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Review

A Comprehensive Review of the Multiple Uses of Water in Aquaculture-Integrated Agriculture Based on International and National Experiences

Lubna A. Ibrahim [1], Mohamed Abu-Hashim [2], Hiba Shaghaleh [3], Elsayed Elsadek [4,5], Amar Ali Adam Hamad [3] and Yousef Alhaj Hamoud [5,6,*]

1 Water Management Research Institute (WMRI), National Water Research Center (NWRC), El-Qanater El-Khairia 13621, Egypt
2 Soil Science Department, College of Agriculture, Zagazig University, Zagazig 44511, Egypt
3 College of Environment, Hohai University, Nanjing 210098, China
4 Agricultural and Biosystems Engineering Department, College of Agriculture, Damietta University, Damietta 34517, Egypt
5 College of Hydrology and Water Recourses, Hohai University, Nanjing 210098, China
6 College of Agricultural Science and Engineering, Hohai University, Nanjing 210098, China
* Correspondence: yousef-hamoud11@hhu.edu.cn

Abstract: Multiple uses of water aquaculture-integrated agriculture systems (AIAS) are inevitable to produce more food per drop of water to address water shortage, food insecurity, and climate change. This survey intends to outline the multiple-use water in pond-based AIAS in light of legal regulations and water salinity. Scenarios for pond-based AIA and their impact on the environment were presented and discussed. Pond-based AIA has been demonstrated to have many social, economic, and environmental benefits. Moreover, international and national experiences and attempts for genuine applications were exhibited. Throughout, pond-based AIA farming practices are seen as a proficient utilization of water that aids food sustainability. It was concluded that pond-based AIA could aid in increasing productivity, income for food producers and soil fertility, ecosystem maintenance, and adaptation to environmental change. AIAS helps adapt to and mitigate climate change by reducing waste and greenhouse gas emissions, reducing pressure on water resources, and recycling nutrients. Finally, developing and promoting the expansion of rotation of wheat-fish and pond-based AIA in the desert and encouraging global collaboration for information and knowledge transfer among different countries were discussed.

Keywords: climate change; multiple-use water; pond-based AIA; rotate wheat-fish; water productivity

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1. Introduction

The current world population is anticipated to reach 8.5, 9.7, and 10.9 billion in 2030 (10%), 2050 (26%), and 2100 (42%), respectively [1]. These future projections imply the imperative of sustainable, high-yield food production systems that maximize water and nutrient reuse while minimizing environmental impact. It is realized that the shift toward a more sustainable food framework is the second goal of the "Sustainable Development Goals (SDG) Zero Hunger" to achieve food sovereignty, enhance nutrition and advance feasible agriculture" [1].

Agriculture is essential for achieving food security in the face of population growth worldwide. Globally, agriculture consumes roughly 69–70% of yearly water withdrawals, while in a few dry countries, it consumes 90% [2]. The intergovernmental and legislative assemblies advocate for sustainable agriculture because agriculture is the major cause and victim of water pollution [2]. Any solution to save water must start by reinforcing water use for irrigation by implementing the "more crops per drop" intensification approach to increase yield, particularly in regions with limited water resources.

Similar to agriculture, aquaculture production pollutes water resources [3]. Fish waste, including excretions and unconsumed fish feed, accumulates, leading to water pollution. Aquaculture is a consumer of water, and its integration with agriculture is logical and coherent, transforming it into a non-consumptive production sector that does not contend with agriculture, which improves the benefits of sustainable farming [4]. Therefore, the multiple usages of water in aquaculture-integrated agriculture systems (AIAS) are effective in enhancing farm and water productivity, improving fish pond water quality, and reducing the environmental impact of nutrient-rich water discharge, cost of water, and amount of chemical fertilizer needed for crops. A potential strategy to increase "crops per drop" is aquaculture-integrated agriculture (AIA), which is sometimes referred to as "more crop per drop" [4].

Aquaculture-integrated agriculture systems (AIAS)-based soil is a sort of sustainable intensification that produces more food from the same land area and water use without ecological impacts [5]. AIA incorporates the joining of fish, fruits, vegetables, and livestock. In AIA, wastes are recycled from one system as inputs to another, and thus, pollution is reduced [6]. AIA has increased sustainability, productivity, profitability, efficiency, and maximally benefits from water, land, and labor [6,7]. AIA has benefits for increasing food production and reducing dangers related to water deficiency [6]. One of the main kinds of AIA systems is pond-based AIA, where fish mature as an essential crop for production and income. Pond-based AIA is environmentally feasible and gives a strategy for water reusing and nutrient recycling [8].

The current survey aims to present an in-depth understanding of the various uses of water in pond-based AIA and to examine the key issues determining the future contribution of the pond-based AIAS to meeting the worldwide requirement for food production through the successful utilization of water. The objective of the current article is to furnish a state-of-the-art review of the potential benefits of pond-based AIA in terms of water use efficiency, food sustainability, and climate change. We examine the performance of pond-based AIA from environmental and socio-economic perspectives. Different international and national experiences are discussed. Furthermore, the benefits and constraints of pond-based AIA, as well as future aspects, prospects, and potential applications, are clarified. Finally, preliminary conclusions are reached on the adoption of pond-based AIA to increase water use efficiency and food sustainability.

2. Methods

The survey was undertaken based on PUBMED, SpringerLink and ScienceDirect for the keyword "fish pond integrated agriculture" from the oldest publications in 2000 to the newest in 2021, resulting in 92, 3376, and 3844 publications, respectively. As a result of the large number of publications, analysis of the keyword "fish pond integrated agriculture" on co-occurrence networks was performed utilizing VOS viewer software (VOS); the entire co-occurrence network was divided into four clusters with different colors, as shown in Figure 1. The center of the green cluster contains the keyword "pond" from which the studies focused on the fish, production system, culture, and growth of Nile tilapia (*Oreochromis niloticus*) were investigated. Meanwhile, the red cluster centers on the keyword "fishpond" associated with the words fish farm feed, fish farming integrated animals (pig and chicken) with agriculture and Vietnam in different studies. The blue cluster includes two hubs: one for aquaculture and the other for water, which includes mainly studies concentrated on pond sediment controls, abundance nitrogen, and China. Meanwhile, the centered yellow cluster is the keyword "species" through which the studies focused on the development, impact on the environment, and activity control. From the above, a comprehensive investigation will focus on an integrated pond-based AIA that includes livestock, considering the words pond, aquaculture, feed, development, and growth of species, water, production, and environmental impact.

