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Review

Optimizing Nutrient Availability in Decoupled Recirculating Aquaponic Systems for Enhanced Plant Productivity: A Mini Review

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Abstract: Nutrient management in coupled aquaponic systems presents significant challenges due to competing requirements between fish and plant production within a single-loop framework. These challenges often result in suboptimal nutrient concentrations, compromised system efficiency, and reduced yields. This critical review examines the Decoupled recirculating aquaponics system (DRAPS) as an innovative solution that separates fish and plant nutrient cycles while maintaining water recirculation benefits. This study provides a comprehensive review of DRAPS, emphasizing how its decoupled structure enhances nutrient management and promotes sustainable production. It specifically evaluates the ability of DRAPS to optimize macronutrient and micronutrient levels, control agronomic factors independently, and improve both nutrient and water use efficiency. Additionally, this review highlights the advantages of using urea as a nitrogen source, which can enhance plant productivity without compromising fish health. The findings indicate that the loops of DRAPS facilitate customized nutrient concentrations, fostering optimal growth conditions for both plants and fish. By safely incorporating urea as a nitrogen source, DRAPS increases plant productivity while reducing the risk of ammonia toxicity for fish. Furthermore, independent control over agronomic factors enhances nutrient uptake, nutrient use efficiency, and water use efficiency. This approach minimizes the risks of cross-toxicity and enables higher levels of essential micronutrients, such as iron and nickel, which are beneficial for plant health but can be toxic in coupled systems. DRAPS signifies a significant advancement in sustainable agriculture, particularly in regions with limited water and land resources. By optimizing nutrient management and supporting the high-density production of plants and fish, DRAPS presents a scalable, resource-efficient model that aligns with sustainable development goals. Its capacity for precise nutrient control with minimal environmental impact positions it as a valuable solution for sustainable, high-yield food production in resource-constrained settings.

Keywords: aquaponics; nitrogen; urea; nickel; iron; pH

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1. Introduction

Aquaponics is a synergistic combination of a continuous recirculation aquaculture system [1–3] with a closed soilless culture and/or hydroponics system [4] that utilizes biological processes [5,6] to produce nitrogen in the preferred form and concentration, which provides the plants with sufficient nitrate. Aquaponics can be established in different settings such as small- or large-scale, urban or rural, and in developed or developing countries [7]. Both coupled [8–12] and decoupled [13–21] aquaponics play a powerful and essential role in the future of sustainable food production. They directly affect the future of food security, especially in countries lacking sufficient water and land resources. Therefore, the significant challenge today is to improve and increase the efficiency of aquaponics. Recently, multiple studies have been undertaken to increase aquaponic production efficiency by optimizing nitrogen use efficiency and reducing nitrogen loss in aquaponic systems [18–21]. Nowadays, researchers pay more attention to improving the efficiency of aquaponic production through innovation to create a new multi-cycle system. Therefore, the main objective of this review is to examine the potential of the decoupled recirculating aquaponics system (DRAPS) in enhancing sustainable food production through optimized nutrient management. By assessing how DRAPS enables precise control of nutrient cycles for both crop and fish production, this critical review aims to highlight its advantages over coupled systems, with a focus on improvements in nutrient use efficiency, water conservation, and overall productivity. This study also explores the role of DRAPS in addressing challenges related to resource limitations, positioning it as a viable solution for sustainable agriculture and food security.

2. Comparative Analysis of Coupled and Decoupled Aquaponic Systems

Recently, aquaponic systems have been divided based on the number of circulations: coupled or single-flow with one loop; decoupled with two separate loops.

2.1. Coupled Recirculation Aquaponics System

The coupled recirculation aquaponics system (CRAPS) is a coupled system linked to the aquaculture production unit and the plant production unit in a circulation system through biological operation, where the fish, microbes, and plants stay in the same loop [8–10]. This minimizes water consumption, which is particularly advantageous in regions with water scarcity. In addition, the system's simplified design and integration of aquaculture and hydroponics in a single circuit reduce the complexity of the infrastructure and associated costs, making it amenable to small-scale applications with limited resources. The environmental benefits are also significant as the system minimizes nutrient discharge into surrounding ecosystems, aligning with sustainable agricultural practices. However, it is documented that CRAPS is a complex system composed for optimizing the physical properties such as pH, EC, DO, and temperature of the water for three types of organisms—fish, nitrifying bacteria, and plants. Fish thrive in a pH range of 6.5–8.0, while plants generally prefer a pH of 5.5–6.5. Nitrifying bacteria, which convert toxic ammonia into nitrates available to plants, perform optimally at a pH value of 7.0–8.0. While most warm water fish thrive at 24–30 °C, plants grow optimally at slightly lower temperatures. Also, changes in parts of CRAPS, such as the health of the fish or waste pollution, can have a direct impact on plant growth and vice versa [8–10].

2.2. Decoupled Recirculation Aquaponics System

DRAPS is a system composed of two separate circulations, one for fish and nitrifying bacteria and the other for plant production [13,14]. This separates the fish and plant units, allowing for independent optimization of the water quality parameters for each subsystem. This ensures that fish and plants are maintained under conditions that maximize their respective health and productivity. Additionally, the ability to tailor nutrient supplementation in the plant subsystem results in higher crop yields compared to CRAPS [19–26]. DRAPS is also more resilient to failures; a malfunction in one unit does not directly affect the other, making it better suited for large-scale or commercial operations. Despite its advantages, DRAPS is associated with higher initial and operational costs due to the need for additional infrastructure, including separate pumps, filters, and monitoring systems. The system's increased complexity requires specialized knowledge for its management, which may limit its adoption by small-scale farmers. Figure 1 shows a diagram of DRAPS. However, the two circulations are the fundamental strength of DRAPS as both the physical and chemical characteristics of the water for the fish and plant units can be controlled independently for optimal conditions.

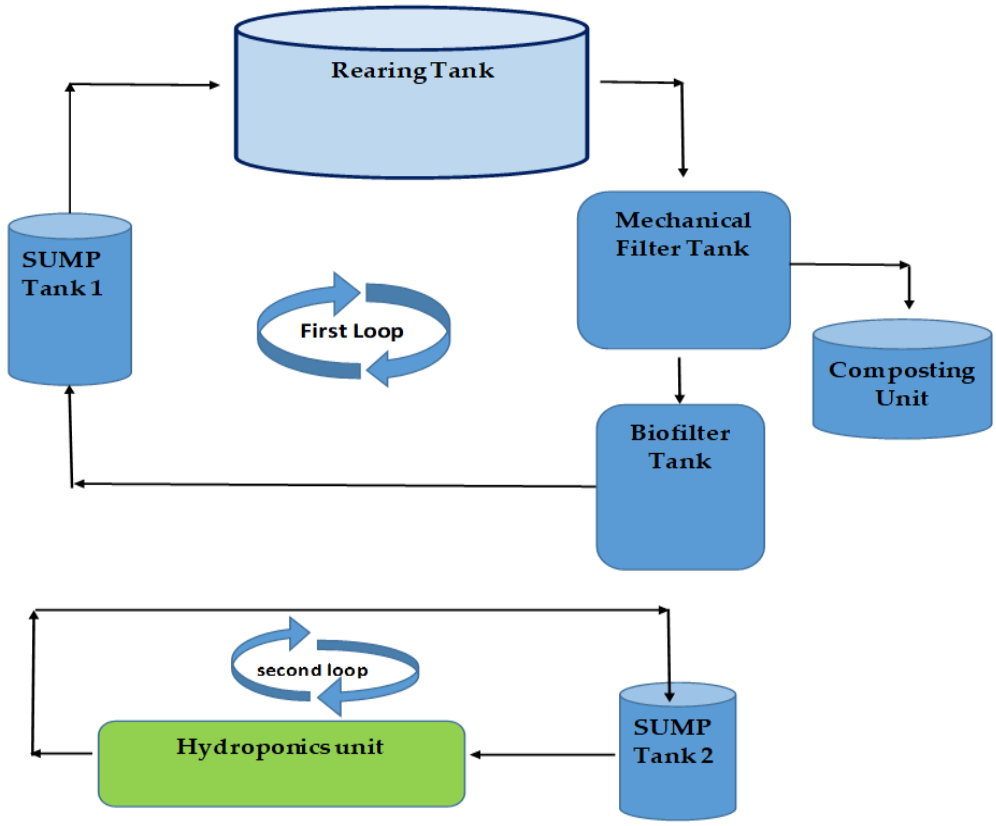

Figure 1. Decoupled recirculation aquaponics system diagram.

3. Types of Soilless Culture Systems in Aquaponic Systems

The major soilless culture systems that have been used in coupled and decoupled aquaponic systems are the nutrient film technique (NFT), deep-water culture (DWC), and substrate culture. Based on the review of most of the aquaponic publications, [22] reported that 43% of aquaponics were using a SC, 33% were using the DWC, 15% were using the NFT, and the remaining 9% were using other less-common hydroponic systems such as drip irrigation or ebb and flow.

The nutrient film technique (NFT) is a water channel technique in which the plant roots grow through the plastic film and grow into a thin film of water that flows continuously in circulation in narrow pipes [27,28]. This technique is widely used in small- and commercial-scale aquaponics. It is characterized by low initial costs and a simple structure. However, the interaction between the plant roots and nutrients in the flowing solution is limited, and NFT has a limited surface area for the nitrifying bacteria to stay on the plant roots. Moreover, DRAPS uses NFT in the second loop, where the plant roots can absorb the nutrients produced from the first loop.

3.1. Deep Water Culture

Deep water culture (DWC) is a deep water technique in which the plant roots are submerged entirely in a nutrient solution that is supplied with oxygen to prevent rot root infections, with a depth ranging from 5 to 20 cm. Love et al. [3] reported that DWC is the most common commercial hydroponic system used in aquaponics. Nevertheless, DWC can also be used in small-scale aquaponic production [13]. This technique is characterized by its capability to maximize root contact with nutrients and support high plant density with minimal materials as well as its low maintenance [29]. In addition, DWC removes higher amounts of NO_3^- from the aquaponics system compared to the NFT and substrate culture [28]. Lennard and Leonard [28] conducted a comparative analysis between NFT and DWC systems, demonstrating marginally enhanced nutrient utilization in DWC configurations; however, their study encompassed multiple nutrient parameters beyond specific NO_3^- removal rates. Several mechanistic factors could potentially support enhanced NO_3^- removal in DWC systems; these include the increased root surface area exposure to nutrient solution, facilitating greater nutrient absorption capacity, or the optimal dissolved oxygen distribution through mechanical aeration, which may have enhanced nutrient uptake efficiency and then the water use efficiency. Previous studies indicate that DWC systems have a lower environmental impact compared to media culture systems, despite their higher water demand.

