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Review Article

Current Status of the Propagation of Basil in Aquaponic Systems: A Literature Review

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Basil (*Ocimum sp*.) is a commercially important herb that has been coupled with several aquatic organisms in aquaponic systems. The goal of this literature review was to aggregate the current knowledge on the status of basil production in aquaponic systems by identifying the different aquatic organisms cultured with basil and hydroponic subsystems cultured with basil species/varieties and address research gaps. Of the 100 reviewed publications, about 90% of the reviewed publications used sweet basil (*Ocimum basilicum* L.) and only three publications used a different basil species; holy basil (*Ocimum tenuiflorum*), lime basil (*Ocimum americanum*), or lemon basil, (*Ocimum africanum*). Of the publications that used sweet basil, Genovese was the most commonly used variety (21 articles), followed by Italian large leaf (6 articles) and purple ruffles (4 articles) varieties. Between the reviewed publications, 38.7% used deep water culture (DWC), 31.1% used media bed (MB), and 17.9% used nutrient film technique (NFT) to grow basil. Tilapia was the most commonly cultured species with basil in aquaponic systems (44%), followed by catfish (14%) and carp (9%). The amount of feed for tilapia *Oreochromis* sp. cultured as a function of grow space area ranged between 20.3 and 81.6 g feed/m^2/day. Values ranged between 29.2 and 68.9 g feed/m^2/day while culturing *Pangasius* sp., 20–25 g feed/m^2/day while culturing catfish (*Ictalurus* sp.), and 4.4–16.9 g feed/m^2/day while culturing carp (*Cyprinus* sp.). The variability in the fish feed-to-plant ratio suggests a need for establishing a recommendation for a species-specific optimal feed input that supplies sufficient nutrients for basil. The current review suggests further investigations comparing different basil varieties, cultivating different basil cultivars with different fish or crustacean species, using alternative hydroponic types, and evaluating feed inputs for establishing a recommendation for species-specific optimal conditions in aquaponic systems.

Keywords: aquaponics; aquatic organisms; basil cultivars; basil varieties; feed amount as a function of grow bed area

1. Introduction

One of the commercially important herbs is basil (*Ocimum sp*.) because of its good nutritional value and wide range of industrial applications. The *Ocimum* genus encompasses over 30 species and is categorized into five main basil types, which include sweet (*Ocimum basilicum*), thai (*O. basilicum* var. *thyrsiflorum*), purple (*O. basilicum* var. *purpurescens*), dwarf bush (*Ocimum minimum*), and lemon (*Ocimum citriodorum*). Their essential oils are recognized for their chemical diversity, quantity, and quality. Basil is known for its pathogen-killing or repellent properties, such as antimicrobial, insecticidal, fungistatic, and nematicidal effects. Because of these special characteristics, basil has several remarkable uses in the perfume, food, pharmaceutical, and traditional medicine industries. Basil leaves develop a distinctive scent through their oil glands [1]. Aside from being an important constituent in the kitchen, basil has several crucial properties, and consequently, is used worldwide in dry and fresh form in nearly all cultures. Research has shown that basil is suitable for soil and soilless cultivation [2].

Aquaponics is quickly emerging as an alternate food production technology on multiple scales to fulfill human nutrient requirements. Aquaponics circulates the nutrient-rich

wastewater from fish culture to the plant subsystem, producing a secondary crop. One of the most common herbs grown in aquaponic systems is basil [3, 4]. It has become an important component in aquaponic systems because of its high fresh market value, rapid growth, no need for pollinators for harvest, and a compact growth habit. Basil displays a higher yield under soilless systems in comparison to conventional farming approaches [5–7].

Basil has been coupled with several aquatic organisms in aquaponic systems. Basil is a fast-growing, high-value herb and has been successfully produced in aquaponic systems with some of the common aquatic organisms raised for human consumption, such as African catfish (*Clarias gariepinus*; [1]), barramundi (Asian sea bass, *Lates calcarifer*; [8]), carp (*Cyprinus carpio*; [6]), crayfish (*Procambarus spp.*; [9]), and Nile tilapia (*Oreochromis niloticus*; [10]). Basil has also been produced in aquaponic systems with ornamental fish such as goldfish (*Carassius auratus*; [11]), and koi (*C. carpio*; [12]). Additional opportunities exist for raising basil in aquaponics as it is tolerant of brackish water (2.5 g/L; [13]). Hence, basil is a good candidate in low-salinity systems with marine shrimp and other marine species [14]. However, there are few formal recommendations for growing basil in brackish aquaponics.

Fish or shrimp feed is the main driving source for the nutrient flow in an aquaponic system. Nutrients such as iron (Fe), calcium (Ca), potassium (K), etc., are required for optimal plant production; however, these nutrients are commonly deficient in an aquaponic system due to the minimal fish requirements for them [5, 15]. Hence, a reduction in crop yield from aquaponic systems has been reported and explained by the suboptimal availability of those nutrients [16]. Additionally, the nutrient availability for the plants is impacted by the pH in the system [15]. The fish and bacteria in the filter prefer an optimum pH of 7–9 [17]. On the contrary, a pH of 5.8–6.5 is optimal for nutrient uptake by the plants [15]. Furthermore, macronutrient absorption (i.e., N, P, Ca, K, S, and Mg) occurs in the plants across a wide range of pH (including $pH > 7$); nevertheless, micronutrient absorption (particularly Fe) frequently takes place between a pH of 5.5–6.0 [18]. Hence, it's recommended to supplement the deficient nutrients through fish diet supplementation [19, 20], into culture water (fertigation; [15]) or via foliar application [5] with the intention of preventing deficiencies and consequently optimizing the production of the plant in an aquaponic setup. Numerous research has been conducted to explore different ways to alleviate nutrient deficiencies of the plant in aquaponic systems, especially in leafy vegetables, herbs, and fruiting vegetables [5, 21–25].

Early research studying the culture of tilapia (*Oreochromis* spp.) and several varieties of lettuce (*Lactuca sativa*) and basil (*O. basilicum* "Genovese") was conducted at the University of the Virgin Islands, St. Croix, U.S. Virgin Islands (UVI; [26, 27]). Rakocy et al. [27] determined the optimal ratio for basil as 99.6 g feed/m^2/day in a four-stage staggered production; however, they explained that the amount of feed was higher because of increased water temperatures, but it resulted in improved feeding response of the fish. The goal of this article was to develop a literature review focused on basil culture in aquaponic systems and address research gaps.

Table 1: Varieties and cultivars of sweet basil (*O. basilicum* L.) reported in 88 of the reviewed publications and the number of times they were reported.

Variety	Cultivar	No.	Total
NR	NR	58	58
Genovese	Sanremo	1	21
	Aroma 2	1	
	NR*	19	
Eleonora	NR*	3	3
Italian large leaf	NR	2	6
	Nufar*	2	
	Tigullio	1	
	Grand Vert	1	
Purple ruffles	NR*	2	4
	Red Rubin*	1	
	Dark Opal	1	
Lettuce leaf basil	Tuscany	1	1
Asian basil	Thai basil "thyrsiflora"*	1	2
	Cinnamon*	1	
Minimum	NR	1	1
Fine leaf basil	Spicy Globe*	1	2
	Aristotle	1	
Total			98

Note: Four articles used/compared multiple varieties or cultivars (presented with an asterisk symbol) in their study.

2. Methodology

A comprehensive literature review of peer-reviewed publications was conducted that included all varieties or cultivars of basil, in conjunction with any aquatic organism. One hundred published research articles were identified and collected from Google Scholar, PubMed, and the USDA National Agricultural Library which includes AGRICOLA, PubAg, and the NAL Digital Collections (NALDC). Keywords used during this review included basil, basil variety, aquaponics system, and production. The focus of this review was global, and the inclusive years were 2000–2024.

Critical information collected from the publications included basil species and variety, hydroponic component, basil yield, species of aquatic organism, feeding, density, final biomass, culture duration, temperature, and flow rate. Moreover, the number of aquatic organisms and crops cultured in conjunction with basil cultivation in aquaponic systems was reported. Whenever sufficient data was available in the published articles, the initial and final density of aquatic organisms were calculated as kg/m^3. The amount of feed in grams per square meter of grow space per day was calculated by dividing the daily amount of feed (in grams) by the grow space area (in square meters).