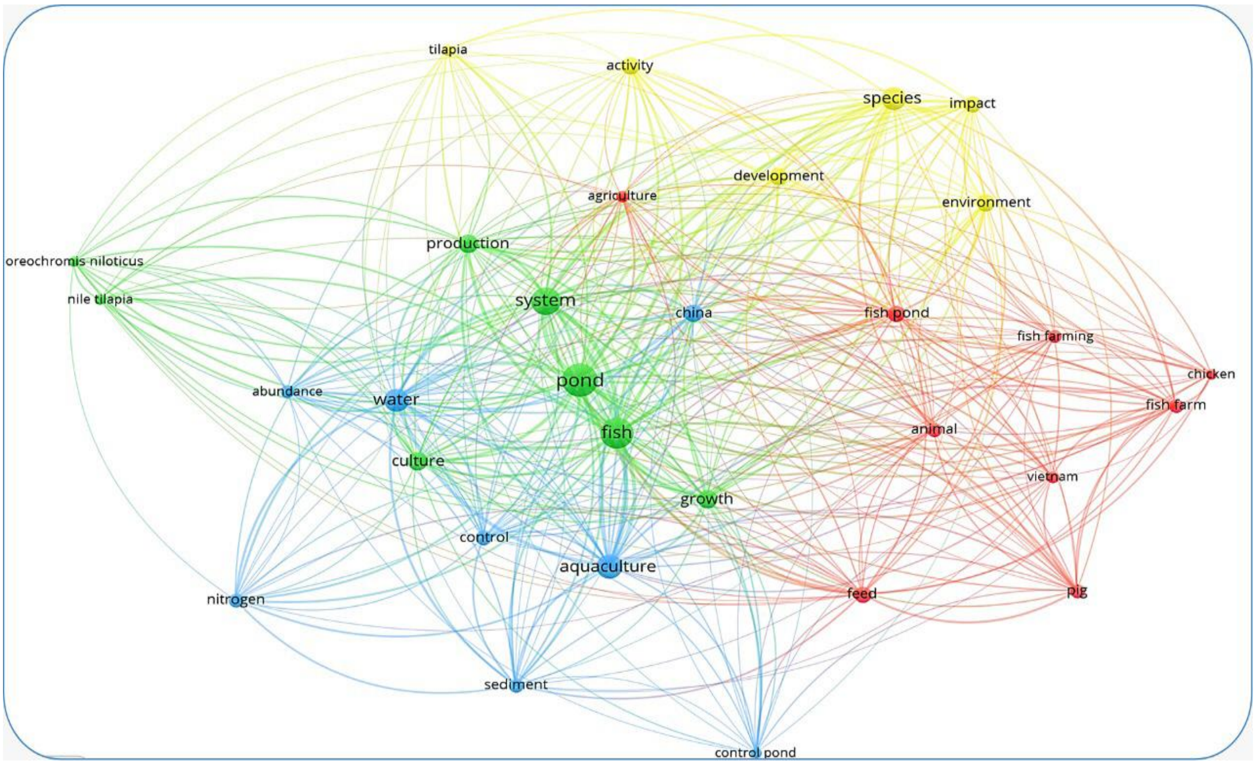

Figure 1. High-frequency words "fish pond integrated agriculture" in abstracts and titles of high-influence publications.

3. Multiple-Use Water

With critical challenges in managing water resources facing the developing world, the need to progress in multiple-use water in AIAS to reinforce both water and crop productivity has acquired critical impact. Multiple-use water could be tracked down in blue water (surface and groundwater) and green water (rain), which entails largely untapped chances to enhance the efficacy and productivity of water use. The distinction between blue and green water utilization in crop production is unclear [9]. Finally, blue water cannot be segregated from green water in aquaculture-integrated agriculture, as the two types of water are closely interrelated and complementary [10].

Various yields for a similar amount of water are obtained through the water use in fish pond aquaculture and reutilizing this water in the irrigation of crops. The water efficacy can also be essentially expanded through (1) the utilization of fertilizers by advancing the growth of fish and plants and yields per unit of water [11]; (2) relying on natural feeds in pond water, which can also increase blue water efficiency [12]; (3) the diversification and intensification of cropping patterns; (4) micro-irrigation for the production of crops in combination with pond-dike cropping [13]; and (5) small ponds or reservoirs that can potentially conserve or storage rainwater for AIAS.

3.1. Aquaculture Species in Different Water Environments

As per water salinity, aquaculture can be classified as freshwater (≤0.5 g/L), brackish (0.5–30 g/L), and marine 30 g/L cultures [14].

- Freshwater (inland) culture mainly produces fish using a culture system such as ponds, flow-through systems, recirculation aquaculture systems (RAS), or other inland waterways created based on economic perspectives. Species raised in inland ponds are the "snakehead, carp, tilapia, trout, palaemonids, goldfish, gourami, the giant freshwater prawn, trout, pike, tench, salmonids, and catfish" [14].

- Brackish (coastal) culture is carried out in coastal ponds, swamps, lagoons, and tidal regimes. This type of fish is called euryhaline, since it can maintain a variety of salinity. Crab, mullet, oyster, and shrimp are common species [15].
- In marine (Mari) culture, highly valuable fish such as salmon, seabass, bream, barramundi, trout, bivalve mollusks, and seaweeds [16] are farmed in artificial facilities for fish farming, such as cages or basins that can be operated conventionally.

Hence, numerous freshwater sorts can be effectively developed in the salinity range of 0.5–30 g/L because most fish types can adapt to the conditions of the new environment.

3.2. Plant Growth under High Salinity

A series of moderate and tolerant plants and their threshold values are depicted in Tables 1 and 2 and experimentally tested [17,18]. Halophyte plants are best suited to growing and living in high-salinity conditions or even seawater [17,18], as demonstrated in Table 3.

To deal with climate change, research will be needed to develop or promote a new strain or breed of aquaculture species and hybrid plant (crops) crops that are tolerant of water with a poorer quality index and high salinity levels. To lessen the effects of environmental change on freshwater, integrated mariculture is necessary. The low cost of feeding, ease of propagation, resistance to disease, tolerance to adverse climatic conditions, rapid growth, and high endurance should be observed for desert aquaculture management.

3.3. Legal Framework

Lately, much consideration has been paid to the role and work of legal organizations in aquaculture improvement [19]. Risk management in aquaculture is mandatory to ascertain the efficacy and safety of production. Chemical waste and pollutants are estimated by legislation in three ways: (A) banning or restricting the utilization of unsafe chemicals to the environment; (B) improving a wastewater discharge licensing system, which is generally controlled by "a water law"; and (C) prohibiting the utilization of specific drugs, chemicals, and hormones that can, unfortunately, influence the physiological performance of fish [20].

Due to the higher risk associated with higher contaminants in ponds, various countries have ordered specific rules relating to the following. (1) First, there is "under an aquaculture-specific legislative text", for instance, the United States (US), Australia, etc. [19]. In the US, the US EPA (Environmental Protection Agency) has established rule production systems for aquaculture, such as lists of detected pollutants and vessel classifications for various degrees of operational discharge [21]. Then, different countries have gone with the same pattern. Farmers must develop further production techniques to meet water quality standards when regulations are authorized based on drainage standards. (2) Second, there is the "under a basic fisheries law", for example, Albania, Belgium, etc. [19]. (3) A third rule is "under management (law cover fisheries or water) in general" such as Brazil, Australia (New South Wales), etc. [19]. For example, Malaysia has guidance for using the Environmental Quality (Industrial Waste) Regulation 2009 as the primary reference. The sewage discharge standard covering three different sewage discharge standards consisting of five sub-standard grades has been implemented in China. (4) Fourth, there is the "under a water law"; countries such as Thailand, Taiwan, etc. [19] have set water quality standards for aquaculture. These standards consist of water quality constraints and restrictions to ensure that waste cannot adversely affect water bodies. (5) Countries that do not have regulations or guidelines can follow those provided by the International Finance Corporation (IFC) or the General Authority for Awqaf (GAA) [14].