3.2. Substrate Culture

Substrate culture is a simple technique that is most widely used in small-scale aquaponic systems. It can be used for most fruity and leafy crops such as tomato, cucumber, pepper, lettuce [11,30], and herbs [31]. It provides more stability for plants with extensive root growth and canopy, and as a result, the plants may adjust well to the system. Various substrate cultures are being used as grow beds to provide root support, which include organic substrates like sawdust, wood bark, coconut coir dust, peat, and burnt paddy rice, as well as inorganic substrates such as tuff, gravel, perlite, vermiculite, sand, pumice, rockwool, and foam mat [27]. In DRAPS, substrate culture is used in the second loop and helps the plants with nutrient uptake, which in turn promotes the growth and development of the plants; however, these substrates cannot provide sufficient surface area for the growth of the microbial community and cannot act as a mechanical filter due their location in the second loop.

4. Opportunity of DRAPS to Increase the Availability of Nutrients

Yep and Zheng [31] reported that nitrogen use efficiency, nutrient availability, and pH are the main challenges and limitations to optimizing plant production and resource use efficiency in aquaponic systems. However, DRAPS has the opportunity to solve these horticulture challenges and increase nutrient availability based on the advantages of the two independent loops. In DRAPS, there are opportunities for increasing nutrient availability through (i) optimizing the nitrification process in the first loop; (ii) optimizing macro- and micronutrient availability; (iii) optimizing the pH and agronomic factors; and (v) increasing the nutrient use efficiency.

4.1. Optimization of Macronutrient and Micronutrient Availability

4.1.1. Fish Feed as the Primary Nutrient Source

In aquaponics, the main source of nutrients is fish feed, composed mainly of protein (organic forms of nitrogen) and phosphorous [9,30,31]. For instance, the protein level in tilapia diets ranges from 32 to 36% based on the size and age of the fish. However, it was reported that the fish used only 40% of the feed for growth, while the remaining 60% was excreted as feces or went uneaten [19]. The nitrifying bacteria to produce nutrients will then break down the fish metabolic waste, which contains 4.47% of Nitrogen (N) and 2.35% of P [32,33]. Therefore, the concentrations of N and P in an aquaponic system depend on the fish feed's protein level, feeding rate, and frequency [5,6,9,34]. The macro- and micronutrients derived solely from the fish feed—like N, P, and particularly K, Ca, Mg, iron (Fe), copper (Cu), and manganese (Mn)—are inadequate for plant growth through the aquaponics [35–38] due to the fish having minimal requirements for Mg, Fe, Cu, Mn, and low requirements for K [39]. As a result, the fish feed is composed of a low level of these nutrients; therefore, the aquaculture effluent has low concentrations. Thus, plant growth requires additional macronutrients such as N, P, K, Ca, Mg, and Sulphur (S) and micronutrients such as Fe, Cu, Zn, and Mn in precise composition and concentrations in the water [27,40,41]. Table 1 shows that the concentration of NO_3^- produced through biological processes in aquaponics is lower than the concentration used in a hydroponics system. The NO_3- concentration in aquaponics ranged from 32.4 to 187 mg/L (Table 1). In addition, Table 1 shows that the concentrations of P, K, Ca, Mg, and S are lower than the concentrations in hydroponics; the concentration of P ranged from 3.5 to 11.49; K ranged from 48 to 104; Ca ranged from 37.30 to 187; and Mg ranged from 7.36 to 20.

Table 1. The concentrations of macronutrients that are produced from fish waste in aquaponic systems.

Plant	Fish Species	Stocking Density (Kg/m^3)	Feeding Rate	Aquaponic Type	NO_3 (mg/L)	P (mg/L)	K (mg/L)	Ca (mg/L)	Mg (mg/L)	S (mg/L)	References
Lettuce	Tilapia	-	40% protein	Coupled	50.31	7.83	59.51	14.72	7.36	10.99	[13]
Cucumber	Tilapia	29.4	36% protein	Decoupled	187	8	104	187	20		[25]
Lettuce, Mint, Mushroom Herb	Nile tilapia	50	-	Coupled	84	3.5	48	90	15		[33]
Basil	Nile tilapia	77	32% protein	UVI	49.60	11.49	48.85	37.30	14.58	21.01	[42]
Tomato	Nile tilapia	19	41% protein	Coupled	32.5	8.83					[43]
Basil	Nile tilapia	20	41% protein	Coupled	35.4	9.1					[43]
Lettuce	Nile tilapia	20.3	41% protein	Coupled	32.5	8.5					[43]

4.1.2. Nitrogen Management and Optimization

Nitrogen (N) is one of the critical macronutrients required for growth and development. It is a limiting factor for the productivity of the leaf crops. Nitrogen is a constituent of plants' amino acids, nucleic acids, vitamins, chlorophyll, and alkaloids [42]. It is well-known that nitrate and ammonium are the most common N forms used in modern agriculture systems such as hydroponics and aquaponics. Nitrate is the main product of the nitrification process in aquaponic systems and the preferred form for most crops. The ideal concentration of N for the leaf crops was 200 mg/L [27] and was composed of 75:25 NO_3^-:NH_4 [4]. However, due to the advantages of the design of two loops in DRAPS, N can be optimized at an adequate concentration and composition without toxifying the fish culture and causing adverse effects on the nitrifying bacteria.

4.1.3. Urea as a Complementary Nitrogen Source

In this review, applying urea as a complementary source of N in aquaponics is the most critical point discussed. The utilization of urea [$CO\ (NH_2)_2$] as a supplementary N source has become possible due to the two-loop design of DRAPS. Urea is well-known for its potential as a reliable N source due to its high N content (46%). However, modern agricultural systems such as hydroponics seldom use urea as an N source due to the concern about the build-up of NH_3-N. This is because urea will be broken down to NH_4-N, and if the concentration rises to 3 mg/L or higher, it can be toxic to the fish. Conversely, this would not be a concern in DRAPS due to the advantages of having two loops. In DRAPS, the fish culture is located in the first loop, which is not affected by the application of urea or its conversion to NH_4-N. The utilization of urea is necessary for aquaponics, especially DRAPS because NO_3-N is the main product of the nitrification process and is the main source of N for most crops such as lettuce. Jones [4] stated that the ideal ratio for NO_3^-:NH_4^+ in the nutrient solution should be 75:25 to ensure optimal growth of all higher plants in hydroponic systems. Research has been conducted to study the possibility of reducing the accumulation of excess NO_3-N that may contribute to toxicity and high levels of NO_3-N in vegetables—which may cause methemoglobinemia and possibly gastric cancer—through the application of urea [44–46]. For instance, Ikeda and Osawa [47] substituted a minor amount of NO_3-N supply with NH_4-N to the lettuce and replaced 20% of the NO_3-N supplementation with urea to the onions. In addition, Khan et al. [48] used 20% of urea as a total replacement of NH_4-N and as a partial replacement of NO_3-N in the nutrient solution for spinach. However, urea can only be supplied as a supplementary source of N due to its toxicity to plants like lettuce. The efficiency of the application of urea to make up the ideal concentration of N in modern agricultural systems such as hydroponics and aquaponics depends highly on different factors such as the plant species; plant type (e.g., leafy, fruit, as well as herbs); the life cycle of the plant; genetic factors of the plants; type of subsystem in the hydroponics or aquaponics (e.g., NFT, DWE, or substrate culture); the composition of nutrients; and the interaction between urea and other elements after its application into the nutrient solution. Also, a profound understanding of the characteristics and metabolism of urea in the nutrient solution is highly encouraged. As discussed previously, efforts to reduce the NO_3-N content in leafy vegetable crops have been highly considered. A high level of NO_3-N will cause harmful effects to human health upon consumption. Thus, it is necessary to identify the optimal ratio of NO_3-N and urea in DRAPS by evaluating the efficiency of urea as the secondary source of N, which will indirectly enhance the multi-loop system. Sambo et al. [49] reported that the yield and quality of crops cultivated hydroponically are highly dependent on the nutrients absorbed by the growing medium. Therefore, it is crucial to identify the hazards of using urea in plant nutrient solutions. This is because high urea absorption will lead to the accumulation of urea in plants, and this may cause chlorosis or stimulate the development of necrosis at the leaf edges [50]. Thus, urea should be hydrolyzed immediately to avoid its adverse effects. The hydrolysis of urea can be achieved through urease enzyme activity [51].

4.1.4. Role of Nickel in Urea Optimization

Nickel (Ni) is one of the critical elements that positively affects the level of urea in the nutrient solution as it is a component of urease, which is required for urea assimilation and hydrolysis by plant tissue [51,52]. The optimal effect of Ni highly depends on the plant species, growth stage, cultivation conditions, Ni concentration, and exposure time [53–55]. The uptake of Ni by plants is mainly carried out through the root system via passive diffusion and active transport [56–59]. Chen et al. [60] reported that the uptake of Ni by plants highly depends on the concentration and form of Ni and the pH of the nutrient solution. Thus, a nutrient solution with an optimized pH is feasible to ensure the efficient uptake of Ni for urea hydrolysis to take place in DRAPS. Pandaa et al. [61] reported that the uptake of Ni by *Lathyrus sativus* was proportional to the increase in pH up to a pH of 5.0 and proceeded to decrease as the pH rose up to 8.0. Other than pH, Ca is another factor that affects the uptake of Ni, particularly at high concentrations. It can reduce the absorption of Ni depending on the plant species. Temp [62] reported that Fe possessed the highest inhibitory effect on the absorption and translocation of Ni from roots to shoots, followed by cobalt (Co), Ca, magnesium (Mg), NH_3-N, K, and sodium (Na). It is essential to apply the suitable form of Ni at an optimum concentration to the nutrient solution to avoid the adverse effects of Ni. It has been reported that a high level of Ni will decrease the shoot and root growth, reduce the leaf area [63,64], decrease the photosynthesis activity [60], inhibit N metabolism [60], and restrict the uptake of other nutrients [60]. Nickel will compete with Ca, Mg, Mn, Fe, Cu, and Zn in the absorption, uptake, and subsequent utilization by the crops due to having some comparable characteristics to these elements [60,65–67]. Therefore, the supplementation of Ni in its suitable form and at an optimum concentration to the nutrient solution is crucial as a high level of Ni may inhibit the absorption of these minerals by plants, decrease their concentrations, and lead to deficiencies in plants [66,68,69]. Nevertheless, Khoshgoftarmanesh et al. [70] reported that Ni supplementation would enhance urease activity, resulting in higher growth rates and lettuce yields. In addition, the supplementation of Ni will also lower the NO_3-N concentration in the lettuce leaves, significantly improving the health quality of the lettuce fertilized with NO_3-N. However, the role of Ni in urea decomposition that occurs in the nutrient solution of aquaponics and its impacts on the yield and leaf NO_3-N content of lettuce remains unclear. Therefore, a profound understanding of the role of Ni in aquaponics is crucial as it enables the optimization of urea uptake by the plants as the source of N in DRAPS through the supplementation of optimum Ni concentration to the nutrient solution formulae such as Hoagland nutrient solution. This area of research needs to be further explored to advance DRAPS to make it a sustainable agricultural production system. However, limited information was available on the absorption of different nutrients by lettuce that is grown in water culture with partial urea application, including the addition of Ni, in both APS and DRAPS.

