dried.	[123]
	Juveniles of black-lip pearl oyster, *P. margaritifera*.	*T. suecica* (dried in a mixture of 1:1 with the life form).	Growth of umbo larvae fed a 1:1 mixture of fresh algae and dried *Tetraselmis* was significantly greater than that of those fed live forms.	[213]
	Larvae of Giant clam, *Tridacna noae*.	*Isochrysis* sp., *Pavlova* sp., *Tetraselmis* sp., *T. weissflogii.*	All experimented microalgae were ingested and, thereafter, digested by larvae, confirming that the investigated algae concentrates were a good food source for the giant clam larvae.	[124]
	Seacucumber			
	Larvae of sandfish, *H. scabra*.	*Isochrysis* sp., *Pavlova* sp., and *T. weissflogii.*	Significantly increased the survival rate, enhanced growth performance, and improved the nutritional value of larvae. Besides, it reduced larvae production cost.	[214]
	Larvae of sandfish, *H. scabra*	*Isochrysis* 1800® (*Isochrysis* sp.), and the product named Shellfish Diet 1800® (consisting of a mix of *Isochrysis* sp., *T. pseudonana*, *Tetraselmis* sp., *Pavlova* sp., *T. weissflogii*, and *C. calcitrans* (with a ratio: 30:30:19:13:6: and 3%, respectively, on a dry weight basis).	The examined microalgal concentrates confirm comparable results to those of the same live feeds traditionally utilized in the commercial production of *H.* scabra (sand-fish) in marine hatcheries.	[158]
	Larvae of sandfish, *H. scabra*.	Live microalgae *Isochrysis* sp. and *C. muelleri* compared to six concentrated algal diets (Instant Algae®, Reed Mariculture Inc.) which were *Isochrysis* sp. *Pavlova* sp., *Tetraselmis* sp., *T. weissflogii*, *T. pseudonana*, and a mixture of *Isochrysis* sp., *Tetraselmis* sp., *T. pseudonana*, and *Pavlova* sp. (Shellfish Diet 1800®).	All experimental algal species (even in live or concentrated form) were ingested by the juveniles. The live form of *C. muelleri* showed the highest juvenile growth. Overall, microalgae concentrates are suitable alternatives to live microalgae through the hatchery stages of sea cucumber, *H. scabra*.	[85,215]

Table 2. *Cont.*

Integration/Applications Type	Aquatic Animal Species	Aquatic Plant Species	Results/Interactions	References
	The orange-footed adult sea cucumber, *Cucumaria frondose.*	A commercial microalgae diet (Shellfish Diet 1800®: a mix of *Isochrysis*, *Tetraselmis*, *T. pseudonana* and *Pavlova*, with a ratio of 40:25:20:15% dry weight 8%), dried powder of seaweed (*S. latissimi* and *A. nodosum)* compared to the control (no diet supplementation).	Adult sea cucumbers fed with powdered macroalgae have similar physiological characteristics to those fed with commercial powdered microalgae diets, confirming that powdered macroalgae diets are a promising feed source for intensive aquaculture of adult individuals of *C. frondosa*.	[159]
		Sea-Urchin		
	Larvae of *P. lividus.*	*D. tertiolecta* and a concentrated algal paste (Shellfish Diet 1800®).	There is no significant difference in survival and metamorphosis rates for larvae fed on live or paste microalgae.	[133]
		Seahorses		
	Juvenile of newborn seahorse *H. reidi.*	*N. oculata* (live form, commercial paste, and flocculated paste).	No significant differences were recorded in the survival rates, dry weight, or ingestion rates of the juvenile seahorse.	[216]
Aqua-Feed Additives and/or Replacement of Diet Ingredients		**Fish**		
	Nile tilapia, *O. niloticus.*	Defatted *N. oculata*, *Schizochytrium* sp., *A. platensis*, *Chlorella* sp., *Anabaena* sp., *Dunaliella* sp., *G. arcuata*, and seaweed liquid extract (TrueAlgaeMax, TAM®, prepared from *U. lactuca*, *J. rubens*, and *P. capillacea*).	Significantly increase productive performance nutrient utilization, survival rate, immune status, antioxidant enzymes, gene expression, histological status, and disease resistance.	[24,217–222]
	Juveniles of European sea bass, *Dicentrarchus labrax.*	*I. lutea*, *T. suecica*, *P. viridis* *Nannochloropsis* sp., *N.* oceanica, defatted *Nannochloropsis* sp., *G. gracilis.*	Significantly improve the muscle tissue composition, growth, nutrient utilization, survival, and nutritional quality.	[52,223–226]
	Juveniles of gilthead seabream *S. aurata.*	Defatted *Tetraselmis* sp., *T. chuii*, Cellulose hydrolyzed *N. gaditana*, *Schizochytrium* sp., *P. tricornutum*, *N. gaditana*, *Navicula* sp., hydrolyzed *A. platensis*, and heat-treated *Gracilaria* sp., and *Ulva* sp.	Significantly improve *S. aurata* weight gain, specific growth rate, feed conversion ratio, survival, nutritional quality, innate immune parameters, and acute hypoxia tolerance.	[175,227–232]
	Salmonids Atlantic salmon, *Salmo salar L.*	*N. oceanica*, defatted *N. oceanica*, *Scenedesmus* sp., *Schizochytrium* sp.	Significantly improve weight gain, specific growth rate, improve FCR, survival, and fatty acid profiles.	[233–235]
	Juveniles and adults Rrainbow trout, *Oncorhynchus mykiss.*	*Nannochloropsis* sp., *Schizochytrium* sp., *Isochrysis* sp., *S. almeriensis*, *U. lactuca*, *E. linza*	Significantly increase weight gain, improve feed conversion ratio and survival rate.	[236–238]