Table 1. Examples of salt resilience of herbaceous crops.

No.	Common Name	The Botanical Name of Crops	Salt Tolerance Parameters			Economic Esteem (Value)
			Resilience in Light of	Threshold EC mS/cm	Rating (T = Tolerant; MT = Medium T)	
1	Rye	*Secale cereale* L.	Grain yield	11.4	T	Flour
2	Canola or rapeseed	*B. napus* L.	Seed yield	11.0	T	The 2nd oilseed crop after soybean
3	Canola or rapeseed	*Brassica campestris* L.	Seed yield	9.7	T	
4	Guar	*Cyamopsis tetragonoloba (L). Taub.*	Seed yield	8.8	T	Vegetable, grain, or green fertilizer crop, anti-diabetic, anti-ulcer, anticholinergic, anticoagulant, hemolytic, cytoprotective, antimicrobial, hypocholesterolemic, and wound healing activity
5	Wheat (semi-dwarf)	*T. aestivum* L.	Grain yield	8.6	T	The 1st significant and key cereal crop for making bread
6	Kenaf	*Hibiscus cannabinus* L.	Stem DW	8.1	T	Fiber, therapeutic plant, and a feasible source of cellulose
7	Barley	*Hordeum vulgare* L.	Grain yield	8.0	T	Human food, fermenting materials, animal feed, bedding, fodder, feed, and malt
8	Rye (forage)	*Secale cereale* L.	Shoot DW	7.6	T	ß-glucan, resistant starch, and bioactive compounds
9	Wheatgrass, tall	*A. elongatum (Hort) Beauvois*	Shoot DW	7.5	T	A rich source of several supplements such as amino acids, minerals, enzymes, and vitamins
10	Sugar beet	*Beta vulgaris* L.	Storage root	7.0	T	Source of sugar
11	Bermuda grass	*Cynodon dactylon* (L.) *Pers.*	Shoot DW	6.9	T	Wind and water disintegration control
12	Sorghum	*Sorghum bicolor* (L.) *Moench*	Grain yield	6.8	T	Animal fodder or as a combustible
13	Wheat	*Triticum aestivum* L.	Grain yield	6.0	MT	Major staple food and cereal crop in the world
14	Barley (forage).	*Hordeum vulgare* L.	Shoot DW	6.0	MT	Fodder and brewing
15	Wheat, Durum	*T. turgidum* L. *var. durum Desf.*	Grain yield	5.9	MT	Durum semolina is consumed as a home-made pasta and cakes, while straw fed by livestock
16	Ryegrass, perennial.	*Lolium perenne* L.	Shoot DW	5.6	MT	The most significant forage species
17	Trefoil, narrow leaf birdsfoot	*L. corniculatus var tenuifolium* L.	Shoot DW	5.0	MT	Perennial legume species, a fodder crop which combines high efficiency, productivity, and nutritional value
18	Soybean	*Glycine max* (L.) *Merrrill*	Seed yield	5.0	MT	High-quality protein, oil, and soybean seed
19	Sunflower	*Helianthus annuus* L.	Seed yield	4.8	MT	Oilseed, all-season crop

Table 2. Salt resilience vegetables and fruit crops.

No.	Common Name	The Botanical Name of Crops	Salt Tolerance Parameters			Economic Esteem or Value
			Resilience in Light of	Threshold (ECe) mS/cm	T = Tolerant; MT = Medium T	
1	Purslane	*Portulaca oleracea* L.	Shoot FW	6.3	T	Anti-rheumatic and anti-fungal
2	Artichoke	*Cynara scolymus* L.	Bud yield	6.1	T	Antioxidant and Antimicrobial
3	Cowpea	*Vigna unguiculata* (L.) *Walp.*	Seed yield	4.9	T	High protein content, protection from drought, enhanced soil fertility, and prevent erosion
4	Squash, zucchini	*C. pepo* L. *var melopepo* (L.) *Alef.*	Fruit yield	4.9	T	Natural antioxidants ß-carotene, folic acid, and vitamins C and E
5	Asparagus	*Asparagus officinalis* L.	Spear yield	4.1	T	Asparagus is a profoundly valued dioeciously modern vegetable harvest, high in folic acid, thiamin, vitamin B6 and a good source of potassium
6	Beet, red	*Beta vulgaris* L.	Storage root	4.0	T	Rich in both fiber and sugars, however, it has a moderate caloric value
7	Turnip (greens)	*Brassica rapa* L. *(Rapifera Group)*	Storage root Top	3.3	T	High dietary benefit and extremely valuable in the development of red blood cells

Table 3. Plants grow in high saline conditions naturally.

No.	Common Name	Botanical Name	Employing
1	Mamoncillo	*Aeluropus lagopoides*	Grass and fodder
2	Hairy Sea Health	*Frankenia hirsute*	Ornamental. The powder is blended with milk to present to cows and camels
3	Golden Samphire	*Limbarda crithmopides*	Fodder, vegetables,
4	Shrubby Samphire	*Sarcocornia fruticose*	Vegetables are considered a source of polyphenolic compounds, fiber, and antioxidant vitamins such as vitamin C
5	Coast-sand Spurrey	*Spergularia media*	Fodder and green compost
6	Seablite	*Suaeda maritima*	Vegetables and seeds (30–35% oil)
7	Athel	*Tamarix aphylla*	Shadow plant and energy crop
8	Nile tamarisk	*Tamarix nilotica*	

By Law in Egypt, as shown in Table 4, the usage of the River Nile for aquaculture activities is disallowed by the current law No. 124/1983. The primary water resources used for aquaculture intentions are underground water and drainage agricultural water [22]. Agricultural drainage negatively impacts farmed fish quality because of pollutants accumulation (agrochemicals) in the fish tissue [23]. Thus, farmers requested a great deal of freshwater since they would reuse it to develop crops, and their demand was not met due to the pressure on freshwater resources.

Fish cultivating is not allowed to be created on agricultural lands. The main guideline influencing land usage is Law 124/1983, which states that only fallow land (not fit for crop production) can be used for fish farming. This regulation aims to prevent the conversion of 'old' agricultural land for other purposes and usage. Yet, it poses complications to the rotation of aquaculture and agriculture, for instance, the growing of cereal crops on the bottom of fishponds during the winter season. Aquaculture is also temporarily permitted for a specified period in salty lands; once the salt is leached and the salts are removed from the land, it turns into agricultural land for the cultivation of crops [24].

Finally, in December 2021, the strategic support of AIA farming systems was allowed by Law No. 146/2021, which granted permission for integrated fish and plant farming.

Table 4. Egypt's legal framework for aquaculture.