4.1.5. Macronutrient Management and Optimization

It has been reported that fish feed is the main source of P [71] and K [14] in aquaponics. However, as a result of Adler et al.'s [72] study, P and K derived solely from the fish feed were inadequate for the plants in an aquaponics system as they were low in concentration. Another study by Seawright et al. [39] also stated that the nutrients derived solely from the fish feed were low in concentrations of P and K. In addition, even though it is well-known that an aquaponics system can obtain a significant amount of P through its biological processes, the concentrations are often not at the ideal levels for crops. Thus, additional nutrients need to be added to an aquaponics system to reach its optimal level to optimize plant production. In DRAPS, P and K can be supplemented to the second loop as inorganic fertilizer with adequate concentrations and compositions without negatively affecting the fish culture and nitrifying bacteria. For leafy crops such as lettuce, the ideal concentration of P was 50 mg/L [27]. Therefore, if we assume the concentration of P that produced the nitrification process was 10 mg/L, it can be supplemented with inorganic fertilizer with the remaining concentration (40 mg of P/L) in the form of dipotassium phosphate or monopotassium phosphate to the hydroponics units to reach the ideal concentration. K was not necessary in aquaponics for fish growth and yield; therefore, its composition in the fish feed was low [73,74]. Thus, K has been reported to be one of the more important limiting nutrients in aquaponics. However, for lettuce, K is one of the basic requirements for plant growth and development. Also, it plays an essential role in iron and ammonium transport, enzyme activation, and moderating osmotic potential [4,75,76]. The ideal concentration of K for lettuce was 210 mg/L. However, as mentioned above, the concentration of K that was produced from the nitrification process was inadequate. Therefore, it must be supplemented to optimize the growth and yield of the plant. In aquaponic systems, the concentration of K can be increased by controlling the pH by adding KOH [8,35]. The macronutrients such as Ca and Mg can be supplied to an aquaponics system through the control and optimization of the system's alkalinity and raise the pH in acidic systems by adding limestone and dolomite. The concentration of Mg has been reported to be around 4 mg/L in aquaponics [39], which is significantly lower than in NFT lettuce hydroponics [27].

4.1.6. Iron Supplementation and Management

In an aquaponics system, Fe is the most limiting nutrient [36–38]. Iron (Fe) is one of the most limiting micronutrients produced from fish waste in an aquaponics system through nitrification [36,37,77]. However, Fe deficiency is common in an aquaponics system and the concentration usually ranges from 0.01 to 0.03 mg L^{-1}, while the ideal Fe concentration for the plants ranges from 2 to 5 mg/L. The sources of iron supplemented to aquaponics for different integration of fish and plants can be shown in Table 2. As mentioned above, Fe is one of the essential elements for the growth and development of crops in all agricultural systems, including hydroponics and aquaponics [78], and Fe deficiency results in poor yields and reduced nutritional quality [79]. Therefore, Fe is a limiting nutrient for plant growth and metabolism [80,81]. Additionally, Fe is a critical co-factor of many enzymes that have a vital role in the biosynthetic pathway of chlorophyll [82,83] and a co-factor for various proteins [82]. It is essential for photosynthesis, enzyme activation, protein synthesis, and osmotic potential. Iron fertilizers are categorized into three fundamental classes: (i) inorganic Fe compounds such as iron salts $FeSO_4{\cdot}7H_2O$, $FeCl_3{\cdot}6H_2O$, and $Fe(NO_3)_3{\cdot}9H_2O$, which are typically used in the foliar application [84–86]; (ii) synthetic Fe chelates such as Fe-EDTA, Fe-DTPA, Fe-EDDHA, and Fe-HBED; and (iii) natural Fe complexes like humates and amino acids [87–89]. Providing plants with an ideal form of Fe is crucial in DRAPS. The two commonly used practices to overcome Fe deficiency issues are the addition of Fe chelates such as Fe-EDTA and Fe-DTPA into the aquaponics water and supplementing iron salts $FeSO_4{\cdot}7H_2O$, $FeCl_3{\cdot}6H_2O$, and Fe $(NO_3)_3{\cdot}9H_2O$ to the plants through a foliar spray. These two methods are considered crop management practices that improve the Fe uptake by the root [88,90]. Vempati and Loeppert [91] reported that the application of Fe to the leaves in the chelated form gave better effects than the inorganic form of Fe. In aquaponics, it was reported that the application of soluble Fe-EDTA or Fe-DTPA at a concentration between 2 and 5 mg/L is ideal for aquaponics [92] as the optimal Fe concentration for the plant is between 0.2 and 2.5 mg/L [93,94].

Table 2. The sources of iron supplementation to aquaponic systems for different integrations of fish and plants.

Plant Name	Fish Species	Type of Aquaponics	Type of Hydroponic Unit	Methods of Application of Fe	Fe Form	Fe Concentration	References
Catalogna chicory Lettuce Swiss Chard	European Carp (*Cyprinus carpio* L.)	Coupled aquaponic	Grow bed	Addition to water	of Fe-EDTA	31 mg/L once for whole season	[11]
Lettuce	Nile tilapia (*Oreochromis niloticus*)	Decoupled aquaponic	NFT	Addition to water	FR	2.5 mg Fe/L	[24]
Lettuce	Nile tilapia (*Oreochromis niloticus*)	Coupled aquaponic	Rafts floating	Addition to water	Iron DTPA solution	3 mg/L	[33]
Basil	Nile tilapia (*Oreochromis niloticus*)	UVI coupled aquaponic	DWC	Addition to water	Iron chelate (13% EDTA Fe)	2 mg/L at 3 week intervals	[36]
Tomato	Common carp (*Cyprinus carpio*)	UVI coupled aquaponic	Substrate culture	Addition to water	Fe-EDDHA	2 mg/L once every two weeks	[95]
Pepper	Common carp (*Cyprinus carpio*)	UVI coupled aquaponic	Substrate culture	Foliar application	$FeSO_4$, Fe-EDTA, and Fe(III)-EDDHA	0.5 g Fe/L	[86]
Tomato	Common carp (*Cyprinus carpio*)	UVI coupled aquaponic	Substrate culture	Addition to water	Fe-EDDHA	2 mg/L once every two weeks	[96]

Table 2. *Cont.*

Plant Name	Fish Species	Type of Aquaponics	Type of Hydroponic Unit	Methods of Application of Fe	Fe Form	Fe Concentration	References
Eggplant	Common carp (*Cyprinus carpio*)	UVI coupled aquaponic	Substrate culture	Foliar application	($FeSO_4$), Fe-EDTA, and Fe(III)-EDDHA	0.5 g/L	[97]
Tomato and Pak choi	Tilapia (*Oreochromis niloticus*)	Coupled aquaponic	Grow bed	Addition to water	Fe-EDTA	2 mg/L	[98]
Pak choi	Tilapias (*Oreochromis niloticus*)	Coupled aquaponic	Grow bed	Addition to water	Fe-EDTA	2 mg/L	[99]
Butterhead Lettuce	Koi carp (*Cyprinus carpio*)	Coupled aquaponic	Rafts floating	Addition to water	chelated iron (Sprint 330, Fe-DTPA)	2 mg/L	[100]

4.2. Optimization of the Biological Process of DRAPS

In DRAPS, the first loop was composed of mechanical and biological filters. Because of the design of DRAPS, optimizing these filters was an essential requirement for controlling the fish water culture to optimize feed utilization and increase fish growth, as well as maximizing N and P production as the main products of the nitrification process.

4.2.1. Mechanical Filter

A mechanical filter (MF) is a section in the tank where the processes of separation and removal of solid and suspended dissolved fish wastes flow from the fish tank [9]. In DRAPS, MF is the essential requirement for substrate culture, the NFT, and DWC at both low and high stocking density to remove any solids in the water before entering the biological filter to reduce heterotrophic bacteria populations [101]. This will reduce the competition between the heterotrophic bacteria and the nitrifying bacteria and encourage the conversion of ammonia (NH_3) or ammonium (NH_4^+) to nitrate (NO_3^-) [102]. In addition, MF is critical to prevent clogging in the grow bed channel of NFT units in DRAPS. As such, MF is crucial in increasing the efficiency of biological filters by removing the excretory products of fish, uneaten feed, and living organisms such as bacteria, fungi, and algae that grow in the first loop of DRAPS. These organic materials will adversely impact the system upon accumulation, such as reduced DO and methane and hydrogen sulfide production. Besides that, MF will prevent the formation of anaerobic zones that affect nutrient uptake. Frequent removal of solid wastes will minimize the formation and accumulation of dissolved materials. There are various types of MF available on the market, and the simplest type of MF is a layer of filter located between the fish tank and the biofilter tank. This kind of simple filter is usually only used in small-scale aquaponic units but is not preferred in larger systems where the amount of solid waste produced is significantly higher [9]. Regardless of the fish stocking density, MF is a critical component of substrate culture, the NFT, and DWC in DRAPS due to the high concentration of total suspended solids in the water [16,35]. In addition, MF is also a critical solution for the long-term operation of DRAPS to avoid clogging and insufficient oxygen levels in the grow bed. Furthermore, [17,18] recommended the installation of different chambers in the MF tank for higher efficiency in retaining N, especially for commercial DRAPS. Thus, MF has a critical role in promoting the nitrification process in the biofilter tank in the first loop of DRAPS, which subsequently will improve the nutrient uptake by plants in the hydroponic units [25].

On the other hand, several factors influence the energy consumption of mechanical filters, including the type of filter, water flow rate, waste load, and system size. In small-scale systems, simple mechanical filters such as static mesh screens or layered filters typically operate using gravity or low-power pumps, resulting in minimal energy consumption. In contrast, commercial-scale systems utilize advanced mechanical filters like drum filters, rotary screens, or pressurized systems, which have higher energy demands due to their motorized components and backwashing mechanisms. Studies indicate that energy consumption ranges from 0.05 to 0.2 kWh per cubic meter of water filtered, depending on flow rate and waste concentration.

To improve energy efficiency in aquaponic systems, various strategies can be employed. These include optimizing the system design by implementing gravity-fed systems where possible to reduce reliance on energy-intensive pumps, as well as optimizing piping layouts and diameters to minimize flow resistance and energy losses. Additionally, selecting energy-efficient mechanical filter equipment, such as drum filters with low energy requirements, can contribute to reducing energy consumption. Furthermore, using solar or wind power to meet the energy demands of mechanical filters, particularly in regions with high renewable-energy availability, can help decrease dependence on conventional energy sources.