3. Results and Discussion

3.1. Basil Subsystem. Table 1 shows a summary of sweet basil varieties and cultivars reported in 88 articles in addition to the

number of times they were reported. Interestingly, 58 out of 88 peer-reviewed publications did not report the variety name or cultivar type. Of the publications that used sweet basil, Genovese was the most commonly used variety (21 articles), followed by Italian large leaf (six articles) and purple ruffles (four articles) varieties. Three peer-reviewed articles reported the following species; holy basil (*Ocimum tenuiflorum*), lime basil (*Ocimum Americanum*), and lemon basil (*Ocimum africanum*). Nine publications reported only "basil" identifying neither the species name nor the variety/cultivar type. Among the reviewed publications, only four articles compared different basil varieties/cultivars. Ferrarezi and Bailey [10] assessed five diverse cultivars of basil in the UVI outdoor commercial aquaponics system in the summer and seven different cultivars in the fall. They concluded that basil yield was higher in summer (May–August) than in the fall (September–November). The authors stated that they visually observed the bolting occurrence in some cultivars throughout the harvesting period of 4 weeks. They explained that the more reoccurring trimming to avoid bolting possibly resulted in stress for the plant and consequently reduced their yield. Morphological characteristics including branching change when plant shoots are harvested multiple times in the cycle may cause variations in their productivity [28]. These authors noticed that basil productivity reduced in the last month of the summer, and they explained that this reduction could be because of the plant senescence due to multiple harvests. Hence, they recommended harvesting basil after 3 months in summer and restarting another cycle. They also reported that between all cultivars, Genovese and spicy globe produced the highest yields in the two seasons (summer and fall) within the geographical and environmental conditions of that study. Further research comparing the different basil varieties or cultivars of the same species and/or different species in aquaponic systems would be a valuable consideration.

Figure 1 illustrates the different hydroponic component types used to cultivate basil in aquaponic systems. From the 100 reviewed publications, 91 articles provided the type of hydroponic component used in their aquaponic system. Most of these papers (72 articles) used one hydroponic subsystem type to grow basil, and 19 articles compared two or more hydroponic components (20.8% of the total number of publications). Between the reviewed publications, 38.7% used deep water culture (DWC), 31.1% used media bed (MB), and 17.9% used nutrient film technique (NFT) to grow basil. Only 12.3% of the reviewed publications used different types of hydroponic systems such as dynamic root floating (DRF), aeroponics (AERO), A-frame ebb and flow, tray ebb and flow, perlite slabs, and floating in the fish system. Aslanidou et al. [29] reported that the most frequently used plant grow beds have been DWC, MB, and NFT, which is in agreement with the current review. Those authors pointed out that the substrate method used in the hydroponic unit of aquaponic systems is a matter that requires further investigation.

Multiple published papers that cultivated basil in aquaponic systems did a comparison between some of the above-mentioned hydroponic components; nevertheless, the results commonly differed from article to article. When comparing

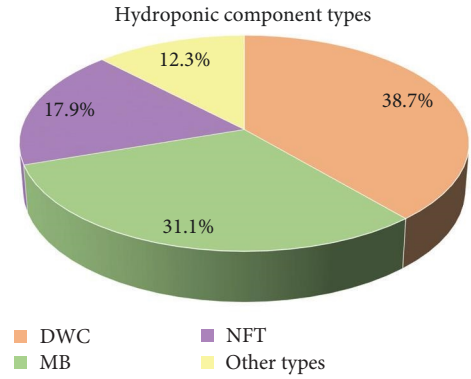


Figure 1: Percentage of papers for each hydroponic component type used to culture basil in aquaponic systems (total number of papers: 91 using one or more types of hydroponic components). Other types such as dynamic root floating (DRF), aeroponics (AERO), A-frame ebb and flow, tray ebb and flow, perlite slabs, and floating in the fish system. DWC, deep water culture; MB, media bed; NFT, nutrient film technique.

basil yield from the different hydroponic components of the different articles, differences in environmental conditions, and aquaponic and/or filtration systems, and different experiences in running an aquaponic system could explain the basil yield variability [30]. Knaus et al. [1] cultivated sweet basil in northern Germany and compared the yield from three diverse hydroponic components; an ebb-and-flood gravel substrate (MB), raft (DWC), and grow pipes (NFT). They found that after 41 culture days, there was no significant difference in the dry and wet weights between the subsystems. However, basil was significantly longer in the MB subsystem (101.8 ± 8.3 cm), next where the grow pipes (96.7 ± 7.0 cm), and lastly DWC (94.8 ± 8.6 cm). When compared with other plant crops, basil requires a higher amount of water for optimal growth in addition to a suitable drainage period [31]. The largest plant biomass occurred with a flooding interval of every 4 min using the ebb-and-flood gravel subsystem. These authors explained that the increased air contact during the dewatering phase could have provided additional nitrification through the beneficial bacteria activity (e.g., *Nitrosomonas* spp., *Nitrobacter* spp.) in the media. The substrate could have performed as a biofilter with supplemental nitrification and directly produced nitrate at the interface of the water-plant root [15]. Additional studies evaluating basil productivity in different types of hydroponic components and comparing different varieties/cultivars of basil are critical requirements.

3.2. Fish Subsystem. Figure 2 shows that tilapia was the most commonly cultured species with basil in aquaponic systems (44%), followed by catfish (14%) and carp (9%). Liang and Chien [32] stated that the foremost fish species produced in an aquaponics system was Nile tilapia. DWC and MB plant grow beds were the most common hydroponic subsystem used for cultivating basil with tilapia and carp, whereas NFT and DWC were the most commonly used with catfish.

Criteria used for the selection of aquatic organisms cultured in aquaponic systems include the availability of juveniles, the

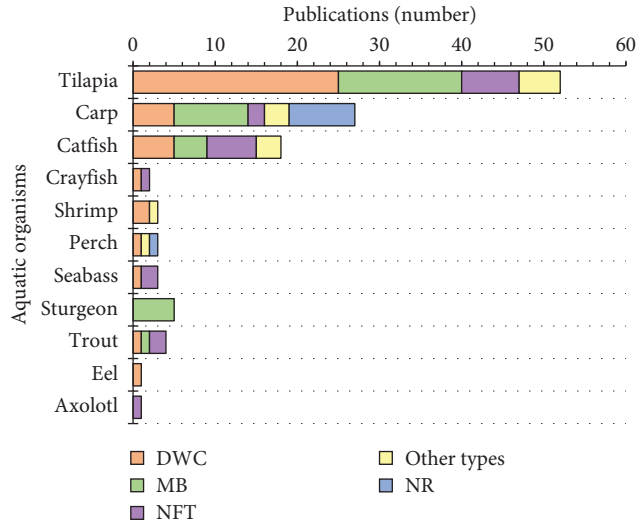


Figure 2: The aquatic organisms cultured with basil via different hydroponic components (total peer-reviewed publications number: 93) regardless of the category (human consumption, ornamental, or conservational purposes). Some articles used multiple fish and/or hydroponic component types. DWC, deep water culture; MB, media bed; NFT, nutrient film technique.

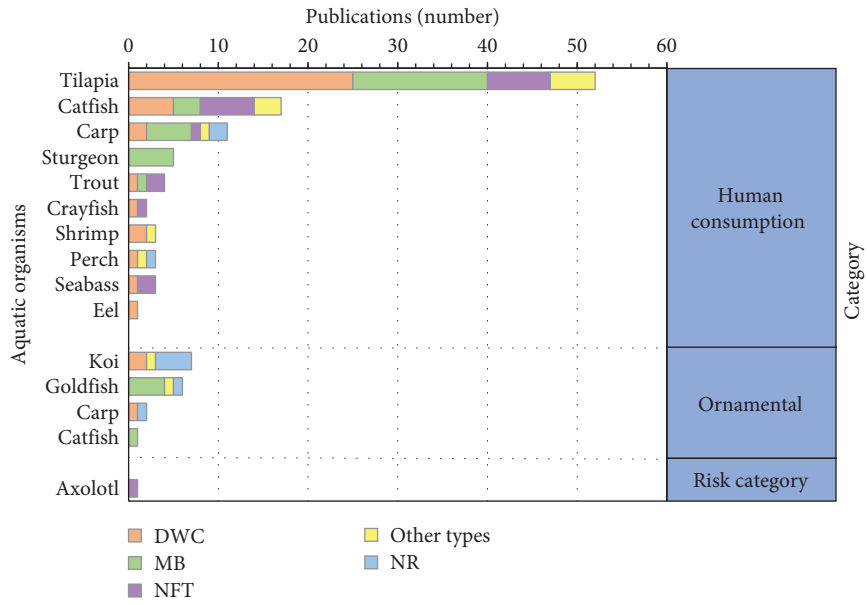


Figure 3: Aquatic organisms cultured with basil via different hydroponic components (total peer-reviewed publications number: 93) are divided into three categories (human consumption, ornamental, or conservational purposes). Some articles used multiple fish and/or hydroponic component types. DWC, deep water culture; MB, media bed; NFT, nutrient film technique.

value of the species of interest, ease of culture, and tolerance of suboptimal water quality factors [33]. The number of aquatic organisms cultured with basil was divided into three categories: human consumption, ornamental, or conservation (total peer-reviewed publications number 93, Figure 3). Of those 93 papers, 86% of the cultured organisms were for human consumption, 13% were ornamental organisms, and 1% were for conservation purposes. Although the price of ornamental species is relatively high compared to fish for human consumption and has increased significantly throughout the last decade, Maucieri et al. [34] stated that research using ornamental species in aquaponic systems is lacking. In 2021, the market of ornamental fish was valued at $5.4 billion; however, a sudden reduction in exports of ornamental fish by 13.1%, from $390 to $339 million, occurred between 2021 and 2022. Currently, the ornamental fish trade represents about 0.0014% of total world trade, and their market is expected to increase at a compound annual growth rate (CAGR) of 8.5% between 2022 and 2030 [35]. The production of ornamental species in aquaponic systems has enormous potential for higher income and productivity with minimum requirements of water, land, labor, and additional inputs.