Laws	Articles
Law No. 124/1983 promulgating the Act on Fishing, Aquatic Life and Fish Farms Regulations	• Only fallow land can be used for cultivating fish and gives the right to initial utilization of the River Nile water just for domestic and agricultural purposes and for fish hatcheries. Fish farms (grow-out) are allowed to use drainage water, lake, and brackish water.
Law 147/2021 of the Ministry of Water Resources and Irrigation (MWRI).	• Article 84; Banning the establishment of farms and cages for the culture of fish in the course of the Nile and its two branches, up to five hundred meters behind Edfina Barrage, Dam, and Damietta Lock, in addition to El-Rayahat, public canals, and Lake Nasser. • The groundwater utilization in the desert land area is important for the land use license given by the MWRI. The permit to utilize groundwater is related to the status of the nearby aquifer.
Law No. 146 of 2021 for the Protection and Development of Lakes and Fisheries.	• Article 53: A permit for integrated farming to cultivate fish and plants might be granted. The executive regulations will determine the controls and procedures directing this.

4. Pond-Based AIA

Fish culture in ponds has long been practiced by rural communities in many or several countries in Asia and is a current practice in Africa. Pond culture is an extremely known aquaculture production strategy. It can be divided into two sorts depending on their water supply, namely levee ponds (1.79 m^3/kg productivity) and watershed (or depression) ponds [25]. Pond sizes fluctuate from 100 to 100,000 m^2, depending on their production scale, site, and species types. Ponds have a typical depth of 1.2–1.5 m [25]. Most fish farming families in rural communities are engaged in extensive and semi-intensive farming because of the absence of resources [26], so fish productivity is variable, as displayed in Table 5 [27–31]. AIA systems typically range from extensive to intensive types of aquacultures, and they frequently rely on fertilization of some kind to produce phytoplankton and zooplankton as natural fish food [32] (Edwards et al., 2000). According to the type of structure utilized in operation, such as cage, pond, or tank farming systems, aquaculture can be further classified. This work focused on the ponds, where most semi-intensive aquaculture methods are used [26]. The production of aquaculture depends on feed ingredients. The value of fish feed ingredients is shown in Table 6 [33]. The production rate of fish relies upon the quantity of feed added while keeping up the water quality [34]. In addition, water use efficiency (WUE) can be increased by using fertilizer and formulated feed [11]. To maintain the optimum growth of fish and prevent disease and poisoning in aquaculture farms, contaminated water should be disposed of at a daily rate of 6–12% volume/day by adding new freshwater [35].

Table 5. Productivity of crops in pond-based AIA among different countries.

Farming System	Country	Productivity (kg/ha)		Fish Species	Stocking Density (Fish/m^2)	Average Feed (tonnes/ha/yr)	Reference
		Fish	Crop				
Pond-Based AIA	Tanzania	2460	1690	Tilapia-catfish	3.9 ± 2.4	7.6 ± 1.1	[27]
	Bangladesh	1983	1470	Prawn, Carp & Mola	19.760 ± 4.725, (2.470 ± 0.825 carp + 19.760 ± 5.194 Mola)	1.093 ± 0.268 for Prawn, 3.948 ± 0.953 for (Carp & Mola)	[28]
	Egypt	3050	5400	Tilapia	-	-	[29]
	Malawi	2017–2134	1645–1796	Tilapia	-	-	[30]
	Vietnam	474	1618	Common carp, silver barb, kissing gourami, tilapia, and catfish	-	-	[31]

This review focused on the integrated ponds that can be stocked with different fish species of carp, catfish, Baitfish, crawfish, milkfish, ornamentals, sports fish, sunfish, yellowfish, prawn, shrimp, and tilapia as they grow in different trophic niches in the water column. Then, the water is reused to irrigate the crops in three scenarios.

The first (1st) most applicable scenario is the entry of pond-dike (dam) crops in rural Bangladesh, Malawi [36], bamboo fish in China, and Egypt as El-Riad-Tourism-Lake [37], where the mud of the pond rich with nutrients is utilized to compost, Figure 2a.

Vegetables and fruit trees allow some fruits to grow on pond dams, for example, bananas, lemon, coconut, guava, palm, orange, bamboo, and papaya. Pond slopes are also utilized for growing vegetables (e.g., beans, squash, and cucumber) using bamboo structures to aid their spread over the pond water [38]. Notwithstanding, a few aquatic weeds are applied as fodder (grain) for fish and livestock, such as “Azolla, duckweed, water hyacinth, and water spinach” [26,39].

The second (2nd) scenario involves raising livestock such as cattle, ducks, goats, pigs, and poultry raised near or directly on the pond [12], Figure 2b. The third (3rd) scenario is tilapia farming—rotary wheat; when the temperature drops in November or December in Egypt, tilapia is harvested from ponds because it becomes unfavorable for the survival of tilapia. In order not to leave the culture ponds deserted until April, they are used in the cultivation of crops such as wheat [40].

Table 6. Nutritional value of some feed ingredients utilized in aquafeed [33].

Ingredient	Moisture	Crude			NFE	Ash	Ingredient	Moisture	Crude			NFE	Ash
		Protein	Lipid	Fiber					Protein	Lipid	Fiber		
Green roughages							Grains and legumes						
Alfalfa (first cut)	86.2	2.1	0.7	2.4	5.9	2.7	Wheat	11.1	8.3	1.8	3.8	73.3	1.8
Alfalfa (second cut)	85.5	1.9	0.4	3.8	6.4	2	White corn	10.3	9.1	4.8	7.2	67.1	1.4
Alfalfa (third cut)	73.4	3.7	0.6	7.5	11.5	3.3	Yellow corn	7.9	8.3	2.9	2.1	82.5	2.1
Corn plant	78.7	1.5	0.5	4.4	12.7	2.2	Sorghum	11	9.2	4.2	2.9	82.7	1.2
Sudan grass (first cut)	85.1	1.3	0.4	4.4	7.2	1.7	Barely	13.2	10.1	1.6	8.2	77.1	3
Sudan grass (second cut)	71.2	2.6	0.8	7	15.2	3.2	Kidney beans	9.8	28	1	5.7	50.7	5.5
Sweet corn (first cut)	92.5	0.6	0.2	2.1	3.8	0.8	Soybean meal	13.5	45.5	16.9	7.5	24.6	5.5
Sweet corn (second cut)	77	1.9	0.6	5.5	12.7	2.4	Cotton seed meal (with hulls)	7.5	27.1	8.5	21.4	27.2	6.9
Sugarcane leaves	71.1	1.3	0.2	7.7	15.5	4.1	Cotton seed meal (without hulls)	7.1	44.4	10.1	5.2	25.7	7.5
Dry forages							Sesame seeds (with hulls)	9	30.2	14.4	18	20.1	17.4
Alfalfa hay (first cut)	9.1	7	0.3	27.7	43.2	12.7	Lentil seed cake	18.5	13.3	10.7	7.1	35.2	7.5
Alfalfa hay (third cut)	10.5	10	1.9	27.4	40.5	9.7	Rice, broken, polished	9.2	11	7.8	1.1	75.9	4.2
Wheat straw	10.2	4.2	1.9	22.2	45.5	16	Rice bran	10.5	13	12.1	10.3	57.2	7.5
Barely straw	10.2	4.1	1.5	21.8	44.1	18.2	Wheat bran, coarse	12	11.1	3.6	17.8	63.8	4.3
Beans straw	13.9	4	0.6	19	51.3	11.3	Wheat bran fine	12	17.1	3	9.4	65.5	4.5
Corn cobs	11.3	2.4	0.3	31.4	51.8	2.9	Corn gluten	5.9	43.9	3.2	4.4	44	3.7
							Sugarcane bagasse	3.2	1.3	0.4	51.1	44.5	2.7
Animal by-products													
Blood meal	9.3	81.2	1	-	-	5.3	Animal gelatine	11.4	85.7	3.1	-	-	-
Broken eggs	4.2	34.7	15	-	-	25.5	Meat and bone meal	4.6	61.8	6	-	-	26
Fishmeal (local)	10.3	65.3	10.5	-	-	16.7	Poultry by-product meal	13	53.9	23	-	-	18.2
Fishmeal (imported)	9	70	6.1	-	-	11.6	Shrimp meal (local)	12.7	51.7	5.6	-	-	26.9