4.2.2. Biological Filter

One of the most critical processes inside the biofilter tank of DRAPS is the nitrification process; this is crucial because it involves nitrifying bacteria that can only be found in the biofilter tank [103,104] and are known to play a significant role in nutrient recycling from waste [104,105], like uneaten feeds originating from fish excretion and decomposed organic solids [105,106]. It was reported that fish excretion is among the most nutritious animal waste among all other livestock wastes because it contains 4.47% N and 2.35% P [32]. Moreover, nitrifying bacteria are vital in maintaining water quality through the nitrification process that converts total ammonia nitrogen (TAN) to NO_3, which the plants can absorb [9,106]. Thus, it is imperative to understand the nitrification in DRAPS, especially the different stages of the nitrification process. The biofilter tank is located in the first loop of DRAPS, and it consists of essential components like biofilter materials and a solution rich in fish waste and nitrifying bacteria. Parameters like pH, EC, water temperature, and DO must be optimized to the ideal range to increase the efficiency of the nitrification processes and improve the water quality [9]. This is especially crucial for nitrite-oxidizing bacteria [105,107], which are always affected by changes in the salinity of the water [108,109]. Hence, it is crucial to maintain a stable quality of fish tank water to ensure a steady supply of nutrients to the plants [31].

Nitrification is the essential biological process in the biofilter tank of aquaponics [110], which involves the biological oxidation of NH_3-N to NO_3-N by nitrifying bacteria [5,6,9,111]. The main role of nitrification is to minimize the need for inorganic nutrient input by converting fish waste to nutrients. The outcome of the nitrification process in the first loop of DRAPS is that the water will be freed of ammonia and the nitrite level will be lowered to near-zero [112,113]. In addition, the nitrification process in the biofilter tank has a synergistic interaction with the three parameters of pH, T, and DO. Hence, these parameters should be optimized to ensure the efficiency of the nitrification process. There are two categories of aerobic microbes in the biofilter tank water, each plays a specific role in the nitrification process [93,109]. The first category of nitrifying bacteria involves the oxidation of NH_3-N to NO_2-N and consists of two distinct groups of microbes: (i) ammonia-oxidizing bacteria (AOB), which made up of Beta- and Gammaproteobacteria like *Nitrosomonas*, *Nitrosococcus*, *Nitrosospira*, *Nitrosolobus*, and *Nitrosovibrio* sp.; (ii) ammonia-oxidizing archaea (AOA). The second category of nitrifying bacteria is nitrite-oxidizing bacteria (NOB) such as *Nitrobacter*, *Nitro-coccus*, *Nitrospira*, and *Nitrospina* sp. that convert NO_2-N to NO_3-N [114–116]. Figure 2 illustrates the nitrification process that occurs in the second and third stages of DRAPS.

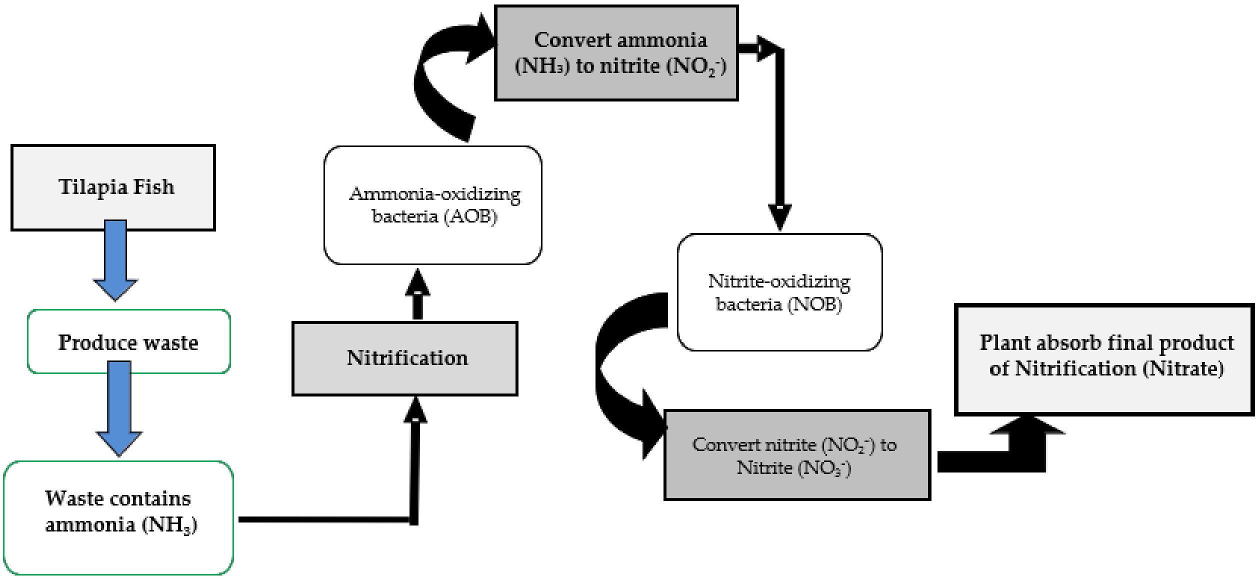

Figure 2. Schematic overview of the nitrification process in aquaponic systems.

Nitrosomonas is a chemoautotrophic bacteria usually found in freshwater, soil, and building surfaces [117], one of the most important genus among AOB. The bacteria from this genus are efficient in the N cycle by limiting carbon dioxide as it contains flagellum in the polar region. In the metabolic process, *Nitrosomonas* oxidizes NH_3-N to NO_2-N and obtains energy from the NH_3-N oxidation process through carbon dioxide fixation in organic compounds. Generally, *Nitrosomonas* prefers a pH range of 6.0 to 9.0 with an optimum temperature of 20 °C to 30 °C [118]. On the other hand, *Nitrobacter* is a Gram-negative, rod-shaped, chemoautotrophic bacteria that converts NO_2-N to NO_3-N in the nitrification process and is one of the most important genus among NOB. Photosynthetic electron transfer for carbon fixation is used to provide the energy required by the bacteria. The optimum pH and temperature for *Nitrobacter* are between 7.3 and 7.5 and 0 °C and 49 °C, respectively [118]. The oxidation of NH_3-N to NO_2-N is the rate-limiting stage in the nitrification process. Jetten et al. [119] stated that the basic oxidation requirements for the nitrification process are provided by anaerobic ammonium oxidation (anammox). In aquaponics, it relies on bacteria to balance the level of NH_3-N in the entire ecosystem. Should the bacteria fail to function properly, the NH_3-N concentration will increase, which will then cause damage to the fish in the ecosystem. Hence, bacteria need to function adequately to lower the level of NH_3-N to as low as possible to ensure a healthy aquaponics system.

4.3. Optimization of the Agronomic Factors

4.3.1. pH

Yep and Zheng [31] reported that pH limitations are the main challenges to optimizing plant production and resource use efficiency in aquaponics. This limitation appeared in the coupled aquaponics system due to fish, microbes, and plants requiring different optimal pH levels. It was reported that the ideal pH for tilapia ranges from 7.0 to 9.0 [120]. The ideal pH for nitrifying bacteria of the genera *Nitrobacter*, *Nitrospira*, and *Nitrosomonas* are 7.5 to 7.8, 8.3, and 7.8, respectively [121–123]. This is to ensure the bacteria can function to its fullest capacity and to maintain the optimal ratio of NH_3 to NH_4^+ in the water; that is, more than 95% of the NH_3-N needs to be in its non-toxic form, which is NH_4^+. This amount of toxic NH_3-N will increase when the pH is higher than 8.0. In addition, the un-ionized form of ammonium is toxic not only to plants but also to fish [124]. For this reason, in coupled aquaponics, the water pH is recommended to be maintained between

7.0 and 7.5 [125] to balance the pH for ammonia biofiltration with the plant's nutritional requirements. This difference in the criteria of pH was the main reason for the precipitation of nutrients in the hydroponic units. Nevertheless, although tilapia can tolerate a wide range of pH, the structure of DRAPS allows for optimizing the pH based on the requirement of the specific tilapia species [125]. This advantage is based on the design of DRPAS that allows the pH of all three parts to be independently controlled. In the soilless subsystem of DRAPS, pH is a crucial factor affecting the nutrient availability plants need for growth, development, and yield. Also, it is a significant factor in maximizing the nutrient use efficiency of aquaponic production systems. The recommended water pH for leafy crops under greenhouse hydroponic production is 5.5–5.8 or 5.8–6.4 [125]. The pH of 5.8 is considered best for optimal nutrient availability in hydroponics for leafy crops such as lettuce and basil. Tyson et al. [123] found that the concentrations of Ca, P, Fe, and Mn in the nutrient solution declined as pH increased. Therefore, optimized pH is a basic requirement for improving the uptake of the nutrients from the solution and prevents the precipitation of iron (Fe^{2+}), manganese (Mn^{2+}), phosphate (${PO_4}^{3-}$), calcium (Ca^{2+}), and magnesium (Mg^{2+}) into insoluble and unavailable salts that may occur at water pH levels > 7.0 [125].

In DRAPS, there is an opportunity to control the pH within the recommended range to avoid restricting the availability of the nutritional requirements for the plant. Therefore, under DRAPS and due to separate loops, the ideal pH can be optimized for various crops. For leafy crops such as lettuce, basil, spinach, and parsley, an ideal pH range of 5.5–5.8 can be achieved [27]. For fruiting crops such as tomatoes, cucumbers, peppers, and strawberries, the pH can also be optimized to an ideal range. Under DRAPS, the optimal pH range for tomato cultivation can be adjusted to 5.8–6.3 [4], 5.5–6.5 [27], 6.0–6.5 [4], and 5.8–6.4. Cucumbers are particularly sensitive to pH fluctuations, with iron and manganese availability significantly affected at pH values above 6.5. In DRAPS, the pH can be optimized to an ideal range of 5.5–6.5 [125] and 5.8–6.0 to ensure optimal growth and yield. For bell peppers and other Capsicum varieties, the pH can be adjusted to an ideal range of 5.5–6.0 [27], 5.8–6.3, and 6.0–6.5. Ropokis et al. [126] demonstrated that pepper plants exhibit enhanced calcium uptake and a reduced incidence of blossom-end rot when the pH is maintained within these ranges. Strawberry plants also require specific pH conditions for optimal growth and fruit production, as indicated by ranges of 5.5–6.2 and 5.8–6.2 [4,27,125]. Thus, optimizing the pH in DRAPS has prevented critical elements like iron from experiencing minimal absorption effectiveness. Therefore, maintaining an optimized pH in the hydroponic unit has increased the efficiency of DRAPS by enhancing nutrient availability and increasing yield. Additionally, the rooting zone pH in hydroponics is vital for plant growth as the availability of toxic ion species is closely connected with this parameter through a broad range of processes, including nutrient availability and uptake.