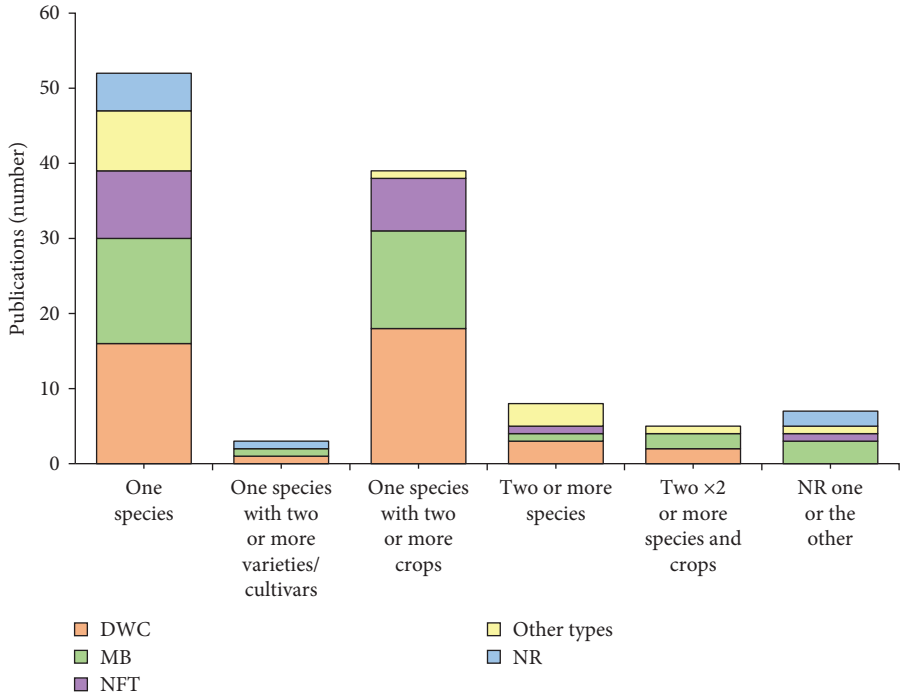


Figure 4: Number of papers that report results on one or more aquatic organism species with basil and/or with one or more other crops and the hydroponic subsystem used (total number of publications: 93). DWC, deep water culture; MB, media bed; NFT, nutrient film technique.

In contrast to food-grade fishes, a limited number of ornamental species have been used in aquaponic systems, which mostly include koi, *Cyprinus rubrofuscus* [33], koi, *C. carpio* [36, 37], and goldfish, *C. auratus* [11, 36, 38]. Among these species, goldfish and koi (*C. rubrofuscus* var. "koi") from the family Cyprinidae are the most popular and draw aquaculturists, hobbyists, and researchers' attention all over the world [33], which agrees with the current review findings. This could be explained by their resilient nature, which makes them an excellent laboratory species besides being an aquarium species. It has been reported that goldfish and koi are resistant to different water quality levels, along with their fast growth ability and high reproduction ability, have made them the perfect ornamental candidates for the culture with plants in aquaponic systems [33, 39]. Further research on the optimal productivity of ornamental species in aquaponic systems with basil and other crops is needed. In addition, intensification of ornamental fish production is required to meet the rising demand from hobbyists and ornamental fish markets.

3.3. Multiple Crop Evaluations. Of the reviewed publications, 93 articles provided the basil species, variety, and/or cultivars grown in aquaponic systems (Figure 4). Among those publications, 55.9% cultured one aquatic organism in conjunction with basil, followed by 41.9% that cultured one aquatic species while growing additional crops with basil. The percent of articles that evaluated more than one species in combination with basil was 8.6%, and 5.4% cultured more than one species while producing basil with one or more crops. The choice of fish species and cultivated plants could impact the stability of an aquaponic system, especially coupled systems. Nevertheless, research on different fish or crustacean species' influence on plants is scarce [40].

Palm, Bissa, and Knaus [41] cultured two fish species (*O. niloticus* and *C. gariepinus*) with basil and other crops including lettuce, cucumber (*Cucumis sativus*), and tomato (*Solanum lycopersicum*) in four plant boxes (2 m^2 each) and reported higher growth of plants in conjunction with tilapia. After a 92-day cycle, basil yielded 159.00 ± 96.91 g when cultured with Nile tilapia, as opposed to 117.94 g ± 92.30 g when cultured with African catfish. It appears the choice of fish or crustacean species has an effect on plant yield as well as aquaponic system stability.

Different basil cultivars can be grown for diverse markets, such as a culinary herb for dry or fresh spices, pharmaceutical companies for the extraction of their essential oils, or ornamental plants [10, 28]. In the current review, only 3.2% of the publications compared more than one basil variety or cultivars of the same species. A comparison between different basil cultivars in aquaponic systems with different fish or crustacean species would be a valuable consideration.

3.4. Feed Amount as a Function of Grow Bed Area. Figure 5 depicts the feed amount (in grams) per square meter of plant grow bed area per day in the aquaponic system (total number of papers 29). A few articles used multiple fish and/or hydroponic component types. Two out-of-range values were not included in Figure 5 (336 and 366 g/m^2 grow space/day; [42, 43]). For tilapia, the amount of feed per square meter of grow space per day ranged between 20.3 and 81.6 g. Amount of feed per square meter grow space per day values ranged between 29.2–68.9 g feed/m^2/day when culturing *Pangasius*,

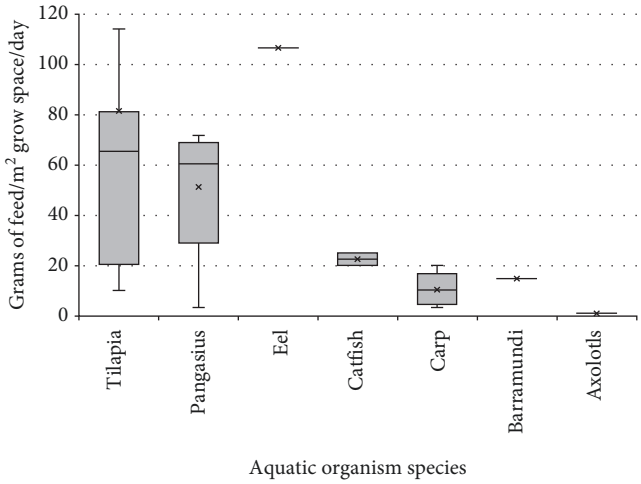


Figure 5: Box plot showing the number of papers for aquatic organism cultured vs. quantity of feed (in grams) per square meter of grow bed area per day in the aquaponic system (total number of papers: 29). Error bars is represented by the standard deviation (SD); line inside the box plot represents the median; X represents the mean.

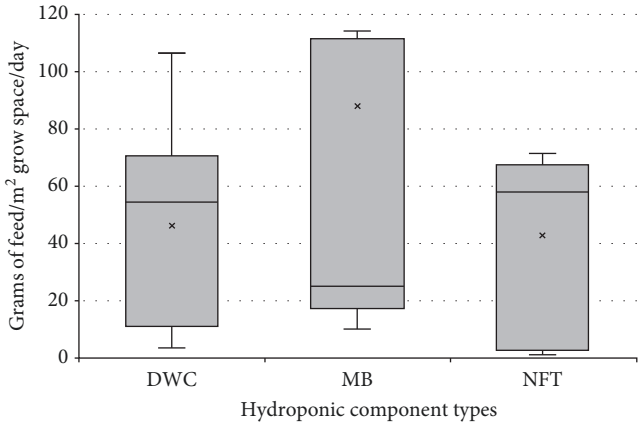


Figure 6: Box plot showing the number of papers for each hydroponic component vs. quantity of feed (in grams) per square meter of grow bed area per day in the aquaponic system (total number of papers: 29; DWC, deep water culture; MB, media bed; NFT, nutrient film technique). Error bars are represented by the standard deviation (SD); the line inside the box plot represents the median; X represents the mean.