Table 2. *Cont.*

Integration/Applications Type	Aquatic Animal Species	Aquatic Plant Species	Results/Interactions	References
	Shellfish			
	Pacific white shrimp, *L. vannamei*, black tiger shrimp, *P. monodon*, and freshwater prawn, *M. rosenbergii.*	*T. suecica*, *Schizochytrium* sp., *Aurantiochytrium* sp., *C. calcitrans*, defatted *H. pluvialis*, *D. salina*, *C. vulgaris*, *A. platensis*, *U. lactuca* and *Gracilaria* sp.	Significantly enhance the growth, immune, nutrient utilization, survival, gene expression, nutritional quality, disease resistance, and improve tolerance stress.	[21,167,217,239–245]
	Sea urchin, *T. gratilla* and *Heliocidaris erythrogramma.*	*E. radiata*, *S. linearifolium*, *Sargassum* spp., *Gracilaria* sp., *Solieria robusta*, *L. kuetzingii*, and *U. lactuca.*	Significantly increase growth performances, feed intake, energy, protein consumption, and improve gonad indices and of *T. gratilla.*	[176,177]
Water Conditioner	Larval Gilthead seabream, *S. aurata*	*N. oculata* (live and freeze-dried forms). *N. gaditana* and *I.* galbana (live and freeze-dried forms).	Applications of different forms (live and/or freeze-dried) of *N. oculata* in the rearing tanks significantly improved growth, survival, and histological status. The complete replacement of live algae in larval rearing tanks with freeze-dried algae resulted in the same survival and growth of larvae reared for 43 days.	[93,178,246]
	Tilapia (mosambique and hybrid tilapia) Nile tilapia, *O. niloticus*	*Nitzschia*, *Pleurosigma*, *Nannochloropsis* and *Oscillatoria*. Seaweed liquid extract (TrueAlgaeMax, TAM®, prepared from *U. lactuca*, *J. rubens*, and *P. capillacea*)	Application of green water is effective in controlling the luminous bacteria. The dominant species of *Nitzschia*, *Pleurosigma*, *Nannochloropsis*, and *Oscillatoria* have a positive effect on the pathogenic bacteria in ponds and hatcheries, in general. It significantly enhances growth performance, immune responses, feed utilization, and zooplankton community and diversity.	[39,185]
	Giant tiger shrimp, *P. monodon*	*Chlorella* sp.	Reduce the white spot disease load in culture ponds of P. monodon.	[187]
Seaweed Co-CultureandIntegration with Aquatic Animals	Black tiger shrimp, *P. monodon*, Nile tilapia, *O. niloticus*, Mediterranean mussels, *M. galloprovincialis*, Pacific white shrimp, *L. vannamei*, sea cucumber, *H. scabra.*	*G. tenuistipitata*, *G. verrucosa*, *G. corticata*, *Ulva*, *K. striatum.*	Improved water quality, shrimp survival, growth, antibacterial activities, and disease resistance significantly.	[46,190,194–198]
	Black rockfish, *Sebastes schlegeli.*	*U. pertusa*, *S. japonica*, and *Gracilariopsis chorda.*	Seaweed significantly removed large amounts of nutrients (NH_4, NO_3, NO_2, and PO_4) from the fish tank effluents.	[191]

Table 2. *Cont.*

Integration/Applications Type	Aquatic Animal Species	Aquatic Plant Species	Results/Interactions	References
	Gilthead seabream, *S. aurata*, and sea urchin, *P. lividus.*	*U. lactuca.*	The IMTA systems between aquatic animals (*S. aurata* and *P. lividus*) and aquatic plants (*U. lactuca*) resulted in a lower FCR, and decreased growth period, enhanced gonadal development and quality, improved economic return, bioremediation efficiency, and decreased the treatment cost of the effluent.	[247]
	Cobia fish, *Rachycentron canadum* and The Brown mussel, *Perna perna.*	*U. lactuca.*	The IMTA systems between aquatic animals (*R. canadum* and *P. perna*) and aquatic plants (*U. lactuca*) increased yield and bioremediation efficiency.	[248]
	Grunt cab, *Isacia conteptionis*, Pacific oyster, *C. gigas*, and Chilean sea urchin, *Loxechinus albus.*	*G. chilensis.*	*G. chilensis* was highly effective in bioremediation of the soluble nutrients.	[249]

3. Future Prospective

It is well known that blue biotechnology can make a significant contribution to the key societal challenges due to the huge biological diversity populating water ecosystems. Globally, to develop and enhance the integrated production of aquatic animals and aquatic plants, several strategies must be pursued to achieve this goal, such as increasing research funding for smart and integrated aquaculture, particularly in developing countries, increasing scientific missions, technology transfer, exchanging information, encouraging the companies producing seaweeds and microalgae to reveal the real data of algae production, and the establishment of international blocs specialized in this vital industry. In conclusion, the applications of granted patents, especially in the equipment and facilities of aquaculture integration technologies, are the future of this vital industry that will improve, enhance, and develop production with low-cost technologies.

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