4.3.2. Optimization of the Root Zone Temperature

One of the significant advantages of DRAPS over CRAPS is the efficiency in optimizing the root zone temperature (RZT). The RZT is a vital factor that affects crop growth [127–129], translocation from the nutrient solution [130], and the photosynthesis process. Marschner [130] reported that the RZT affects root growth and root-cell differentiation [131,132]; in addition, the RZT affects the uptake of nutrients like N and results in the accumulation of N. Li et al. [133] supported the effects of the RZT on the growth, nutrient uptake, and contents of lettuce. They reported that the fresh yield of lettuce was significantly reduced at a higher RZT, which was 30 to 35 °C, compared to the RZT at 25 °C. The maximum dry mass of lettuce was obtained at 24 °C, which is the optimal temperature for N uptake. The RZT can be optimized efficiently in DRAPS as the crops are located in the second loop, which is separated from the fish and bacteria culture. In short, DRAPS has the advantage of optimizing the RZT to obtain optimal N uptake, which is essential for the photosynthesis process. In addition, He et al. [132] reported that the RZT at 20 °C was optimal for leafy crops like lettuce as this temperature is optimal for the uptake of N and other elements. In general, the ideal RZT for leafy crops ranges from 20 to 25 °C [132]. At this range, the metabolic activity in roots is optimal, promoting nutrient absorption and water uptake. A lower RZT (<15 °C) may reduce root activity and hinder nutrient transport, while a higher RZT (>30 °C) can lead to reduced yields due to oxygen depletion. Under DRAPS, fruity crops such as tomato, cucumber, and pepper generally require a slightly higher RZT compared to leafy greens, ranging from 22 to 27 °C, with an ideal range around 24–26 °C. This range ensures the efficient uptake of nutrients critical for fruit development, such as Ca and K. At an RZT exceeding 28 °C, fruiting crops may exhibit issues—such as blossom-end rot in tomatoes—due to reduced calcium uptake. Moreover, the DO in DRAPS using the NFT and DWC will not be affected at the optimal RZT. Finally, optimizing the RZT is critical for achieving maximum growth and yield efficiency in DRAPS. For leafy crops, maintaining an RZT of 20–25 °C enhances nitrogen uptake and biomass production. For fruiting crops, an RZT of 22–27 °C ensures optimal nutrient uptake and fruit quality. The ability to regulate RZT independently in DRAPS provides a distinct advantage, enabling precise adjustments tailored to the specific needs of different crop types.

4.3.3. Optimization of the Flow Rate

An optimized flow rate is one of the significant advantages of DRAPS. The two-loop structure in DRAPS allows the flow rate in each loop to be independent. In the first loop of DRAPS, the nutrients will flow by gravity from the fish tank, mechanical tanks, biofilter, collecting tank, and lastly, to the sump tank. At the same time, the nutrients will flow in a one-way direction from the first loop to the second loop, depending on the plant's nutrient requirements. Endut et al. [134] stated that an optimized flow rate in the first loop could increase the efficiency of the BP and the ideal flow rate is 9.2 m^3 day^{-1} or 6.4 L/min. At the same time, Resh [27] stated that the flow rate of the nutrient solution in the second loop in hydroponics with the NFT could be optimized independently from the first loop to an ideal flow rate of 1 to 2 L/min. An ideal flow rate in the NFT is essential for the plant's roots to absorb all the required elements as it ensures proper contact time between the roots and nutrient solutions. The NFT is more sensitive to the flow rate than the substrate culture and DWC methods. The substrate culture is less susceptible to the flow rate because the inert substrates such as peat moss and tuff in MBC [135–137] have water-holding capacity and, hence, are able to hold the nutrients for the roots. In contrast, DWC is less dependent on water flow due to its floating system. Resh [27] recommended flow rates at 2 to 3 L/min for hydroponic systems with DWC. Under DRAPS, flow rate optimization is crucial for nutrient delivery, water use efficiency, and nutrient use efficiency. Resh [27] reported that the rates of 1–2 L/min are recommended to ensure sufficient contact time between roots and the nutrient solution for an NFT system for leafy crops such as lettuce. This enhances nutrient uptake efficiency and supports optimal growth and yield [27]. While DWC systems are less dependent on flow rate due to their floating design, maintaining flow rates of 2–3 L/min is suggested to ensure adequate nutrient distribution and prevent stagnation for leafy crops such as lettuce, parsley, and spinach. The substrate culture method is less sensitive to flow rate due to using a drip irrigation system. In DRAPS, the dual-loop design allows for the independent optimization of flow rates in the fish and plant loops, ensuring efficient nutrient delivery tailored to the specific needs of the plants. In conclusion, an optimized nutrient solution flow rate in systems with the NFT is crucial for the uptake of elements to ensure optimal growth, development, and yield. In addition, it significantly affects both water use efficiency and nutrient use efficiency.

5. Conclusions

This review paper concludes that the two-circulation structure is a key advantage of DRAPS as the two production units in DRAPS are independent. DRAPS plays a powerful and important role in the future of sustainable food production, especially for food and water security in countries that lack water and land resources. The levels of macronutrients and micronutrients in DRAPS can be optimized based on the needs of the plants to increase the quality and yield without affecting the fish and nitrifying bacteria cultures. Moreover, DRAPS allows for the application of urea to the APS as a supplementary N source without affecting fish welfare. DRAPS can apply the ideal Fe concentration to its hydroponic unit without affecting the fish and microbe cultures. Therefore, it is the only aquaponics that can avoid Fe toxicity to the fish and microbes, thanks to its two-loop structure. One of the most crucial advantages of DRAPS is that it allows for the conditions and imbalances to be controlled and adjusted independently for the fish, microbes, and plants. It can be concluded that DRAPS can solve the pH horticultural challenges and increase nutrient availability based on its advantage of two independent loops. In addition, DRAPS can optimize pH and other agronomic factors such as root zone temperature and water flow.

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References

1. Rakocy, J.E. Aquaponics—Integrating fish and plant culture. In *Aquaculture Production Systems*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2012; pp. 344–386. [CrossRef]
2. Timmons, M.B.; Ebeling, J.M. *Recirculating Aquaculture*, 3rd ed.; Ithaca Publishing Company: Reading, UK, 2013. Available online: https://www.abebooks.com/9780971264656/Recirculating-Aquaculture-3rd-Edition-Michael-0971264651/plp (accessed on 17 March 2020).
3. Love, D.C.; Fry, J.P.; Li, X.; Hill, E.S.; Genello, L.; Semmens, K.; Thompson, R.E. Commercial aquaponics production and profitability: Findings from an international survey. *Aquaculture* **2015**, *435*, 67–74. [CrossRef]
4. Jones, J.B. *Hydroponics: A Practical Guide for the Soilless Grower*; CRC Press: Boca Raton, FL, USA, 2005.
5. Wongkiew, S.; Hu, Z.; Chandran, K.; Lee, J.W.; Khanal, S.K. Nitrogen transformations in aquaponic systems: A review. *Aquac. Eng.* **2017**, *76*, 9–19. [CrossRef]
6. Wongkiew, S.; Popp, B.N.; Kim, H.J.; Khanal, S.K. Fate of nitrogen in floating-raft aquaponic systems using natural abundance nitrogen isotopic compositions. *Int. Biodeterior. Biodegrad.* **2017**, *125*, 24–32. [CrossRef]
7. Junge, R.; König, B.; Villarroel, M.; Komives, T.; Jijakli, M.H. Strategic Points in Aquaponics. *Water* **2017**, *9*, 182. [CrossRef]
8. Rakocy, J.E.; Masser, M.P.; Losordo, T.M. Recirculating aquaculture tank production systems: Aquaponics—Integrating fish and plant culture. *SRAC Publ.* **2006**, *454*, 1–16.
9. Somerville, C.; Cohen, M.; Pantanella, E.; Stankus, A.; Lovatelli, A. *Small-Scale Aquaponic Food Production. Integrated Fish and Plant Farming*; FAO Fisheries and Aquaculture Technical Paper No. 589; FAO: Rome, Italy, 2014; 262p.
10. Pérez-Urrestarazu, L.; Lobillo-Eguíbar, J.; Fernández-Cañero, R.; Fernández-Cabanás, V.M. Suitability and optimization of FAO's small-scale aquaponics systems for joint production of lettuce (*Lactuca sativa*) and fish (*Carassius auratus*). *Aquac. Eng.* **2019**, *85*, 129–137. [CrossRef]
11. Maucieri, C.; Nicoletto, C.; Zanin, G.; Birolo, M.; Trocino, A.; Sambo, P.; Borin, M.; Xiccato, G. 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* **2019**, *14*, e0217561. [CrossRef]