20–25 g feed/m^2/day when culturing catfish, and 4.4–16.9 g feed/m^2/day when culturing carp in an aquaponic system with basil. A minor number of publications were found studying eel, barramundi, and axolotls in aquaponic systems. The number of papers using different types of hydroponic components with the quantity of feed per square meter of grow bed area per day regardless of the aquatic species in the aquaponics system is presented in Figure 6. Values ranged between 11.8 and 71.5 g feed/m^2 for DWC, 18.3–112.6 g feed/m^2 of grow area per day when using MB, and 2.6–67.5 g feed/m^2 of grow area per day when using NFT. In a recent review of tilapia and lettuce in aquaponic systems, the amount of feed offered to tilapia varied with the type of hydroponic component [44]. Research has shown that the hydroponic system type can influence plant growth and nutrient uptake efficiency. A review by Somerville et al. [45] on aquaponics discusses how different system designs impact plant nutrient availability and overall system performance. However, it remains unclear if the difference in feed input values in the published papers signifies the plant subsystem requirements or is dependent upon the fish density and feed consumption.

Alarcón-Silvas et al. [46] argued that the feeding rate ratio (FRR; g feed/m^2/day) data for diverse aquaponic systems are usually not comparable due to variations in the experimental conditions, including size and growth phase of aquatic organism, their densities, nutritional requirements and dietary nutrient concentrations, and crop species. Delaide et al. [47] proposed a FRR of 42 g feed/m^2/day for a tilapia-lettuce aquaponic system, which is lower than the amount recommended by UVI (57 g feed/m^2/day; [26]). Mariscal-Lagarda et al. [48] used a FRR of 24 g feed/m^2/day for a shrimp–tomato aquaponic system. This variation suggests the need for establishing a recommendation for a species-specific optimal feed input that supplies sufficient nutrients for specific crops, which can serve as a basis for future research. Furthermore, future studies on feed input, nutrient budgets, and system modeling under controlled conditions are necessary to distinguish between plant subsystem requirements, fish needs, and density effects.

3.5. Abiotic/Environmental Factors. Temperature is one of the major factors that affect the growth and development of plants and aquatic organisms in a controlled environment [45, 49]. The majority of vegetables have a wide range of suitable temperatures from 18 to 30°C. However, it has been recommended that the optimal water temperature for basil growth is 20.0–25.0°C [9, 10, 28], and the maximum recommended temperature is 30.0°C [45]. Data in Table 2 indicates basil evaluations have been conducted within a large range of water temperatures (17.4–31.6°C). Some of the recorded variation may be attributed to meeting the thermal optima of the aquatic organisms. Nevertheless, about 90% of the reviewed publications reported experimental temperatures between 23.6 and 26.6°C, which indicates that the majority of publications were conducted within the recommended range for cultivating basil.

Somerville et al. [45] stated that warm-water species such as tilapia, catfish, and common carp, as well as the nitrifying bacterial community in the system, grow well in elevated water temperatures of 22−29°C, along with many of the common vegetables like basil. Hendrickson et al. [72] compared the growth of 17 cultivars of basil (Italian large leaf, Spicy bush, Amethyst, Sweet Thai, Red rubin, Prospera, Cardinal, Nufar, Cinnamon, Karpoor tulsi, Elide lemon, Dark opal, Rutgers devotion, Lime, and Genovese) from six main types at three different temperatures 23, 27.5, and 31°C to determine the optimal temperature for growing different basil types hydroponically. They concluded that the yield of all basil cultivars except Italian large leaf and purple basil grown in hydroponic systems was higher when cultivated at a water temperature of 27.5°C. The highest yield for Italian large leaf and purple basil

Table 2: Sweet basil (*O. basilicum* L.) grown with different aquatic organisms in coupled aquaponic systems reported in 29 peer-reviewed articles of the reviewed global publications.

Hydroponic component	Basil species, variety, or cultivar	Basil density	Yield	Basil culture duration	Aquatic organism	Aquatic organism initial density (kg/m^3)	Aquatic organism final density (kg/m^3)	*g* feed/m^2 grow space/day	Temp. (°C)	Flow rate (L/min; C, I)	Aquatic organism culture duration	Reference
DWC	*O. basilicum* 'Tuscany'	NR	0.63–0.67 kg/m^2 (36.02 and 38.76 g/plant)	NR	Nile tilapia	3.05	NR	10.16	25.88 ± 2.18	NR	NR	[50]
	O. basilicum	16 plants/m^2	1.12–2.2 kg/m^2	64 days	Shrimp (*Litopenaeus vannamei*)	0.05	0.62, 0.56	14 and 13	31.6 ± 2.1	2	7 weeks	[46]
	O. basilicum	48, 144 basil/unit	8.08, 14.08 kg/m^2	13 weeks	African catfish, *C. gariepinus*	11.0–11.7	14.95–19.35	20	22.6, 28.6	15.19	85 days	[51]
	O. basilicum	44 plants/m^2	NR	NR	Carp (NR)	13.07	NR	3.56	NR	8	NR	[52]
	O. basilicum var. Grand Vert	30.73, 31.26 plants/m^2	1.3 kg/m^2/harvest	35 days	Nile tilapia (*O. niloticus*)	19.45	55.98	42	25.6 ± 2.5	85.5	164 days (No harvest)	[47]
	O. basilicum 'Italian Large Leaf'	NR	NR	Harvest every 28 days	Barramundi (*L. calcarifer*)	12.5	NR	14.84	23.2 ± 5.2	20.8	118 days	[8]
	Five cultivars in summer and seven in the fall	16.15 plants/m^2	Summer: (Genovese: 14.91, Spicy Globe: 13.99, Purple Ruffles: 4.18 kg/m^2); fall: (Genovese: 6.70, Cinnamon: 6.60, Spicy Globe: 6.35, Purple Ruffles: 1.68 kg/m^2)	every 4 weeks in summer and 3 weeks in fall	Nile tilapia	77 fish/m^3	NR[a]	Summer: 66, fall; 74	26.63 ± 0.85	378.5	Summer 112 days; fall 87 days	[10]
	O. basilicum, Tigullio	40, 30 plant/m^2	5.5, 4.1 kg/m^2 (136.7 g/plant)	5 harvests (1 month each)	European eel (*Anguilla anguilla*)	6.4	3.98	106.67	21.8 ± 2.82	25	126 days	[53]
	O. basilicum	2 plant/m^2	1.3 kg/m^2	3 months	Red hybrid tilapia *Oreochromis sp.*	5.64–7.32	~53.3	80	24.6 ± 2.8 to 32.1 ± 2.3	NR	6 months	[54]
	O. basilicum 'Genovese'	8 plants/m^2	Batch: 25.0 kg/m^2, staggered: 23.4 kg/m^2	2 trials (~3–4 months each)	Nile, Red tilapia	5.39, 10.78	2.89 ton	Batch 81.4, staggered 99.6	24–29	378	24 weeks	[27]
	basil (NR)	6 plant/m^2	1.4, 4.9, and 5.9 kg/m^2	42 days	Common carp (*C. carpio*), grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*)	0.26, 0.6, 0.43	1.79, 3.66, and 1.4	4.41, 10.18, 7.29	25.7 ± 0.82	NR	6 months	[5]
	Genovese basil	NR	13–42 kg/m^2/year	8 weeks	Tilapia	48	336	13.66 end 27.32	24.8	400	24 weeks	[55]
	O. basilicum	NR	NR	84 days	Nile tilapia (*O. niloticus*)	4.71 ± 0.02	NR	20.28–40.2	NR	6.1	84 days	[56]
	O. basilicum var. Genovese	26.4 plants/m^2	1.79–4.97 kg/m^2	14-day	Nile tilapia	13.28	18.06	60	26.4 ± 1.3	NR	14 days	[57]
	O. basilicum cv. Genovese	NR	74.1–84.2 g/plant	1-month	Nile tilapia (*O. niloticus*)	19, 25	NR	64.29	26.5–26.9	NR	1 month	[58]
	O. basilicum 'Genovese'	NR	306.3 g/plant	3 months	Nile tilapia	20	NR	69	26–28	NR	3 months	[59]
	O. basilicum 'Genovese'	NR	15.2 g/plant	3 months	Nile tilapia	20	26.84	69	26–28	NR	3 months	[60]

Table 2: Continued.