NFE = nitrogen-free extract

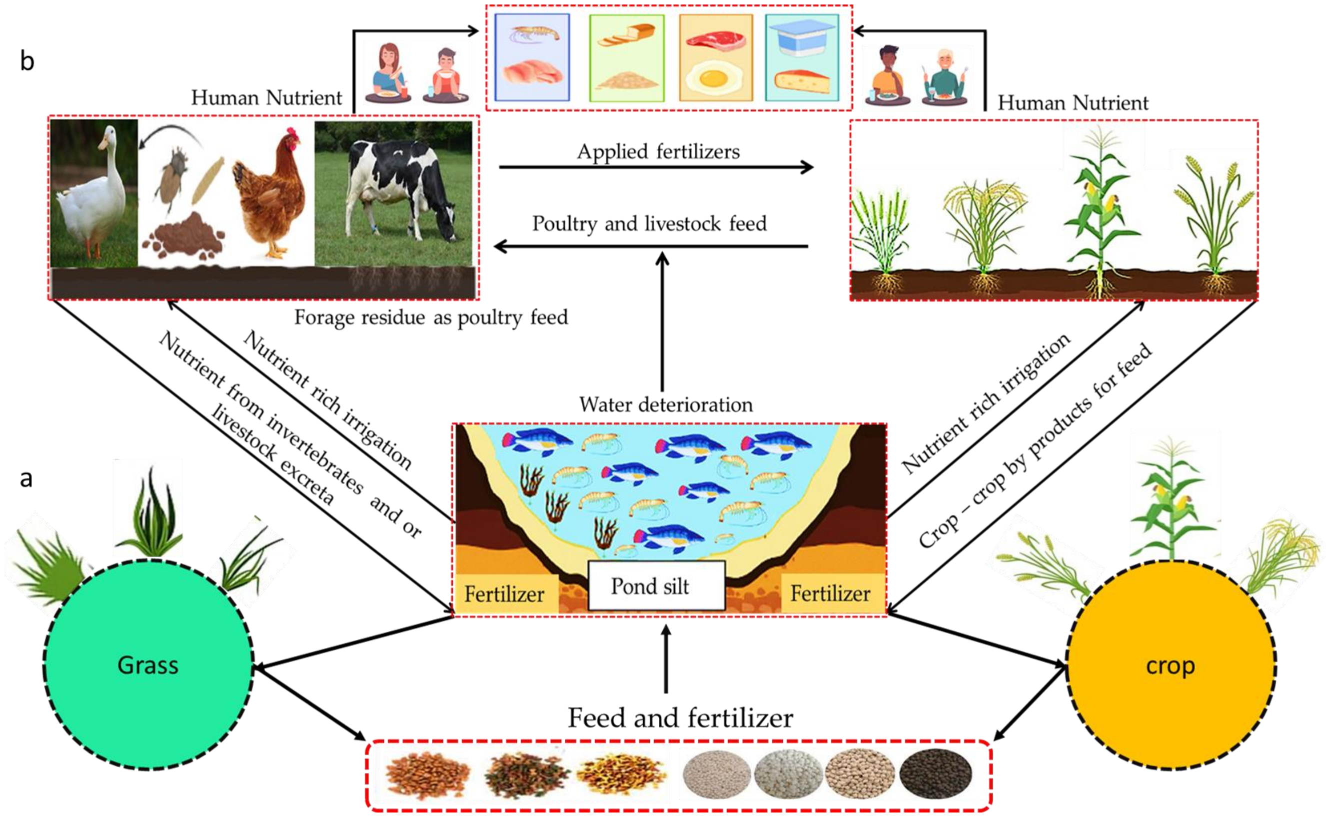

Figure 2. (**a**) Pond-dike cropping and (**b**) Fish–livestock–agriculture integration.

4.1. Impact of Pond-Based AIA on Soil, Fish, and Plant Characteristics

Fish pond wastewater is sometimes utilized as a potential irrigation resource to grow vegetables around places that are directly or indirectly used by humans [41]. The presence of organic feeding waste, nitrogen, and phosphorus in the lower part of the pond contrasted with the surface water could directly influence water quality, increment parasite infection, nutrient accessibility, fish growth, and production due to the exchange of substances among soil and water [42,43]. Total alkalinity and ammonia nitrogen (TN) are higher at the soil–water interface when contrasted with the surface water [44]. The accumulation of nutrients in the sediment increases directly with total nutrient input in a limited-scale freshwater pond [45]. Recycling water in an AIA is not only an approach to saving water, but it can also be a source of fertilizer (organic) to soils with lower fertility to give a higher efficiency of crops. The efficiency of nutrient water aquaculture (17–340 g of protein/m^3 water) is the most noteworthy among all significant food-producing sectors, including the production of animals and vegetables [46]. Fish wastewater irrigation was good for enhancing soil physical and chemical properties, the nutrient perquisites of the soil, growth parameters, and productivity of crops such as maize, okra, and cucumbers [47–49].

Overall, we recommend applying effluent from the fish pond on soil with low fertility, especially in arid regions, to increase the field capacity of the soil and facilitate its cultivation. Continuous monitoring for soil and plant qualities must be implemented.

4.2. Water Use Efficiency (WUE)

Table 7 [50–59] compares the WUE values for the major crops. The range of average WUE is reported to be 0.56–1.59 and 0.94–1.10 kg/m^3 for maize, and wheat, respectively. For aquaculture, WUE accounts for 0.21–0.37, 0.71–2, and 0.02 kg/m^3 in well-managed ponds, super-intensive recirculating, and extensive systems, respectively [57]. The WUE in pond-based AIA systems is 2.13 kg/m^3 for fish–maize production and up to 8.46 kg/m^3 for fish–vegetable production [4]. The upshot is that the WUE in pond-based AIA is more than in the non-AIA system. Therefore, using fish pond effluent to irrigate crops in integrated systems is preferable.

Table 7. Comparative WUE among crops under the different farming systems (FS).