12. Zhu, Z.; Yogev, U.; Keesman, K.J.; Gross, A. Promoting circular economy: Comparison of novel coupled aquaponics with anaerobic digestion and conventional aquaponic systems on nutrient dynamics and sustainability. *Resour. Conserv. Recycl.* **2024**, *208*, 107716. [CrossRef]
13. Kloas, W.; Groß, R.; Baganz, D.; Graupner, J.; Monsees, H.; Schmidt, U.; Staaks, G.; Suhl, J.; Tschirner, M.; Wittstock, B.; et al. A new concept for aquaponic systems to improve sustainability, increase productivity, and reduce environmental impacts. *Aquac. Environ. Interact.* **2015**, *7*, 179–192. [CrossRef]
14. Delaide, B.; Goddek, S.; Gott, J.; Soyeurt, H.; Jijakli, M. Lettuce (*Lactuca sativa* L. var. Sucrine) growth performance in complemented aquaponic solution outperforms hydroponics. *Water* **2016**, *8*, 467. [CrossRef]
15. Suhl, J.; Dannehl, D.; Kloas, W.; Baganz, D.; Jobs, S.; Scheibe, G.; Schmidt, U. Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics. *Agric. Water Manag.* **2016**, *178*, 335–344. [CrossRef]
16. Monsees, H.; Kloas, W.; Wuertz, S. Decoupled systems on trial: Eliminating bottlenecks to improve aquaponic processes. *PLoS ONE* **2017**, *12*, e0183056. [CrossRef]
17. Suhl, J.; Dannehl, D.; Baganz, D.; Schmidt, U.; Kloas, W. An innovative suction filter device reduces nitrogen loss in double recirculating aquaponic systems. *Aquac. Eng.* **2018**, *82*, 63–72. [CrossRef]
18. Suhl, J.; Dannehl, D.; Zechmeister, L.; Baganz, D.; Kloas, W.; Lehmann, B.; Scheibe, G.; Schmidt, U. Prospects and challenges of double recirculating aquaponic systems (DRAPS) for intensive plant production. *Acta Hortic.* **2018**, *1227*, 449–456. [CrossRef]
19. Aslanidou, M.; Elvanidi, A.; Mourantian, A.; Levizou, E.; Mente, E.; Katsoulas, N. Evaluation of productivity and efficiency of a large-scale coupled or decoupled aquaponic system. *Sci. Hortic.* **2024**, *337*, 113552. [CrossRef]
20. Aslanidou, M.; Elvanidi, A.; Mourantian, A.; Levizou, E.; Mente, E.; Katsoulas, N. Nutrients Use Efficiency in Coupled and Decoupled Aquaponic Systems. *Horticulturae* **2023**, *9*, 1077. [CrossRef]
21. Rodgers, D.; Won, E.; Timmons, M.B.; Mattson, N. Complementary nutrients in decoupled aquaponics enhance basil performance. *Horticulturae* **2022**, *8*, 111. [CrossRef]
22. Timmons, M.B.; Ebeling, J.M.; Wheaton, F.W.; Summerfelt, S.T.; Vinci, B.J. *Recirculating Aquaculture Systems*, 2nd ed.; Northeastern Regional Aquaculture Center Publication 01-002; Cayuga Aqua Ventures: Ithaca, NY, USA, 2002.
23. Goddek, S.; Espinal, C.A.; Delaide, B.; Jijakli, M.H.; Schmautz, Z.; Wuertz, S.; Keesman, K.J. Navigating towards decoupled aquaponic systems: A system dynamics design approach. *Water* **2016**, *8*, 303. [CrossRef]
24. Monsees, H.; Suhl, J.; Paul, M.; Kloas, W.; Dannehl, D.; Würtz, S. Lettuce (*Lactuca sativa*, variety Salanova) production in decoupled aquaponic systems: Same yield and similar quality as in conventional hydroponic systems but drastically reduced greenhouse gas emissions by saving inorganic fertilizer. *PLoS ONE* **2019**, *14*, e0218368. [CrossRef]
25. Blanchard, C.; Wells, D.E.; Pickens, J.M.; Blersch, D.M. Effect of pH on Cucumber Growth and Nutrient Availability in a Decoupled Aquaponic System with Minimal Solids Removal. *Horticulturae* **2020**, *6*, 10. [CrossRef]
26. Maucieri, C.; Nicoletto, C.; Junge, R.; Schmautz, Z.; Sambo, P.; Borin, M. Hydroponic systems and water management in aquaponics: A review. *Ital. J. Agron.* **2017**, *13*, 1012. [CrossRef]
27. Resh, H.M. *Hydroponic Food Production*; Taylor & Francis: London, UK, 2022; ISBN 9781003133254.
28. Lennard, W.A.; Leonard, B.V. A Comparison of Three Different Hydroponic Subsystems (gravel bed, floating and nutrient film technique) in an Aquaponic Test System. *Aquac. Int.* **2006**, *14*, 539–550. [CrossRef]
29. Pattillo, D.A. An overview of aquaponic systems: Hydroponic components. *NRAC Tech. Bull. Ser.* **2017**, *19*, 1–10.
30. Schmautz, Z.; Loeu, F.; Liebisch, F.; Graber, A.; Mathis, A.; Griessler Bulc, T.; Junge, R. Tomato productivity and quality in aquaponics: Comparison of three hydroponic methods. *Water* **2016**, *8*, 533. [CrossRef]
31. Yep, B.; Zheng, Y. Aquaponic trends and challenges—A review. *J. Clean. Prod.* **2019**, *228*, 1586–1599. [CrossRef]
32. Khiari, Z.; Kaluthota, S.; Savidov, N. Phosphorus Delays the Onset of Nitrification during Aerobic Digestion of Aquaculture/Aquaponic Solid Waste. *Biochem. Eng. J.* **2020**, *155*, 107493. [CrossRef]
33. Nozzi, V.; Graber, A.; Schmautz, Z.; Mathis, A.; Junge, R. Nutrient management in aquaponics: Comparison of three approaches for cultivating lettuce, mint and mushroom herb. *Agronomy* **2018**, *8*, 27. [CrossRef]
34. Yavuzcan Yildiz, H.; Robaina, L.; Pirhonen, J.; Mente, E.; Domínguez, D.; Parisi, G. Fish welfare in aquaponic systems: Its relation to water quality with an emphasis on feed and faeces—A review. *Water* **2017**, *9*, 13. [CrossRef]
35. Rakocy, J.; Shultz, R.C.; Bailey, D.S.; Thoman, E.S. Aquaponic production of tilapia and basil: Comparing a batch and staggered cropping system. *Acta Hortic. (ISHS)* **2004**, *648*, 63–69. [CrossRef]
36. Al Tawaha, A.R.; Wahab, P.E.M.; Jaafar, H.B.; Zuan, A.T.K.; Hassan, M.Z. Effects of fish stocking density on water quality, growth performance of tilapia and yield of butterhead Lettuce grown in decoupled recirculation aquaponic systems. *J. Ecol. Eng.* **2021**, *22*, 8–19. [CrossRef]
37. Al Tawaha, A.R.; Megat Wahab, P.E.; Binti Jaafar, H.; Kee Zuan, A.T.; Hassan, M.Z.; Al-Tawaha, A.R.M. Yield and nutrients leaf content of butterhead lettuce (*Lactuca sativa*) in response to fish nutrient solution in a small scale of aquaponic systems. *Ecol. Eng. Environ. Technol.* **2021**, *22*, 85–94. [CrossRef]

38. Villarroel, M.; Alvariño, J.M.R.; Duran, J.M. Aquaponics: Integrating fish feeding rates and ion waste production for strawberry hydroponics. *Span. J. Agric. Res.* **2011**, *9*, 537. [CrossRef]
39. Seawright, D.E.; Stickney, R.R.; Walker, R.B. Nutrient dynamics in integrated aquaculture–hydroponics systems. *Aquaculture* **1998**, *160*, 215–237. [CrossRef]
40. Sonneveld, C.; Voogt, W.; Sonneveld, C.; Voogt, W. *Plant Nutrition in Future Greenhouse Production*; Springer: Dordrecht, The Netherlands, 2009; pp. 393–403.
41. Roy, R.N.; Finck, A.; Blair, G.J.; Tandon, H.L.S. Plant nutrition for food security. A guide for integrated nutrient management. *FAO Fertil. Plant Nutr. Bull.* **2006**, *16*, 201–214.
42. Ferrarezi, R.S.; Bailey, D.S. Basil performance evaluation in aquaponics. *HortTechnology* **2019**, *29*, 85–93. [CrossRef]
43. Yang, T.; Kim, H.J. Comparisons of nitrogen and phosphorus mass balance for tomato-, basil-, and lettuce-based aquaponic and hydroponic systems. *J. Clean. Prod.* **2020**, *274*, 122619. [CrossRef]
44. Hung, H.C.; Joshipura, K.J.; Jiang, R.; Hu, F.B.; Hunter, D.; Smith-Warner, S.A.; Colditz, G.A.; Rosner, B.; Spiegelman, D.; Willett, W.C. Fruit and vegetable intake and risk of major chronic disease. *J. Natl. Cancer Inst.* **2004**, *96*, 1577–1584. [CrossRef] [PubMed]
45. Santamaria, P. Nitrate in vegetables: Toxicity, content, intake and EC regulation. *J. Sci. Food Agric.* **2006**, *86*, 10–17. [CrossRef]
46. Vahed, S.; Mosafa, L.; Mirmohammadi, M.; Lakzadeh, L. Effect of some processing methods on nitrate changes in different vegetables. *J. Food Meas. Charact.* **2015**, *9*, 241–247. [CrossRef]
47. Ikeda, H.; Osawa, T. Lettuce growth as influenced by N source and temperature of the nutrient solution. In Proceedings of the 6th International Congress on Soilless Culture, Lunteren, The Netherlands, 29 April–5 May 1984; ISOSC: Wageningen, The Netherlands.
48. Khan, N.K.; Watanabe, Y. Effect of different concentrations of urea with or without Ni addition on spinach (*Spinacia oleracea* L.) growth under hydroponic culture. *Soil Sci. Plant Nutr.* **1999**, *45*, 569–575. [CrossRef]
49. Sambo, P.; Nicoletto, C.; Giro, A.; Pii, Y.; Valentinuzzi, F.; Mimmo, T.; Lugli, P.; Orzes, G.; Mazzetto, F.; Astolfi, S.; et al. Hydroponic solutions for soilless production systems: Issues and opportunities in a smart agriculture perspective. *Front. Plant Sci.* **2019**, *10*, 923. [CrossRef]
50. Gerendas, J.; Sattelmacher, B. Significance of N source (urea vs. NH4N03) and Ni supply for growth, urease activity and nitrogen metabolism of zucchini (*Cueurbita pepo* convar. giromontiina). *Plant Soil* **1997**, *196*, 217–222. [CrossRef]
51. Dixon, N.E.; Hinds, J.A.; Fihelly, A.K.; Gazzola, C.; Winzor, D.J.; Blakeley, R.L.; Zerner, B. Jack bean urease (EC 3.5.1.5). IV. The molecular size and the mechanism of inhibition by hydroxamic acids. Spectrophotometric titration of enzymes with reversible inhibitors. *Can. J. Biochem.* **1980**, *58*, 1323–1334. [CrossRef]
52. Witte, C.P. Urea metabolism in plants. *Plant Sci.* **2011**, *180*, 431–438. [CrossRef] [PubMed]
53. Marschner, H. *Mineral Nutrition of Higher Plants*, 2nd ed.; Academic Press: London, UK, 1995.
54. Kabata-Pendias, A.; Pendias, H. *Trace Elements in Soils and Plants*; CRC Press: Washington, DC, USA, 2001.
55. Assunção, A.G.; Bookum, W.M.; Nelissen, H.J.; Vooijs, R.; Schat, H.; Ernst, W.H. Differential metal-specific tolerance and accumulation patterns among Thlaspi caerulescens populations originating from different soil types. *New Phytol.* **2003**, *159*, 411–419. [CrossRef] [PubMed]
56. Baran, E.J. Nickel and its role in plant physiology. In *Molecular Physiology of Abiotic Stresses in Plant Productivity*; Scientific Publishers: Jodhpur, India, 2018; pp. 291–313.
57. Ahmad, M.S.A.; Ashraf, M. Essential Roles and Hazardous Effects of Nickel in Plants. In *Reviews of Environmental Contamination and Toxicology*; Whitacre, D.M., Ed.; Springer: New York, NY, USA, 2012; Volume 214, pp. 125–167.
58. Yusuf, M.; Fariduddin, Q.; Hayat, S.; Ahmad, A. Nickel: An overview of uptake, essentiality and toxicity in plants. *Bull. Environ. Contam. Toxicol.* **2011**, *86*, 1–17. [CrossRef] [PubMed]
59. Seregin, I.V.; Kozhevnikova, A.D. Physiological role of nickel and its toxic effects on higher plants. *Russ. J. Plant Physiol.* **2006**, *53*, 257–277. [CrossRef]
60. Chen, C.; Huang, D.; Liu, J. Functions and toxicity of nickel in plants: Recent advances and prospects. *Clean* **2009**, *37*, 304–313. [CrossRef]
61. Panda, G.C.; Das, S.K.; Bandopadhyay, T.S.; Guha, A.K. Adsorption of nickel on husk of Lathyrus sativus: Behavior and binding mechanism. *Colloids Surf. B Biointerfaces* **2007**, *57*, 135–142. [CrossRef] [PubMed]
62. Temp, G.A. *Nickel in Plants and Its Toxicity: Ustoichivost'k Tyazhelym Metallam Dikorastushchikh Vidov (Resistance of wild Species to Heavy Metals)*; Alekseeva-Popova, N.V., Ed.; Lenuprizdat: Leningrad, Russia, 1991; pp. 139–146.
63. Shaw, B.P.; Sahu, S.K.; Mishra, R.K. Heavy metal inducedoxidative damage in terrestrial plants. In *Heavy Metal Stress in Plants: From Biomolecules to Ecosystems*; Prasad, M.N.V., Ed.; Narosa Publishing House: New Delhi, India, 2004; pp. 84–126.
64. Molas, J. Changes of chloroplast ultrastructure and total chlorophyll concentration in cabbage leaves caused by excess of organic Ni (II) complexes. *Environ. Exp. Bot.* **2002**, *47*, 115–126. [CrossRef]
65. Gajewska, E.; Wielanek, M.; Bergier, K.; Skłodowska, M. Nickel-induced depression of nitrogen assimilation in wheat roots. *Acta Physiol. Plant* **2009**, *31*, 1291–1300. [CrossRef]