Hydroponic component	Basil species, variety, or cultivar	Basil density	Yield	Basil culture duration	Aquatic organism	Aquatic organism initial density (kg/m^3)	Aquatic organism final density (kg/m^3)	*g* feed/m^2 grow space/day	Temp. (°C)	Flow rate (L/min; C, I)	Aquatic organism culture duration	Reference
MB	*O. basilicum*	NR	~3.5 kg/m^2	12-month	*O. mossambicus*	2.93	55.79	114.29	17.40–26.80	NR [I]	52 weeks	[61]
	O. basilicum	11.11 plant/m^2	0.53 ± 0.049 kg total/m^2	30 days	Tilapia (*O. niloticus* L. var. Stirling)	7.34	9	366.93	21.1–26.1	NR [C]	30 days	[42]
	Basil (*O. basilicum* L.),	11.11 plant/m^2	1.45 ± 0.33 kg total plant/m^2	50 days	Tilapia (*Oreochromis niloticus* L. var. Stirling)	6.73	8.26	336.5	20.4–25.6	NR [C]	50 days	[43]
	Basil (*O. basilicum*, Genovese F1)	NR	Flood 2.35 kg/m^2; constant 1.55 kg/m^2	6 weeks	Common carp (*C. carpio*)	8.43	11.92–13.03	16.94	23.41–24.20	27.5 [I, C]	6 weeks	[62]
	O. basilicum, Genovese F1)	3 plant/m^2	4.256–5.367 kg/m^2	58 days	Common carp (*C. carpio*)	8.43	12.58, 13.25	31	23.66–24.20	NR [I]	58 days	[63]
	O. basilicum	6 plant/m^2	With carp 0.13 with tilapia 0.09 kg/m^2 (22.1 ± 17.5, 16.1 ± 13.8 g)	70 days	Common carp (*Cyprinus carpio*) in Unit I and Nile tilapia (*O. niloticus*) in Unit II	carp 5.57; tilapia 5.74	carp 10; tilapia 10.81	carp 20.06, tilapia 19.63	carp 25.9 ± 2.3, tilapia 26.3 ± 2.1	2 [I]	70 days	[64]
	O. basilicum	1.5 basil/m^2	NR: They reported "Further investigations must verify the different plant growth parameters."	49 days (SE I), 56 days (SE II) and 55 days (SE III)	Nile tilapia fry (*O. niloticus*)	0.08	SE I: 6.27, SE II: 5.29	SE I: 21.87, SE II: 58.13, SE III: 25	24.94–25.42	NR [I]	49 days (SE I), 56 days (SE II) and 55 days (SE III)	[65]
	O. basilicum	NR	With catfish 0.015, with tilapia; 0.019 kg/m^2 (6.55, 8.83 g/plant)	53 days	African catfish (*C. gariepinus*) and Nile tilapia (*O. niloticus*)	Catfish 6.72, tilapia 5.62	Catfish 12.23; tilapia 10.94	25	23.46 ± 1.31 23.84 ± 1.39	0.05 [I]	83 days	[41]
NFT	*O. basilicum*	24 plants/m^2	0.73, 0.89, 1.02 kg/m^2	90 days (harvest every 30 days)	Pangasius (*Pangasianodon hypophthalmus*)	T1 (2.5), T2 (2.75), T3 (3.0), and T4 (3.25)	8.95 ± 0.16, 9.19 ± 0.07, 9.88 ± 0.02 10.29 ± 0.04, 10.06 ± 0.10	55.1, 60.6, 66.1, 71.65	24.05 to 26.860	7	90 days	[66]
	O. basilicum	24 plants/m^2	1.39–1.93 kg/m^2	Harvest every 30 days	Pangasius (*Pangasianodon hypophthalmus*)	3	7.99–8.55	3.18	26.83–26.98	7	120 days	[67]
	O. basilicum	65.62 plants/m^2	Nursery 0.61, Juvenile 0.59 kg/m^2	70 days	Axolotls (*Ambystoma mexicanum*)	Nursery 0.11, Juvenile 0.15	4.89, 4.9	0.98	22 ± 2	16.67	70 days	[68]

Abbreviations: Hydroponic component: DWC, deep water culture; I, intermittent flow rate; MB, media bed; NFT, nutrient film technique. Flow rate: C, continuous flow rate.
[a]Already published in Rakocy et al. [15, 27, 69–71].

was found to be variable between temperatures of 23 and 31°C. Hence, basil is considered a heat-tolerant crop [28]; however, it is considered sensitive to temperatures below 10°C, which has been shown to damage the developmental and growth processes [73]. Basil has been cultured with both warm-water species (tilapia, catfish, carp, seabass, and shrimp) and cool—and cold-water species (trout, sturgeon, and perch). Considering this wide range of cultured aquatic organisms with basil, the optimum temperature determination for species-specific culture with different varieties of basil is a critical necessity to enhance the production of both species.

In coupled aquaponic systems, water flow rate is one of the factors that affect the physiological requirements for optimal fish and crop production, energy consumption, and nutrient loading. The water flow rate in the aquaponic systems ranged between 0.05 and 400 L/min in the reviewed literature. However, about 90% of the reviewed publications reported a flow rate between 6.3 and 71 L/min (Table 2). Most of the articles that used MB applied intermittent flow using the flood and drain techniques except two articles that used a pump inside the grow bed. Water flow rate directly influences the hydraulic loading rates (HLRs) for optimum production of different fish and plant species in an aquaponic system [74, 75]. Endut et al. [74] stated that the HLR (m/day) of an aquaponic system can be calculated by "dividing the flow rate of water, Q (m^3/day) through the system by the surface area of the grow bed, A (m^2). Angkha et al. [76] compared four HLR (0.72, 1.44, 2.16, and 2.88 m/day) in an aquaponic system and reported the effects on the performance of tilapia and basil. They found that tilapia and basil production were the highest at an HLR of 1.44 m/d compared with the other treatments. They also found that the highest nitrate ($42.25 \pm 1.56\%$), potassium ($40.44 \pm 1.270\%$), and phosphate ($64.80 \pm 2.011\%$) removal percentages were observed at HLR of 1.44 m/d. Based on those findings, these authors recommended an HLR of 1.44 m/d for the culture of Nile tilapia and holy basil in aquaponic systems. It has been reported that the optimal flow rate in aquaponics depends on the specific requirements of the fish, plants, and the system design. It balances the delivery of oxygen, nutrient supply, and removal of waste [3, 15, 45]. Further investigations are required to identify the optimal water flow rate and HLR for the cultivation of basil with different aquatic organisms in aquaponic systems. Additionally, studies on how the flow rate influences nutrient uptake and fish health under varying environmental conditions (e.g., temperature, pH) are a crucial requirement.

3.6. Basil's Economic Value. In an international survey by Love et al. [77], 70%, 69%, and 64% of the survey respondents cultivated basil, tomatoes, and salad greens, respectively, in their aquaponic systems. In contrast, the most frequently grown crops in aquaponics systems recently recorded by industry-wide survey respondents were lettuce (83%), and leafy greens (81%), followed by basil (73%; [78]). Engle and Beem [79] compared the production and selling prices of basil and lettuce from UVI publications and other literature and reported that the production price was \$6.15–\$12.40/case of lettuce (24 heads of lettuce weighing 20–26 pounds) and \$0.75/lb for basil cultivated in an aquaponic system. The market price is \$20/case of lettuce (~\$0.9/lb) and \$10.20/lb of basil, suggesting that basil is a more profitable crop. Lobillo-Eguíbar et al. [80] stated that basil and lettuce represented more than 10% of the total market value of both vegetable/fish aquaponic production (the former because of its high price and the latter because of its high production). However, aquaponic producers still grow lettuce and other leafy greens more frequently than basil despite its higher profitability due to market demand and consumer preference, growth cycle considerations, and economic factors. In terms of market demand and consumer preference, lettuce is versatile and has a more established global market due to its popularity in salads and ready-to-eat meals such as sandwiches and wraps [81], while basil is more niche, primarily used as a culinary herb or for specific recipes [82]. Additionally, lettuce has a relatively shorter growth cycle, typically reaching market size in 30–45 days in aquaponic systems [83], compared to basil, which takes longer to mature (typically 50–70 days), which means fewer harvests per year [6]. Lastly, while basil can be more profitable due to its higher market value, the overall economic risk is higher. Lettuce, being less expensive per unit but much more reliable in terms of production volume, hence providing a steadier cash flow for producers. Given the shorter growth cycle and fewer risks associated with growing lettuce, it often represents a more stable financial investment.

4. Conclusions

This literature review has identified the major aquatic organisms cultured with basil in the literature as well as some of the major research gaps (Table 3) in the production of basil in aquaponic systems. It seems clear that the choice of fish species, cultivated plants, and hydroponic components can impact the stability of an aquaponic system, especially coupled systems. The current review suggests streamlined research evaluating fish feed-to-plant ratios for establishing a recommendation for a species-specific optimal feed input that supplies sufficient nutrients for specific crops, which can serve as a basis for future research. More studies are needed, especially on the intensification of ornamental or food fish and plant production per unit volume and area, cultivation that optimizes the medicinal qualities of basil, and determination of optimal environmental factors in the system. The current review suggests further investigations using alternative hydroponic approaches, comparing different basil varieties, and cultivating different basil cultivars with different fish or crustacean species in aquaponic systems. It also recommends that the temperature of both fish and plants, flow rate, and hydraulic retention rate while cultivating basil in aquaponic systems require further investigations, as they can eventually affect the productivity of the system. Commercial aquaponic producers have incorporated basil into their operations largely due to market characteristics; it is more valuable in many markets. This information summarizes approaches and emerging technology trends and provides recommendations to guide current and future producers interested in producing basil in aquaponic systems. Further research is needed to understand the broader economic impact of different crop selections on aquaponic system profitability.