Farming	Crop	Type of Study	WUE (Kg/m^3)	Reference
Agriculture (river water)	Maize	Field experiment	0.56	[50]
		Field experiment	1.01	[51]
		Field experiment	1.51	[52]
		Remote sensing monitoring	1.59	[53]
		Review	1.80	[54]
	Wheat	Review	1.09	
		Crop production and land use	0.94	[55]
		Experimental	1.1	[56]
			1.01	[52]
Aquaculture	Fish	Assessment	0.21	[57]
			0.37	
		Review	0.36	[58]
AIAS	Fish–maize	Field experiment	2.13 (fish 0.22 + crop 1.91)	[4]
	Fish–vegetable		8.46 (fish 0.22 + crop 8.24)	
	Fish–potato		5.52 (fish 0.22 + crop 5.3)	[59]
	Fish–Chinese cabbage		6.66 (fish 0.22 + crop 6.44)	[27]
	Fish–amaranth		4.98 (fish 0.22 + crop 4.76)	

4.3. Economics, Social, and Environmental Benefits of Pond-Based AIA

Reusing wastewater from fish farming for irrigation reduces fertilizer costs [59]. The gross revenue from tilapia production (on 1 ha of land) for two production cycles in a year is US$ 960 × 20 with net revenue of US$ 384 × 20, while the gross margin is about US$ 466 × 20 per year [60]. The rate of return on investment represented by percent profit is 66.7%, which is equivalent to a 1.67 production efficiency index that shows how beneficial tilapia cultivation is, despite tilapia farmers exceeding cost by 67% [60]. In Malawi [38], AIAS was 11% more fertile than non-AIAS, and the incomes of AIAS farmers increased by 134%/ha. The median annual income of farmers in AIAS and non-AIAS was $185 and $115, respectively. Therefore, fish farming directly contributed to an increase in productivity, profitability, and income for the AIA farm.

In Kilombero [7], AIA-based farming systems, including fish and vegetables (*B. Rapa Chinensis*), resulted in a three and 2.5-fold increase in net production compared to fish and vegetable farming alone in non-integrated systems, respectively. In selected areas of Bangladesh [61], it has been observed that a large number of agricultural enterprises (crop, poultry, fisheries, cattle, etc.) and a large area of land ponds increase the income of farmers [62]. Finally, pond-based AIA produced fish, crops, and protein and increased farm productivity and farm net income per hectare (ha) by 11% and 134%, respectively, compared to pond-fish culture or non-AIA [7,37,62].

Pond-based-AIA is considered an ecologically sustainable system as it provides water/nutrients recycling ability and increases both productivity and water usage efficiency [8]. Fish waste improves soil fertility by increasing the number of organic fertilizers and renewing nitrogen and phosphorous elements. The fertilizer is dredged from the bottom (lower part) of the ponds to be used as a successful fertilizer to enhance crop production [12]. Furthermore, vegetables and herbs were grown on the pond sediments to protect the embankments (dikes or levees) from erosion by rain.

5. International Experiences in Light of the Potential for Climate Change Adaptation, Food Security, and Mitigation

In 1943, based on industrial monoculture, the mixed farm slowly gave way to the cultivation of specialty crops. These days, the green revolution has shown its ecological limits [63] and has not been adapted to smallholders' rural farms. Hence, mixed systems are seen as an alternative to sustainable agriculture. AIAS is more developed in Asia than in any other region of the world and was traditionally practiced for many years in southeast Asia and Africa [8] and was explored especially in China in the late 1970s. Examples of AIAS are reported in Bangladesh [64], Malawi [30,37], Tanzania in Tarime [65], Cameroon [66,67], Vietnam [68], Kilombero [7], UAE [69], Mexico [70], and China [71,72]. Grass-fed fishponds are being used primarily in China and Thailand. At the same time, the cultivation of brackish water fish and shrimps in fenced-off mangrove forests is utilized mainly in Malaysia, Philippines, and Vietnam. In Bangladesh, significant successes have been accomplished in recent years [6,12,28,64]. In India, composite carp culture has been widely influential [73]. In Myanmar, pond fertilization is not widespread, but 80% of the country's aquaculture production involves the indirect use of off-farm rice bran and peanut cake with pelleted feed [74]. In Thailand, feedlot livestock/fish integration is common (ibid). In Vietnam, especially in the Red River Delta, traditional AIA is widely practiced, such as the VAC (Garden (V), pond (A) and livestock pen (C)) method, allowing farmers to recycle most agricultural and household wastes within the system, and utilizing available tools and supplies in the farm [75,76]. In Laos, rice–fish culture is now being promoted [77].

AIAS is increasingly developed for commercial, income-generating purposes in Asia and Western countries [78]. A very efficient agro-industrial scale of AIA farming in Israel, incorporating various aquaculture and irrigated horticulture operations, is now well established. In Australia, AIAS is utilized to optimize the economic and environmentally sustainable use of existing energy, resources, and infrastructure [78].

In Africa, research on small-scale AIA was widespread in the 1980s–1990s (4). A few notable instances of pond-based AIA frameworks involving fish (mainly tilapia and catfish) and livestock-integrated vegetables have been documented in Malawi, Ethiopia, South Africa, and Kenya [79]. Integrated aquaculture with existing farming systems can provide additional income to improve farmers' livelihoods, contribute to diversified farming activities and protect the environment by recycling resources. One of the reasons for the limitations of these systems is the high capital costs of intensive aquaculture [79]. Future research should focus on the sustainability of aquaculture without ignoring the environmental impacts.

Table 8 [4,27,76,80] displays a few pond-based AIA international experiences. It is clear from previous studies that multiple usages of water in pond-based AIA reported a significant increase in on-farm productivity, water efficiency, and an increased farmer's income irrigated their crops with fish effluents. AIAS was practiced under different irrigation systems such as traditional, drip, and sprinkler. No research has been published on introducing innovative, precision, and agriculture 4.0 in pond-based AIAS.

Table 8. International experience for pond-based AIAS.

Location	AIA	Irrigation Types	Main Findings	Reference
Beirut	Tilapia–maize, Tilapia–radish	Drip irrigation vs. well water and fish effluent under unfertilized and fertilized	Fish production improved the water value index and use efficiency. Fish effluent could replace inorganic fertilizers with a better crop production	[4]
Sweden	Tilapia–Chinese Tilapia–cabbage Tilapia–amaranth	Low, medium, and high fish stocking with no and partial fertilizers	The net return from AIAS was significantly ($p < 0.05$) higher than when practiced as stand-alone activities	[27]
Brazil	*Enterolobium contortisiliqum* seedlings (Nursery)	Saline aquaculture effluent—0.54 (0% effluent), 1.56 (25% effluent), 2.52 (50% effluent), 3.44 (75% effluent), and 4.25 (100%)	The dilution of saline water aquaculture (25%–50%) for *E. contortisiliquum* irrigation increased shoot growth and the total dry weight. These outcomes indicate that the effluent of saline aquaculture can be reutilized to irrigate tree species	[80]
Red River Delta, Vietnam	Survey on 167 families of aquaculture	Four existing AIAS “traditional VAC, animal fish (AF), new VAC, and commercial fish (FS) systems.” (Garden (V), pond (A), and livestock pen (C)	The most proficient and powerful models are the traditional VAC and new VAC systems	[76]

The emissions of greenhouse gas (GHG) from traditional pond-based AIA are negligible because these systems are semi-intensive and require limited feed, nutrient inputs, and electricity. Using manure of animals (livestock) and agriculture waste as feed for fish prevents their decomposition to methane and nitrous oxide emissions. The Intergovernmental Panel on Climate Change (IPCC) has found that AIAS can significantly contribute to the resilience of food systems and the reduction in greenhouse gas (GHG) emissions [81]. Providing more protein for household diets may also reduce the demand for other kinds of meat production, including less sustainable aquaculture. In the integrated garden–fish pond livestock, pond water can be used for irrigation, making farms more resilient to changes in rainfall. In cases of water scarcity, it will increase the use efficiency of the limited resources. In addition, it recycles excess waste, provides additional nutrients, especially nitrogen and phosphorus, for fish production, and reduces the pressure on natural aquatic resources.