66. Rubio, M.P.; Correa, K.M.; Ramesh, V.; MacCollin, M.M.; Jacoby, L.B.; von Deimling, A.; Gusella, J.F.; Louis, D.N. Analysis of the neurofibromatosis 2 gene in human ependymomas and astrocytomas. *Cancer Res.* **1994**, *54*, 45–47. [PubMed]
67. Barceló, J.U.A.N.; Poschenrieder, C. Plant water relations as affected by heavy metal stress: A review. *J. Plant Nutr.* **1990**, *13*, 1–37. [CrossRef]
68. Labidi, O.; Kouki, R.; Hidouri, S.; Bouzahouane, H.; Caçador, I.; Pérez-Clemente, R.M.; Sleimi, N. Impact of nickel toxicity on growth, fruit quality and antioxidant response in zucchini squash (*Cucurbita pepo* L.). *Plants* **2024**, *13*, 2361. [CrossRef] [PubMed]
69. Van Assche, F.; Clijsters, H. Effects of metals on enzyme activity in plants. *Plant Cell Environ.* **1990**, *13*, 195–206. [CrossRef]
70. Khoshgoftarmanesh, A.H.; Hosseini, F.; Afyuni, M. Nickel supplementation effect on the growth, urease activity and urea and nitrate concentrations in lettuce supplied with different nitrogen sources. *Sci. Hortic.* **2011**, *130*, 381–385. [CrossRef]
71. Cerozi, B.D.S.; Fitzsimmons, K. Phosphorus dynamics modeling and mass balance in an aquaponics system. *Agric. Syst.* **2017**, *153*, 94–100. [CrossRef]
72. Adler, P.; Takeda, F.; Glenn, D.; Summerfelt, S. Utilizing byproducts to enhance aquaculture sustainability. *World Aquac.* **1996**, *27*, 24–26.
73. Graber, A.; Junge, R. Aquaponic Systems: Nutrient recycling from fish wastewater by vegetable production. *Desalination* **2009**, *246*, 147–156. [CrossRef]
74. Harika, N.; Verma, A.K.; Krishnani, K.K.; Hittinahalli, C.M.; Reddy, R.; Pai, M. Supplementation of potassium in aquaculture wastewater and its effect on growth performance of basil (*Ocimum basilicumin* L) and pangasius (*Pangasianodon hypophthalmus*) in NFT-based aquaponics. *Sci. Hortic.* **2024**, *323*, 112521. [CrossRef]
75. Gajdanowicz, P.; Michard, E.; Sandmann, M.; Rocha, M.; Corrêa, L.G.G.; Ramírez-Aguilar, S.J.; Gomez-Porras, J.L.; González, W.; Thibaud, J.B.; van Dongen, J.T.; et al. Potassium (K+) gradients serve as a mobile energy source in plant vascular tissues. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 864–869. [CrossRef] [PubMed]
76. Gierth, M.; Mäser, P. Potassium transporters in plants–involvement in K+ acquisition, redistribution and homeostasis. *FEBS Lett.* **2007**, *581*, 2348–2356. [CrossRef]
77. Farooq, A.; Verma, A.K.; Hittinahalli, C.M.; Harika, N.; Pai, M. Iron supplementation in aquaculture wastewater and its effect on the growth of spinach and pangasius in nutrient film technique based aquaponics. *Agric. Water Manag.* **2022**, *277*, 108126. [CrossRef]
78. Kasozi, N.; Tandlich, R.; Fick, M.; Kaiser, H.; Wilhelmi, B. Iron supplementation and management in aquaponic systems: A review. *Aquac. Rep.* **2019**, *15*, 100221. [CrossRef]
79. Rout, G.R.; Sahoo, S. Role of iron in plant growth and metabolism. *Rev. Agric. Sci.* **2015**, *3*, 1–24. [CrossRef]
80. Zuo, Y.; Zhang, F. Soil and crop management strategies to prevent iron deficiency in crops. *Plant Soil* **2011**, *339*, 83–95. [CrossRef]
81. Samaranayake, P.; Peiris, B.D.; Dssanayake, S. Effect of excessive ferrous (Fe2+) on growth and iron content in rice (*Oryza sativa*). *Int. J. Agric. Biol.* **2012**, *14*, 296–298.
82. Kosegarten, H.; Wilson, G.H.; Esch, A. The effect of nitrate nutrition on iron chlorosis and leaf growth in sunflower (*Helianthus annuus* L.). *Eur. J. Agron.* **1998**, *8*, 283–292. [CrossRef]
83. Vigani, G. Discovering the role of mitochondria in the iron deficiency-induced metabolic responses of plants. *J. Plant Physiol.* **2012**, *169*, 1–11. [CrossRef] [PubMed]
84. Álvarez-Fernández, A.; García-Laviña, P.; Fidalgo, C.; Abadía, J.; Abadía, A. Foliar fertilization to control iron chlorosis in pear (*Pyrus communis* L.) trees. *Plant Soil* **2004**, *263*, 5–15. [CrossRef]
85. Borowski, E.; Michalek, S. The effect of foliar fertilization of French bean with iron salts and urea on some physiological processes in plants relative to iron uptake and translocation in leaves. *Acta Sci. Polonorum. Hortorum Cultus* **2011**, *10*, 183–193.
86. Roosta, H.R.; Mohsenian, Y. Effects of foliar spray of different Fe sources on pepper (*Capsicum annum* L.) plants in aquaponic system. *Sci. Hortic.* **2012**, *146*, 182–191. [CrossRef]
87. Chen, D.; Martell, A.E.; McManus, D. Studies on the mechanism of chelate degradation in iron-based, liquid redox H2S removal processes. *Can. J. Chem.* **1995**, *73*, 264–274. [CrossRef]
88. Fernàndez, V.; Ebert, G.; Winkelmann, G. The use of microbial siderophores for foliar iron application studies. *Plant Soil* **2005**, *272*, 245–252. [CrossRef]
89. Chatzistathis, T. *Micronutrient Deficiency in Soils and Plants*; Bentham Science Publishers: Oak Park, IL, USA, 2014; pp. 38–55.
90. Godsey, C.B.; Schmidt, J.P.; Schlegel, A.J.; Taylor, R.K.; Thompson, C.R.; Gehl, R.J. Correcting iron deficiency in corn with seed row–applied iron sulfate. *Agron. J.* **2003**, *95*, 160–166. [CrossRef]
91. Vempati, R.K.; Loeppert, R.H. Chemistry and mineralogy of Fe-containing oxides and layer silicates in relation to plant available iron. *J. Plant Nutr.* **1988**, *11*, 1557–1574. [CrossRef]
92. Radzki, W.; Gutierrez Mañero, F.J.; Algar, E.; Lucas García, J.A.; García-Villaraco, A.; Ramos Solano, B. Bacterial siderophores efficiently provide iron to iron-starved tomato plants in hydroponics culture. *Antonie Van Leeuwenhoek* **2013**, *104*, 321–330. [CrossRef] [PubMed]