Table 3: Some of the gaps identified in the publications and recommendations for future research when using basil in conjunction with different aquatic organisms.

No.	Some of the gaps identified in the publications and recommendations for future research while cultivating basil in conjunction with different aquatic organisms
1	Further research comparing the different basil varieties or cultivars of the same species and/or different species in aquaponic systems would be a valuable consideration.
2	The substrate method used in the hydroponic unit of aquaponic systems is a matter that requires further investigation.
3	Further research on the optimal productivity of ornamental species in aquaponic systems with basil and other crops is needed. In addition, intensification of ornamental fish production is required to meet the rising demand from hobbyists and ornamental fish markets.
4	A comparison between different basil cultivars in aquaponic systems with different fish or crustacean species would be a valuable consideration.
5	This variation suggests the need for establishing a recommendation for a species-specific optimal feed input that supplies sufficient nutrients for specific crops, which can serve as a basis for future research.
6	Future studies on feed input, nutrient budgets, and system modeling under controlled conditions are necessary to distinguish between plant subsystem requirements, fish needs, and density effects.
7	Considering the wide range of cultured aquatic organisms with basil, the optimum temperature determination for species-specific culture with different varieties of basil is a critical necessity to enhance the production of both species.
8	Further investigations are required to identify the adequate water flow rate and hydraulic loading rate for the cultivation of basil with different aquatic organisms in aquaponic systems.
9	Studies on how the flow rate influences nutrient uptake and fish health under varying environmental conditions (e.g., temperature, pH) are a crucial requirement.
10	Further research is needed to understand the broader economic impact of different crop selections on aquaponic system profitability.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Disclosure

An earlier version of this article was presented as an oral presentation at the Aquaponics Association conference 2024 in Dallas, Texas, USA, September 12–15th (https://aquaponicsconference.org/schedule-and-current-speakers).

Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] U. Knaus, M. Pribbernow, L. Xu, S. Appelbaum, and H. W. Palm, "Basil (*Ocimum basilicum*) Cultivation in Decoupled Aquaponics With Three Hydro-Components (Grow Pipes, Raft, Gravel) and African Catfish (*Clarias gariepinus*) Production in Northern Germany," *Sustainability* 12, no. 20 (2020): 8745.

[2] R. Rehman, M. A. Hanif, Z. Mushtaq, B. Mochona, and X. Qi, "Biosynthetic Factories of Essential Oils: The Aromatic Plants," *Natural Products Chemistry & Research* 4, no. 4 (2016): 1–11.

[3] D. C. Love, J. P. Fry, X. Li, et al., "Commercial Aquaponics Production and Profitability: Findings From an International Survey," *Aquaculture* 435 (2015): 67–74.

[4] D. N. Mokat and T. D. Kharat, "Essential Oil Composition in Leaves of, *Ocimum*, Species Found in Western Maharashtra, India," *Journal of Essential Oil Bearing Plants* 25, no. 1 (2022): 1–8.

[5] H. R. Roosta, "Comparison of the Vegetative Growth, Eco-Physiological Characteristics and Mineral Nutrient Content of Basil Plants in Different Irrigation Ratios of Hydroponic: Aquaponic Solutions," *Journal of Plant Nutrition* 37, no. 11 (2014): 1782–1803.

[6] R. M. Filep, Ş. Diaconescu, M. Costache, M.-M. Stavrescu-Bedivan, L. Bădulescu, and C. G. Nicolae, "Pilot Aquaponic Growing System of Carp (*Cyprinus Carpio*) and Basil (*Ocimum Basilicum*)," *Agriculture and Agricultural Science Procedia* 10 (2016): 255–260.

[7] J. S. Mangmang, R. Deaker, and G. Rogers, "Inoculation Effect of *Azospirillum brasilense* on Basil Grown Under Aquaponics Production System," *Organic Agriculture* 6, no. 1 (2016): 65–74.

[8] S. Elumalai, A. Shaw, D. Pattillo, C. Currey, K. Rosentrater, and K. Xie, "Influence of UV Treatment on the Food Safety Status of a Model Aquaponic System," *Water* 9, no. 1 (2017): 27.

[9] S. Saha, A. Monroe, and M. R. Day, "Growth, Yield, Plant Quality and Nutrition of Basil (*Ocimum basilicum* L.) Under Soilless Agricultural Systems," *Annals of Agricultural Sciences* 61, no. 2 (2016): 181–186.

[10] R. S. Ferrarezi and D. S. Bailey, "Basil Performance Evaluation in Aquaponics," *HortTechnology* 29, no. 1 (2019): 85–93.