AIAS greatly aids global nutrition and food security. According to Ahmad et al. [12], synergistic aquaculture integration has been promoted to increase food production, conserve the environment by reducing waste, and improve overall food production and security [82]. According to the global study of AIAS in 18 nations in 2010 [83], AIAS is necessary for feeding the growing urban population. AIAs products are valuable sources of protein and minerals for health and diet. Fish is the primary source of food for approximately 3.0 billion people worldwide, making up at least 15% of animal protein [84]. Aquaculture is one of the quickest developing sectors of food production universally, with a yearly growth rate of 5.3%/year in the period 2001–2018, granting a mean of 46% of worldwide fish production, as it increased from 25.7% in 2000. Therefore, it is expected to fill the gap of fish demands [85,86]. In Africa, aquaculture production is still low, contributing about 2.7% of the globe’s aquaculture production [87]. In the AIAS, farmers can produce multiple outputs from the same farm in a relatively friendly manner to the environment. Among the benefits of the AIAS are the farm’s water reuse and soil quality. The total yield under AIAS generally produces higher than that under monoculture systems, producing greater social, economic, and environmental benefits. In light of these assertions, AIAS is inventive in enhancing household incomes and global food security. If the pond-based AIA were to expand to 25% of the potential area, global fish production would increase by 3.08 million tonnes/year, and carbon storage would increase by 95.4 million tonnes/year.

6. National Case Studies

In Egypt, the three scenarios were applied as displayed in Table 9 [58,88–93] but in low cases. For example, the 1st was observed in El-Riad-Tourism–Lake [37]. The 2nd scenario has been applied since 2010 in the Egyptian desert using water with salinity ranging from 0.5 to 26 g/L by both government-backed companies. It also applied to the private sector based on the use of eight species of fish (Nile tilapia (accounts for 90% of the total species), red hybrid tilapia, North African catfish, common carp, carp (silver and grass), high salinity-tolerant species and ornamental species] [37,76]. The 3rd scenario is in the Governorate of Kafr El-Sheikh and Abbassa; the wheat is planted in the bottom of ponds in November and harvested in early May. This practice is considered highly efficient and productive for water use [88,89].

Table 9. National experience on fish-based–AIAS.

Location	AIA Type	Field-Water Salinity (g/L)	Main Findings	Reference
Abbassa, agriculture research center"	Rotation: wheat–Nile tilapia	Growing wheat in the ponds. Using only the water remaining in the pond bottom without any fertilization and extra irrigation water.	The best economic profit was obtained when tilapia was grown in ponds fertilized with poultry manure, followed by wheat cultivation.	[88]
Qorada research station WMRI, NWRC and Kafr El-Sheikh		Conventional agriculture vs. farming wheat in the harvested pond)—Salinity is 0.46–0.54 and 1.57–3.2 for surface water and fish effluent, respectively.	The salinity of fish ponds is suitable for the growing of wheat. Water productivity for fish ponds (11 L.E/m^3) is higher than that obtained from freshwater (2 L.E./m^3)	[89]
Agriculture research center and Faculty of agriculture/Kafr Elsheikh	Lettuce–Nile tilapia	Surface irrigation vs. drip irrigation–surface water salinity and effluent fish bond are 0.198 and 0.417, respectively.	Reusing drainage water (fishponds) enhanced lettuce yield under drip irrigation.	[90]
Wadi-ElNatrun station, WMRI, National Water Research Center	Sesame crop–tilapia	Drip vs. sub-drip irrigation—The salinity of well water is 0.76, while for the effluent fish bond is 0.417	Aquaculture drainage gave the best results in all aspects compared to the use of well water.	[91]
Nubaria/national research center station	Potato–tilapia	Sprinkler vs. drip irrigation system/Salinity was 0.26 and 1.15 surface and drainage water, respectively.	Sprinkler irrigation is the best system, with 60% fertilization.	[59]
Upper Egypt/Qena/Egypt	Squash–tomato–tilapia	Salinity is 1.503 for fish waste effluent	Aquaculture produced 50% better production for squash and tomato.	[92]
The American University in Cairo	Marjoram	Salinity is 0.48 for fish effluent	Growing marjoram with a mixed treatment would give the best herbage yields and the highest essential oils.	[93]

Table 9. *Cont.*

Location	AIA Type	Field-Water Salinity (g/L)	Main Findings	Reference
El-Riad—Tourism—Lake-commercial	Vegetables	Groundwater salinity 2–4 g/L	Tilapia, carp and mullets, vegetables and flower	[37]
Wadi Tal village Farm-commercial	Vegetables	Salinity 8–12 g/L	Tilapia and mullet spp. 50 t/year—tomatoes, goat (meat and manure), vegetables, crops	

Despite the medium prevalence of small and commercial AIA pod-based systems in Egypt, the general authority for fish resources development (GAFRD) statistics did not indicate these systems' productivity. However, they are the most productive systems to benefit from increased yield and optimal use of land and water units. Until now, no extension has been applied in pond-integrated agriculture in a rural area in Egypt. The grass or the residue of the plant was not utilized for fish integration in a small-scale pond in research stations.

7. AIAS in Coastal Areas

In recent decades, saltwater shrimp cultivation has increased significantly in Asia's inner and coastal areas, including river deltas, with well-known environmental effects on mangroves and other biotas [94,95]. Additionally, agriculture has significant repercussions, particularly in Thailand, Bangladesh, and Vietnam [95,96]. In the inland areas of Thailand, where rice is grown extensively with irrigation that traditionally relies on free water, interference between agriculture and aquaculture is notable [96–98]. During the dry season, saltwater naturally enters these areas, and during the wet season, it can be retained in ponds and mixed with fresh water to provide saltwater shrimp with ideal conditions for growth. In the 1990s, the seepage and release of water from ponds caused severe pollution of irrigation water and agricultural soils [95,99]. In 1998, the Thai government responded by prohibiting shrimp aquaculture in some areas [95]. However, enforcement has not always been consistent. Shrimp are favored by economic incentives to such an extent that hypersaline water and even bagged salt are trucked in to maintain shrimp growth conditions, despite the adverse effects on nearby agriculture [95,100].