93. Bartelme, R.P.; McLellan, S.L.; Newton, R.J. Freshwater recirculating aquaculture system operations drive biofilter bacterial community shifts around a stable nitrifying consortium of ammonia-oxidizing archaea and comammox Nitrospira. *Front. Microbiol.* **2017**, *8*, 101. [CrossRef] [PubMed]
94. Rakocy, J.E.; Bailey, D.S.; Shultz, R.C.; Thoman, E.S. Update on Tilapia and vegetable production in the UVI aquaponic system. In *New Dimensions in Farmed Tilapia*; Creative Unlimited: Old Bridge, NJ, USA, 2004.
95. Roosta, H.R.; Hamidpour, M. Effects of foliar application of some macro- and micro-nutrients on tomato plants in aquaponic and hydroponic systems. *Sci. Hortic.* **2011**, *129*, 396–402. [CrossRef]
96. Roosta, H.R.; Hamidpour, M. Mineral nutrient content of tomato plants in aquaponic and hydroponic systems: Effect of foliar application of some macro-and micro-nutrients. *J. Plant Nutr.* **2013**, *36*, 2070–2083. [CrossRef]
97. Roosta, H.R.; Mohsenian, Y. Alleviation of alkalinity-induced Fe deficiency in eggplant (*Solanum melongena* L.) by foliar application of different Fe sources in recirculating system. *J. Plant Nutr.* **2015**, *38*, 1768–1786. [CrossRef]
98. Hu, Z.; Lee, J.W.; Chandran, K.; Kim, S.; Brotto, A.C.; Khanal, S.K. Effect of plant species on nitrogen recovery in aquaponics. *Bioresour. Technol.* **2015**, *188*, 92–98. [CrossRef] [PubMed]
99. Ru, D.; Liu, J.; Hu, Z. Improvement of aquaponic performance through micro- and macro-nutrient addition. *Environ. Sci. Pollut. Res.* **2017**, *24*, 16328–16335. [CrossRef] [PubMed]
100. Anderson, T.S.; De Villiers, D.; Timmons, M.B. Growth and tissue elemental composition response of butterhead lettuce (*Lactuca sativa*, cv. Flandria) to hydroponic and aquaponic conditions. *Horticulturae* **2017**, *3*, 43. [CrossRef]
101. Nelson, R. *Aquaponic Food Production: Growing Fish and Vegetables for Food and Profit*; Nelson and Pade, Inc.: Montello, WI, USA, 2008.
102. Timmons, N.; Timmons, M.B.; Ebeling, J.M. Recirculating aquaculture system (RAS) technologies. *Aquaculture Magazine*, 2006; 32–39.
103. Gutierrez-Wing, M.T.; Malone, R.F. Biological filters in aquaculture: Trends and research directions for freshwater and marine applications. *Aquac. Eng.* **2006**, *34*, 163–171. [CrossRef]
104. Ebeling, J.M.; Timmons, M.B.; Bisogni, J.J. Engineering analysis of the stoichiometry of photoautotrophic, autotrophic, and heterotrophic removal of ammonia–nitrogen in aquaculture systems. *Aquaculture* **2006**, *257*, 346–358. [CrossRef]
105. Kuhn, D.D.; Drahos, D.D.; Marsh, L.; Flick Jr, G.J. Evaluation of nitrifying bacteria product to improve nitrification efficacy in recirculating aquaculture systems. *Aquac. Eng.* **2010**, *43*, 78–82. [CrossRef]
106. Stewart, N.T.; Boardman, G.D.; Helfrich, L.A. Characterization of nutrient leaching rates from settled rainbow trout (*Oncorhynchus mykiss*) sludge. *Aquac. Eng.* **2006**, *35*, 191–198. [CrossRef]
107. Singh, S.; Ebeling, J.; Wheaton, F. Water quality trials in four recirculating aquacultural system configurations. *Aquac. Eng.* **1999**, *20*, 75–84. [CrossRef]
108. Malone, R.F.; Pfeiffer, T.J. Rating fixed film nitrifying biofilters used in recirculating aquaculture systems. *Aquac. Eng.* **2006**, *34*, 389–402. [CrossRef]
109. Emparanza, E.J. Problems affecting nitrification in commercial RAS with fixed-bed biofilters for salmonids in Chile. *Aquac. Eng.* **2009**, *41*, 91–96. [CrossRef]
110. Prinsloo, J.F.; Roets, W.; Theron, J.; Hoffman, L.C.; Schoonbee, H.J. Changes in some water quality conditions in recycling water using three types of biofiltration systems during the production of the sharptooth catfish *Clarias gariepinus* (Burchell). Part I: Relative efficiency in the breakdown of nitrogenous wastes by the different biofiltration units. *Water SA* **1999**, *25*, 239–252.
111. Shan, H.; Obbard, J. Ammonia removal from prawn aquaculture water using immobilized nitrifying bacteria. *Appl. Microbiol. Biotechnol.* **2001**, *57*, 791–798.
112. Mnyoro, M.S.; Munubi, R.N.; Pedersen, L.-F.; Chenyambuga, S.W. Evaluation of biofilter performance with alternative local biomedia in pilot scale recirculating aquaculture systems. *J. Clean. Prod.* **2022**, *366*, 132929. [CrossRef]
113. Avnimelech, Y. Bio-filters: The need for an new comprehensive approach. *Aquac. Eng.* **2006**, *34*, 172–178. [CrossRef]
114. Kowalchuk, G.A.; Stephen, J.R. Ammonia-oxidizing bacteria: A model for molecular microbial ecology. *Annu. Rev. Microbiol.* **2001**, *55*, 485–529. [CrossRef] [PubMed]
115. Gerardi, M.H. *Nitrification and Denitrification in the Activated Sludge Process*; John Wiley & Sons: Hoboken, NJ, USA, 2002.
116. Panuvatvanich, A.; Koottatep, T.; Kone, D. Influence of sand layer depth and percolate impounding regime on nitrogen transformation in vertical-flow constructed wetlands treating faecal sludge. *Water Res.* **2009**, *43*, 2623–2630. [CrossRef]
117. Li, M.; Cao, H.; Hong, Y.; Gu, J.D. Spatial distribution and abundances of ammonia-oxidizing archaea (AOA) and ammonia-oxidizing bacteria (AOB) in mangrove sediments. *Appl. Microbiol. Biotechnol.* **2011**, *89*, 1243–1254. [CrossRef]
118. Elia, E.; Popa, D.C.; Nicolae, C.G. Startup stages of a low-tech aquaponic system. *Sci. Pap. Ser. D Anim. Sci.* **2014**, *57*, 263–269.
119. Jetten, M.S.; Strous, M.; Van de Pas-Schoonen, K.T.; Schalk, J.; van Dongen, U.G.; van de Graaf, A.A.; Logemann, S.; Muyzer, G.; van Loosdrecht, M.C.; Kuenen, J.G. The anaerobic oxidation of ammonium. *FEMS Microbiol. Rev.* **1998**, *22*, 421–437. [CrossRef] [PubMed]

120. Ross, L.G. Environmental physiology and energetics. In *Tilapias: Biology and Exploitation*; Fish and Fisheries Series; Beveridge, M.C.M., McAndrew, B.J., Eds.; Springer: Dordrecht, Switzerland, 2000; Volume 25. [CrossRef]
121. Keen, G.A.; Prosser, J.I. Interrelationship between pH and surface growth of Nitrobacter. *Soil Biol. Biochem.* **1987**, *19*, 665–672. [CrossRef]
122. Blackburne, R.; Vadivelu, V.M.; Yuan, Z.; Keller, J. Kinetic characterization of an enriched Nitrospira culture with comparison to Nitrobacter. *Water Res.* **2007**, *41*, 3033–3042. [CrossRef] [PubMed]
123. Tyson, R.V.; Simonne, E.H.; Davis, M.; Lamb, E.M.; White, J.M.; Treadwell, D.D. Effect of nutrient solution, nitrate-nitrogen concentration, and pH on nitrification rate in Perlite medium. *J. Plant Nutr.* **2007**, *30*, 901–913. [CrossRef]
124. Lemarié, G.; Dosdat, A.; Coves, D.; Dutto, G.; Gasset, E.; Person-Le Ruyet, J. Effect of chronic ammonia exposure on growth of European seabass (*Dicentrarchus labrax*) juveniles. *Aquaculture* **2004**, *229*, 479–491. [CrossRef]
125. Resh, H.M. *Hydroponic Food Production*, 6th ed.; New Concept Press Publishing Co.: Mahwah, NJ, USA, 2004.
126. Ropokis, A.; Ntatsi, G.; Kittas, C.; Katsoulas, N.; Savvas, D. Impact of cultivar and grafting on nutrient and water uptake by sweet pepper (*Capsicum annuum* L.) grown hydroponically under Mediterranean climatic conditions. *Front. Plant Sci.* **2018**, *9*, 1244. [CrossRef] [PubMed]
127. Tan, L.P.; He, J.; Lee, S.K. Effects of root-zone temperature on the root development and nutrient uptake of *Lactuca sativa* L. "Panama" grown in an aeroponic system in the tropics. *J. Plant Nutr.* **2002**, *25*, 297–314. [CrossRef]
128. Tan, X.W.; Ikeda, H.; Oda, M. The absorption, translocation, and assimilation of urea, nitrate or ammonium in tomato plants at different plant growth stages in hydroponic culture. *Sci. Hortic.* **2000**, *84*, 275–283. [CrossRef]
129. He, J.; See, X.E.; Qin, L.; Choong, T.W. Effects of Root-Zone Temperature on Photosynthesis, Productivity and Nutritional Quality of Aeroponically Grown Salad Rocket (*Eruca sativa*) Vegetable. *Am. J. Plant Sci.* **2016**, *7*, 1993–2005. [CrossRef]
130. Marschner, H.; Kirkby, E.A.; Cakmak, I. Effect of mineral nutritional status on shoot—Root partitioning of photoassimilates and cycling of mineral nutrients. *J. Exp. Bot.* **1996**, *47*, 1255–1263. [CrossRef] [PubMed]
131. Yan, Q.; Duan, Z.; Mao, J.; Li, X.; Dong, F. Effects of root-zone temperature and N, P, and K supplies on nutrient uptake of cucumber (*Cucumis sativus* L.) seedlings in hydroponics. *Soil Sci. Plant Nutr.* **2012**, *58*, 707–717. [CrossRef]
132. He, J.; Tan, L.P.; Lee, S.K. Root-zone temperature effects on photosynthesis, 14 C-photoassimilate partitioning and growth of temperate lettuce (*Lactuca sativa* cv. 'Panama') in the tropics. *Photosynthetica* **2009**, *47*, 95–103. [CrossRef]
133. Li, R.R.; Zhu, Y.L.; Takagaki, M.; Yamori, W.; Yang, L.F. Effects of root zone temperature on the growth and mineral elements content of hydroponically grow lettuce. *Acta Agric. Shanghai* **2015**, *31*, 48–52.
134. Endut, A.; Jusoh, A.; Ali, N.; Nik, W.W.; Hassan, A. A study on the optimal hydraulic loading rate and plant ratios in recirculation aquaponic system. *Bioresour. Technol.* **2010**, *101*, 1511–1517. [CrossRef] [PubMed]
135. Al-Tawaha, A.R.; Al-Karaki, G.; Al-Tawaha, A.R.; Sirajuddin, S.N.; Makhadmeh, I.; Wahab, P.E.M.; Youssef, R.A.; Al Sultan, W.; Massadeh, A. Effect of water flow rate on quantity and quality of lettuce (*Lactuca sativa* L.) in nutrient film technique (NFT) under hydroponics conditions. *Bulg. J. Agric. Sci.* **2018**, *24*, 791–798.
136. Alu'datt, M.H.; Rababah, T.; Alhamad, M.N.; Al-Tawaha, A.; Al-Tawaha, A.R.; Gammoh, S.; Ereifej, K.I.; Al-Karaki, G.; Hamasha, H.R.; Tranchant, C.C.; et al. Herbal yield, nutritive composition, phenolic contents and antioxidant activity of purslane (*Portulaca oleracea* L.) grown in different soilless media in a closed system. *Ind. Crops Prod.* **2019**, *141*, 111746. [CrossRef]
137. Makhadmeh, I.M.; Al-Tawaha, A.; Edaroyati, P.; Al-Karaki, G.; Tawaha, A.R.A.; Hassan, S.A. Effects of different growth media and planting densities on growth of lettuce grown in a closed soilless system. *Res. Crops* **2017**, *18*, 294–298. [CrossRef]