[11] M. Crețu, L. Dediu, T. Coadă, et al., "Comparative Study on the Growth and Development of Thyme and Basil Herbs in Aquaponic System and Hydroponic System," *Scientific Papers. Series D. Animal Science* LXV, no. 1 (2022): 573–580.
[12] D. Rodgers, E. Won, M. B. Timmons, and N. Mattson, "Complementary Nutrients in Decoupled Aquaponics Enhance Basil Performance," *Horticulturae* 8, no. 2 (2022): 111.
[13] J. Reyes-Pérez, B. Murillo-Amador, A. Nieto-Garibay, et al., "Tolerance to Salinity in Basil Varieties (*Ocimum basilicum* L.) at the Germination, Emergence and Initial Growth Stages," *University and Science* 29, no. 2 (2013): 101–112.
[14] J. Fierro, G. Rodriguez, J. Leon, et al., "Production and Management of Shrimp (*Penaeus vannamei*) in Co Culture with Basil (*Ocimum basilicum*) Using Two Sources of Low Salinity Water," *Latin American Journal of Aquatic Research* 46, no. 1 (2018): 63–71.
[15] J. E. Rakocy, M. P. Masser, and T. M. Losordo, "Recirculating Aquaculture Tank Production Systems: Aquaponics—Integrating Fish and Plant Culture," *Southern Regional Aquaculture Center* 454 (2006): 1–16.
[16] P. Stathopoulou, E. Tsoumalakou, E. Levizou, T. Vanikiotis, S. Zaoutsos, and P. Berillis, "Iron and Potassium Fertilization Improve Rocket Growth Without Affecting Tilapia Growth and Histomorphology Characteristics in Aquaponics," *Applied Sciences* 11, no. 12 (2021): 5681.
[17] H. Y. Yıldız and S. Bekcan, "Role of Stocking Density of Tilapia (*Oreochromis aureus*) on Fish Growth, Water Quality and Tomato (*Solanum lycopersicum*) Plant Biomass in the Aquaponic System," *International Journal of Environment, Agriculture and Biotechnology* 2, no. 6 (2017): 2819–2824.
[18] C. Maucieri, C. Nicoletto, G. Zanin, et al., "Effect of Stocking Density of Fish on Water Quality and Growth Performance of European Carp and Leafy Vegetables in a Low-Tech Aquaponic System," *PLoS ONE* 14, no. 5 (2019): e0217561.
[19] O. Siqwepu, K. Salie, and N. Goosen, "Evaluation of Chelated Iron and Iron Sulfate in the Diet of African Catfish, to Enhance Iron Excretion for Application in Integrated Aquaponics Systems," *Journal of the World Aquaculture Society* 51, no. 4 (2020): 1034–1053.
[20] O. Siqwepu, K. Salie, and N. Goosen, "Evaluation of Potassium Diformate and Potassium Chloride in the Diet of the African Catfish, *Clarias gariepinus* in a Recirculating Aquaculture System," *Aquaculture* 526 (2020): 735414.
[21] V. Nozzi, A. Graber, Z. Schmautz, A. Mathis, and R. Junge, "Nutrient Management in Aquaponics: Comparison of Three Approaches for Cultivating Lettuce, Mint and Mushroom Herb," *Agronomy* 8, no. 3 (2018): 27.
[22] D. Ru, J. Liu, Z. Hu, et al., "Improvement of Aquaponic Performance Through Micro- and Macro-Nutrient Addition," *Environmental Science and Pollution Research* 24, no. 19 (2017): 16328–16335.
[23] B. Angkha, A. K. Verma, S. H. Kumar, C. Prakash, and R. M. Thomas, "Mobilization of Mica by Bacillus sp. and Its Effect on Nile Tilapia (*Oreochromis niloticus*) Cum Holy Basil (*Ocimum tenuiflorum*)–based Aquaponic System," *Aquaculture International* 28, no. 5 (2020): 2045–2058.
[24] R. M. Peter, A. K. Verma, M. H. Chandrakant, and D. Mamatha, "Effect of Different Potassium (K+) Doses on Growth of Tomato (*Solanum lycopersicum*) With Pearlspot (*Etroplus suratensis*) in a Recirculating Aquaponic System," *Journal of Experimental Zoology-India* 24 (2021): 951–959.
[25] V. C. John, A. K. Verma, K. K. Krishnani, M. H. Chandrakant, V. S. Bharti, and T. Varghese, "Optimization of Potassium (K+) Supplementation for Growth Enhancement of, *Spinacia oleracea*, L. and *Pangasianodon hypophthalmus* (Sauvage, 1878) in an Aquaponic System," *Agricultural Water Management* 261 (2022): 107339.
[26] J. Rakocy, "Hydroponic Lettuce Production in a Recirculating Fish Culture System," (1988): 4–10, 3. Virgin Islands Agricultural Experiment Station, Island Perspectives (1988): 4–10.
[27] J. Rakocy, R. C. Shultz, D. S. Bailey, and E. S. Thoman, "Aquaponic Production of Tilapia and Basil: Comparing a Batch and Staggered Cropping System," *Acta Horticulturae* 648 (2004): 63–69.
[28] K. J. Walters and C. J. Currey, "Hydroponic Greenhouse Basil Production: Comparing Systems and Cultivars," *HortTechnology* 25, no. 5 (2015): 645–650.
[29] M. Aslanidou, A. Elvanidi, A. Mourantian, E. Levizou, E. Mente, and N. Katsoulas, "Nutrients Use Efficiency in Coupled and Decoupled Aquaponic Systems," *Horticulturae* 9, no. 10 (2023): 1077.
[30] B. Yep and Y. Zheng, "Aquaponic Trends and Challenges—A Review," *Journal of Cleaner Production* 228 (2019): 1586–1599.
[31] M. Meyers, *Basil: An Herb Society of America Guide* (The Herb Society of America, Kirtland, OH, USA, 2003): 6–7.
[32] J.-Y. Liang and Y.-H. Chien, "Effects of Feeding Frequency and Photoperiod on Water Quality and Crop Production in a Tilapia-Water Spinach Raft Aquaponics System," *International Biodeterioration & Biodegradation* 85 (2013): 693–700.
[33] M. A. O. K. Albadwawi, Z. F. R. Ahmed, S. S. Kurup, M. A. Alyafei, and A. Jaleel, "A Comparative Evaluation of Aquaponic and Soil Systems on Yield and Antioxidant Levels in Basil, An Important Food Plant in Lamiaceae," *Agronomy* 12, no. 12 (2022): 3007.
[34] C. Maucieri, A. A. Forchino, C. Nicoletto, et al., "Life Cycle Assessment of a Micro Aquaponic System for Educational Purposes Built Using Recovered Material," *Journal of Cleaner Production* 172 (2018): 3119–3127.
[35] S. H. Hoseinifar, F. Maradonna, M. Faheem, et al., "Sustainable Ornamental Fish Aquaculture: The Implication of Microbial Feed Additives," *Animals* 13, no. 10 (2023): 1583.
[36] M. Abbey, N. O. Anderson, C. Yue, et al., "Basil, *Ocimum basilicum*, Yield in Northern Latitudinal Aquaponic Growing Conditions," *Journal of the World Aquaculture Society* 53, no. 1 (2022): 77–94.
[37] R. Braglia, P. Costa, G. Di Marco, et al., "Phytochemicals and Quality Level of Food Plants Grown in an Aquaponics System," *Journal of the Science of Food and Agriculture* 102, no. 2 (2022): 844–850.
[38] H. Y. Yen and J. H. Chou, "Water Purification by Oyster Shell Bio-Medium in a Recirculating Aquaponic System," *Ecological Engineering* 95 (2016): 229–236.
[39] P. A. Patil, K. Dube, A. K. Verma, N. K. Chadha, J. K. Sundaray, and P. Jayasankar, "Growth Performance of Goldfish, *Carassius auratus* and Basil, *Ocimum basilicum* in Media Bed Aquaponics," *Indian Journal of Fisheries* 66, no. 1 (2019): 112–118.
[40] U. Knaus and H. W. Palm, "Effects of Fish Biology on Ebb and Flow Aquaponical Cultured Herbs in Northern Germany (Mecklenburg Western Pomerania)," *Aquaculture* 466 (2017): 51–63.
[41] H. W. Palm, K. Bissa, and U. Knaus, "Significant Factors Affecting the Economic Sustainability of Closed Aquaponic Systems Part II: Fish and Plant growth," *Aquaculture, Aquarium, Conservation & Legislation Bioflux* 7, no. 3 (2014): 162–175.

[42] E. A. Espinosa Moya, C. A. Angel Sahagún, J. M. Mendoza Carrillo, P. J. Albertos Alpuche, C. A. Álvarez-González, and R. Martínez-Yáñez, "Herbaceous Plants as Part of Biological Filter for Aquaponics System," *Aquaculture Research* 47, no. 6 (2016): 1716–1726.

[43] A. Espinosa-Moya, A. Alvarez-Gonzalez, P. Albertos-Alpuche, R. Guzman-Mendoza, and R. Martínez-Yáñez, "Growth and Development of Herbaceous Plants in Aquaponic Systems," *Acta Universitaria* 28, no. 2 (2018): 1–8.

[44] A. S. Hussain and P. B. Brown, "A Literature Review of Tilapia/Lettuce Aquaponics—Production Status, Varieties, and Research Gaps," *Aquaculture Research* 2024 (2024): 2642434.

[45] C. Somerville, M. Cohen, E. Pantanella, A. Stankus, and A. Lovatelli, *Small-Scale Aquaponic Food Production: Integrated Fish and Plant Farming* (FAO Fisheries and Aquaculture Technical Paper, 2014).

[46] S. G. Alarcón-Silvas, J. A. León-Cañedo, J. F. Fierro-Sañudo, et al., "Water Quality, Water Usage, Nutrient use Efficiency and Growth of Shrimp *Litopenaeus vannamei* in an Integrated Aquaponic System With Basil *Ocimum basilicum*," *Aquaculture* 543 (2021): 737023.

[47] B. Delaide, G. Delhaye, M. Dermience, J. Gott, H. Soyeurt, and M. H. Jijakli, "Plant and Fish Production Performance, Nutrient Mass Balances, Energy and Water Use of the PAFF Box, A Small-Scale Aquaponic System," *Aquacultural Engineering* 78 (2017): 130–139.

[48] M. M. Mariscal-Lagarda, F. Páez-Osuna, J. L. Esquer-Méndez, I. Guerrero-Monroy, A. R. Del Vivar, and R. Félix-Gastelum, "Integrated Culture of White Shrimp (*Litopenaeus vannamei*) and Tomato (*Lycopersicon esculentum* Mill) With Low Salinity Groundwater: Management and Production," *Aquaculture* 366-367 (2012): 76–84.

[49] H. A. Ahmed, T. Yu-Xin, and Y. Qi-Chang, "Optimal Control of Environmental Conditions Affecting Lettuce Plant Growth in a Controlled Environment With Artificial Lighting: A Review," *South African Journal of Botany* 130 (2020): 75–89.

[50] M. Abd El-Baset, "Response of Tuscany Basil (*Ocimum basilicum* 'Tuscany') to Foliar Application and Different Growing Media Under Aquaponic Unit," *Journal of Plant Production* (2023): 295–302.

[51] B. Baßmann, H. Harbach, S. Weißbach, and H. W. Palm, "Effect of Plant Density in Coupled Aquaponics on the Welfare Status of African Catfish, *Clarias gariepinus*," *Journal of the World Aquaculture Society* 51, no. 1 (2020): 183–199.

[52] L. Dediu and A. Docan, "Influence of Substrate Type on the Physiological Profile of the Heterotrophic Bacterial Community in Recirculating Aquaponic Systems," *Scientific Papers. Series D. Animal Science* LXII, no. 1 (2019): 489–497.

[53] B. Fronte, L. Incrocci, G. Galliano, G. Carmassi, A. Pardossi, and C. Bibbiani, "Preliminary Study on Eel Breeding and Vegetables Production in an Aquaponic System," *Acta Horticulturae* 1305 (2021): 415–422.

[54] N. Mashaii, F. Rajabipour, H. Hosseinzadeh, and M. Hafezieh, "Greenhouse Tilapia Culture in Aquaponic System," *Journal of Survey in Fisheries Sciences* 7, no. 2 (2021): 209–217.