In Bangladesh, shrimp aquaculture relies on trapped seawater carried inland by tides through constructed and natural channels. The ponds allow water to escape through percolation and overflow, accumulating sediment from upstream runoff. During the growth season, water is also frequently released, and then after each annual cycle of shrimp culture, the contents of ponds are pumped onto adjacent land [95]. Soils can become unsuitable for agriculture as a result of sedimentation and the release of saltwater from ponds in this manner [95].

In the UAE [69], the desalinated water is used to irrigate a wide variety of high-value crops such as radish, cauliflower, maize, lettuce, spinach, amaranthus, carrot, tomato, mustard, asparagus, eggplant, and quinoa. On the other hand, about 150 m^3/day of brine water is utilized for aquaculture, which is followed by irrigation salinity-tolerant forage grasses and halophytes. The outcomes obtained within four months demonstrated that the weight of fish increased by 200% and the length of fish increased by 60%. Two species of fish, *Sparidentex hasta* (sobaity seabream) and *Oreochromis spilurus* (tilapia), demonstrated remarkable adaptability to the local conditions.

In Brazil [80], diluted brackish aquaculture effluent is used to irrigate *Enterolobium contortisiliqum* seedlings. The outcomes revealed increased shoot growth and the total dry weight in *E. contortisiliqum*. These outcomes indicate that saline aquaculture effluent can be reutilized to irrigate tree species.

In Egypt, some projects were completed in a salty environment, such as El-Gouna Park (water salinity 15 g/L) [37] rula for land reclamation (RLR) [37]. In the RLR project, groundwater with a salinity of more than 26 g/L was utilized for European seabass

(*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*) cultivations. After that, water was used for *Sarcocornia* planting. RLR is not operational due to the high cost of electricity, which in the end represented more than 30% of the total production cost and made further use unprofitable.

Salinity is an emerging issue that results in significant yield losses in many parts of the world, particularly in arid and semiarid regions. Soil acidification, groundwater pollution, land subsidence, and other hydrological perturbations can shift away from agriculture [95,101]. However, it is challenging to mitigate soil salinization. Consequently, the long-term economic benefits of fish and shrimp culturing may not be realized. As a result, economic stimuli and localized environmental factors significantly influence the integration that makes up the precarious balance between aquaculture and agriculture [95,102]. Farmers frequently face a difficult choice: They can continue fish and shrimp cultivations, mitigate cropland salinization, or maintain agriculture.

Under various salinity conditions, some halophytes yield satisfactorily with economic value, Table 3. Therefore, the use of salt-tolerant crops or halophytes in arid and semiarid regions is recommended for their full potential to maximize crop yields. The use of halophytes is an environmentally friendly and cost-effective method for removing salts from the soil during site remediation.

8. Constraints and Challenges

Despite the several advantages mentioned in the current survey concerning the application of pond-based AIAS, some limitations constantly challenge the scientists. (1) In pond-based AIA, there is a lack of technical or specialized skills and good quality fish seeds and feeds. (2) Integrated systems and innovations that lead to more intensive fish and crop production in freshwater (more kg product/m^3 water) deserve support and further review [63,103]. (3) The expansion and development of pond-based AIAS to the desert were taking place, so attention should be given to minimal burden to the environment. (4) Modern intensive aquaculture systems deserve serious consideration due to their water utilization efficiency and the impact of fertilizing [29,104]. (5) The volume of water required by the crops and the irrigation times must be adapted to the volume and timing of effluent drainage from the fish culture basins and ponds [29,63,105]. (6) More fertilizers are required to increase water productivity and feed the fish. (7) The power purchase costs of AIA's commercial projects threaten their sustainability, such as the Rula for Land Reclamation (RLR) project in Egypt [37,106]. (8) Recently, there has been speculation that fish farming integrated with pigs–poultry may be the cause of influenza epidemics.

9. Future Aspects

Internationally, further research needs to be conducted to answer the following questions. (1) How can pond-based AIAS contribute to adaptation and the reduction in greenhouse gas emissions in light of intelligent technology? (2) How can pond-based AIAS be utilized to produce chemical-free and organic products? (3) How can pond-based AIAS be used with intercropping to increase land and WUE? Does the integration of fish with pigs and poultry cause influenza epidemics?

In addition to the internationally mentioned points, the national points need, firstly, to integrate expansion in intensive farming and AIA, especially in the desert, as it will be the best investment of arid lands and under-groundwater with avoidance of resource competition with agriculture and urban development. Secondly, research will be needed to develop a new strain of aquaculture species and hybrid plants (crops) that are tolerant to the higher level of salinity and the lower quality of water to adapt to changes driven by environmental change. Moreover, there is a demand to move toward integrated mariculture to mitigate the impact of environmental change on the freshwater. Since Egypt has extensive experience in raising freshwater ponds and tilapia rearing, while Vietnam, Malaysia, the Philippines, and Bangladesh has extensive experience in mariculture, it is possible to participate in providing simple and not expensive technological solutions. Thirdly, sprinkler systems (wash for 10 min at the start and before the end of irrigation), sub-drip, and drip irrigation systems with a suitable filtration system must be used to minimize clogging. Fourthly, alternate energy systems such as solar and hydrogen fuel can be used to power farms. Finally, there must be support for production requirements, the most important of which is fodder and the tendency to cultivate feed materials.

10. Conclusions

This survey confirmed that integrating aquaculture and agricultural-based soil activities is an effective way to use the same land resource for the successive production of animal carbohydrates and proteins, enhancing nutrient recycling and increasing resource use efficiency and thus the sustainability of agriculture. The practice of pond-based AIAS in three scenarios was recognized as an efficient use of water that increases crop yields per drop and thus reduces reducing risks associated with water scarcity at both global and local levels. The benefit of incorporating fish and plants is a significant increase in annual net production compared to growing independently. Applying effluent from the fish pond on soil with low fertility, especially in arid regions, increases the field capacity of the soil and facilitates its cultivation. Pond-based AIAS helps achieve SDGs 2, 6, and 14 as it accomplishes food security, climate acclimation, and poverty eradication, especially in rural regions, and protecting our water resources from harmful fertilizer.

This review recommends increasing pond-based AIA's extension rate locally or globally. International funders should promote the implementation of the pond-based AIA as a strategy for poverty alleviation, livelihood diversification, food security, and climate change adaptation and mitigation by providing project financing, policy support, and capacity building in research and development. International organizations' support will help apply pond-based AIAS at the level of governmental, private projects, and individuals.

Egypt is the first in Africa and among the world's top ten countries in aquaculture, which gives us an excellent opportunity to save large quantities of water. However, the water from fish farming is recycled in integrated agriculture. Integrated pond-based AIA in the coastal environment is not an innovation. It has been practiced and utilized effectively in Vietnam, Thailand, Malaysia, the Philippines, Bangladesh, etc., and it provides expertise for creating both cultures (crops and fish). The community should be made aware of the importance of pond-based AIA. Extension into the desert required a futuristic innovation to study how pond-based AIA could increase production, especially in areas where seawater permeates. So, knowledge must be transferred through projects or grants to improve and sustain practical research between Egypt and pioneer countries in that field.

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