[55] N. A. Savidov, E. Hutchings, and J. E. Rakocy, "Fish and Plant Production in a Recirculating Aquaponic System: A New Approach to Sustainable Agriculture in Canada," *Acta Horticulturae* 742 (2007): 209–221.

[56] M. A. Soliman, K. F. El-Kholy, M. A. E. El-helaly, and A. Soluma, "Effect of Replacing Soybean Meal by Slaughterhouse Poultry by-Products Meal on Nutrient Digestibility Ecoefficiency and Accumulation of Elements of the Nile Tilapia (*Oreochromis niloticus* L.) Under Aquaponics System Conditions," *Egyptian Journal of Aquatic Biology and Fisheries* 26, no. 6 (2022): 719–736.

[57] R. C. Shultz, S. D. Coyle, L. A. Bright, J. V. Hager, and J. H. Tidwell, "Evaluation of Different Artificial Light Technologies for Indoor Aquaponic Production of Bibb Lettuce, *Lactuca sativa* var. *capitata*, and Compact Basil, *Ocimum basilicum* var," *Journal of the World Aquaculture Society* 53, no. 3 (2022): 703–713.

[58] T. Yang and H.-J. Kim, "Nutrient Management Regime Affects Water Quality, Crop Growth, and Nitrogen Use Efficiency of Aquaponic Systems," *Scientia Horticulturae* 256 (2019): 108619.

[59] T. Yang and H.-J. Kim, "Characterizing Nutrient Composition and Concentration in Tomato-, Basil-, and Lettuce-Based Aquaponic and Hydroponic Systems," *Water* 12, no. 5 (2020): 1259.

[60] T. Yang and H.-J. Kim, "Comparisons of Nitrogen and Phosphorus Mass Balance for Tomato-, Basil-, and Lettuce-Based Aquaponic and Hydroponic Systems," *Journal of Cleaner Production* 274 (2020): 122619.

[61] A. Babatunde, R.-A. Deborah, M. Gan, and T. Simon, "Effects of Plant Density and Stem Pruning on Plant Biomass Yield and Economic Benefits in a Low-Cost Gravel Bed Aquaponic System," *Journal of Applied Aquaculture* 35, no. 3 (2023): 837–863.

[62] D. Homoki, D. Minya, L. Kovács, et al., "Comparison of the Technological Background of Aquaponic Systems," *Acta Agraria Debreceniensis*, no. 1 (2020): 47–52.

[63] D. Homoki, T. Odunayo, D. Minya, et al., "Effect of Dissolved Oxygen on Common Carp (*Cyprinus carpio*) and Basil (*Ocimum basilicum*) in the Aquaponics System," *Acta Agraria Debreceniensis* 89–96, no. 1 (2021): 89–96.

[64] U. Knaus, S. Appelbaum, and H. W. Palm, "Significant Factors Affecting the Economic Sustainability of Closed Backyard Aquaponics Systems Part IV: Autumn Herbs and Polyponics," *Aquaculture, Aquarium, Conservation & Legislation* 11, no. 6 (2018): 1760–1775.

[65] H. W. Palm, R. Seidemann, S. Wehofsky, and U. Knaus, "Significant Factors Affecting the Economic Sustainability of Closed Aquaponic Systems. Part I: System Design, Chemo-Physical Parameters and General Aspects," *Aquaculture, Aquarium, Conservation & Legislation Bioflux* 7, no. 1 (2014): 20–32.

[66] N. Harika, A. K. Verma, K. K. Krishnani, et al., "Stocking Density Optimisation of Pangasius (*Pangasianodon hypophthalmus*) Fingerlings With Basil (*Ocimum basilicum* L.) in Nutrient Film Technique (NFT) Based Aquaponics," *Indian Journal of Fisheries* 70, no. 3 (2023): 63–72.

[67] N. Harika, A. K. Verma, K. K. Krishnani, C. M. Hittinahalli, R. Reddy, and M. Pai, "Supplementation of Potassium in Aquaculture Wastewater and Its Effect on Growth Performance of Basil (*Ocimum basilicum* L) and Pangasius (*Pangasianodon hypophthalmus*) in NFT-Based Aquaponics," *Scientia Horticulturae* 323 (2024): 112521.

[68] M. G. Huitzitl-López, M. del Carmen Monroy-Dosta, J. Castro-Mejía, G. Vázquez-Silva, and E. M. C. Serrano, "Growth Evaluation of *Ambystoma mexicanum* and *Ocimum basilicum* With Application of *Bacillus subtilis* Probiotic in Aquaponic System," *International Journal of Aquatic Science* 9, no. 2 (2018): 93–98.

[69] J. E. Rakocy, D. S. Bailey, R. C. Shultz, and J. J. Danaher, "A Commercial-Scale Aquaponic System Developed at the University of the Virgin Islands," in *Better Science, Better*

Fish, Better Life: Proceeding of the Ninth International Symppsium, eds. L. Liping and K. Fitzsimmons, (Tilapia Aquaculture, Shanghai, China, 2011).

[70] J. E. Rakocy, D. S. Bailey, E. S. Thoman, and R. C. Shultz, "Intensive Tank Culture of Tilapia With a Suspended, Bacterial-Based, Treatment Process," in *Proceedings 6th International Symposium on Tilapia in Aquaculture*, eds. R. B. Bolivar G. C. Mair and K. Fitzsimmons, pp. 584–596, (Manila, Philippines, 2004), 584–596.

[71] J. E. Rakocy, D. S. Bailey, K. A. Shultz, and W. M. Cole, "Evaluation of a Commercial-Scale Aquaponic Unit for the Production of Tilapia and Lettuce," in *Tilapia Aquaculture: Proceedings of the Fourth International Symposium on Tilapia in Aquaculture*, (Orlando, Florida, 1997), 357–372.

[72] T. Hendrickson, B. L. Dunn, C. Goad, B. Hu, and H. Singh, "Effects of Elevated Water Temperature on Growth of Basil Using Nutrient Film Technique," *HortScience* 57, no. 8 (2022): 925–932.

[73] T. C. Barickman, O. J. Olorunwa, A. Sehgal, C. H. Walne, K. R. Reddy, and W. Gao, "Yield, Physiological Performance, and Phytochemistry of Basil (*Ocimum basilicum* L.) Under Temperature Stress and Elevated CO_2 Concentrations," *Plants* 10, no. 6 (2021): 1072.

[74] A. Endut, A. Jusoh, N. Ali, W. B. Wan Nik, and A. Hassan, "A Study on the Optimal Hydraulic Loading Rate and Plant Ratios in Recirculation Aquaponic System," *Bioresource Technology* 101, no. 5 (2010): 1511–1517.

[75] E.-S. Khater, A. Bahnasawy, S. Ali, W. Abbas, O. Morsy, and A. Sabahy, "Study on the Plant and Fish Production in the Aquaponic System as Affected by Different Hydraulic Loading Rates," *Scientific Reports* 13, no. 1 (2023): 17505.

[76] B. Angkha, A. K. Verma, M. H. Chandrakant, R. M. Thomas, and R. M. Peter, "Growth Performance of Nile Tilapia (*Oreochromis niloticus*) With Holy Basil (*Ocimum tenuiflorum*) Using Mica and Bacterial Dosage at Different Hydraulic Loading Rates in Aquaponics," *Journal of Experimental Zoology-India* 24 (2021): 801–807.

[77] D. C. Love, J. P. Fry, L. Genello, et al., "An International Survey of Aquaponics Practitioners," *PLoS One* 9, no. 7 (2014): e102662.

[78] D. A. Pattillo, J. V. Hager, D. J. Cline, L. A. Roy, T. R. Hanson, and P. K. Pandey, "System Design and Production Practices of Aquaponic Stakeholders," *PLoS One* 17, no. 4 (2022): e0266475.

[79] C. R. Engle and M. Beem, "Economics of Aquaponics—Oklahoma State University," Oklahoma Cooperative Extension Service SRAC-5006 (2017).

[80] J. Lobillo-Eguíbar, V. M. Fernández-Cabanás, L. A. Bermejo, and L. Pérez-Urrestarazu, "Economic Sustainability of Small-Scale Aquaponic Systems for Food Self-Production," *Agronomy* 10, no. 10 (2020): 1468.

[81] M. L. Gullino, G. Gilardi, and A. Garibaldi, "Ready-to-Eat Salad Crops: A Plant Pathogen's Heaven," *Plant Disease* 103, no. 9 (2019): 2153–2170.

[82] S. Belsinger and A. O. Tucker, *Grow Your Own Herbs: The 40 Best Culinary Varieties for Home Gardens* (Timber Press, 2019).

[83] S. Sapkota, S. Sapkota, and Z. Liu, "Effects of Nutrient Composition and Lettuce Cultivar on Crop Production in Hydroponic Culture," *Horticulturae* 5, no. 4 (2019): 72.