resources

MDPI

Review

Advancing Circularity in Small-Scale Rural Aquaponics: Potential Routes and Research Needs

Laura Silva [1,2,*], Francisco Javier Martinez-Cordero [1], Gösta Baganz [3], Daniela Baganz [3], Ariadne Hernández-Pérez [4], Eva Coronado [2] and Maria Celia Portella [5,*]

1 Centro de Investigación en Alimentación y Desarrollo, Mazatlán 82112, Mexico; cordero@ciad.mx
2 Escuela Nacional de Estudios Superiores, Unidad Mérida, Universidad Nacional Autónoma de México, Mérida 97357, Mexico; eva.coronado@enesmerida.unam.mx
3 Leibniz Institute of Freshwater Ecology and Inland Fisheries, 12587 Berlin, Germany; goesta.baganz@senmvku.berlin.de (G.B.); daniela.baganz@ba-tk.berlin.de (D.B.)
4 Departamento de Medicina y Zootecnia de Abejas, Conejos y Organismos Acuáticos, Facultad de Medicina Veterinaria y Zootecnia, Universidad Nacional Autónoma de México, México City 04510, Mexico; ariadne.hernandez@comunidad.unam.mx
5 Aquaculture Center of Unesp, Sao Paulo State University (Unesp), Jaboticabal 14884-900, Brazil
* Correspondence: laura.silva@enesmerida.unam.mx (L.S.); maria.c.portella@unesp.br (M.C.P.)

Abstract

Small-scale fisheries and aquaculture play a crucial role in securing food, income, and nutrition for millions, especially in the Global South. Rural small-scale aquaculture (SSA) is characterized by limited investment and technical training among farmers, diversification and dispersion of farms over large areas, reduced access to competitive markets for inputs and products, and family labor. Small-scale integrated circular aquaponic (ICAq) systems, in which systems' component outputs are transformed into component inputs, have significant potential to increase circularity and promote economic development, especially in a rural context. We offer an integrated and comprehensive approach centered on aquaponics or aquaponic farming for small-scale aquaculture units. It aims to identify and describe a series of circular processes and causal links that can be implemented based on deep study in SSA and ICAq. Circular processes to treat by-products in ICAq include components like composting, vermicomposting, aerobic and anaerobic digestion, silage, and insect production. These processes can produce ICAq inputs such as seedling substrates, plant fertilizers, bioenergy, or feed ingredients. In addition, the plant component can supply therapeutic compounds. Further research on characterization of aquaponic components outputs and its quantifications, the impact of using circular inputs generated within the ICAq, and the technical feasibility and economic viability of circular processes in the context of SSA is needed.

Keywords: agri-aquaculture systems; circular food production; circular economy; aquaponics waste management

check for updates

Academic Editor: Benjamin McLellan

Received: 17 June 2025
Revised: 14 July 2025
Accepted: 18 July 2025
Published: 23 July 2025

Citation: Silva, L.; Martinez-Cordero, F.J.; Baganz, G.; Baganz, D.; Hernández-Pérez, A.; Coronado, E.; Portella, M.C. Advancing Circularity in Small-Scale Rural Aquaponics: Potential Routes and Research Needs. *Resources* **2025**, *14*, 119. https://doi.org/10.3390/resources14080119

1. Introduction

By 2032, aquatic animal production from aquaculture is expected to increase by 17.4% compared to 2022, primarily through intensified and expanded sustainable aquaculture practices [1]. It is also projected that in 2032, aquaculture will supply 60% of global fish food consumption [1]. Aquaculture externalities can be either negative or positive, and the way aquaculture develops could positively influence human well-being and environmental health outcomes, especially in regions where economic policies focus on social equity and environmental sustainability [2]. Primary negative environmental impacts come from fed aquaculture (specifically pollution and global warming) and water access and usage; thus, promoting recycling systems that reduce water consumption and promote nutrient recovery and reuse is essential [3].

Currently, 95% of aquaculture production occurs in developing countries in the so-called Global South, with 70–80% of individuals involved in aquaculture being small-scale, defined by FAO as "aquaculture that use relatively small production units with relatively low input and low output, and limited levels of technology and small capital investment" [4,5]. Globally, the fisheries and aquaculture sector provides jobs and secures livelihoods for approximately 61.8 million people [1]. This primarily occurs in Global South countries, specifically within small-scale fisheries (SSFs) and small-scale aquaculture (SSA) [1,6,7]. SSA has the potential to contribute to sustainable rural development through various means such as ensuring food security, fostering wealth generation, diversifying livelihoods, generating employment opportunities, and leveraging family labor, among other benefits [6,8]. Rural SSA systems involve farms that own or have access to aquatic resources, typically with limited investment in assets and operational costs. These farms may operate with family or community ownership and labor, and they may or may not be the main source of livelihood [6]. Integrated systems that include the SSA often combine the use of terrestrial manure or sewage as fertilizer for fishponds, along with fertigation for culture fields and fruit trees [6,9]. These systems typically operate with informal management structures and often have limited access to technical resources, expertise, formal education, and information—including market information—which can be reflected in the low sales values achieved on farms, local markets, or through intermediaries [6,9,10].

Farming diversification through the integration of diverse resource-sharing farming is a characteristic of small-scale aquaculture farming in rural and peri-urban areas, especially benefiting impoverished communities [11]. Integrated aquaculture–agriculture value chain activities are appropriate for resource-poor households [12]. Furthermore, according to FAO [3], circular and sustainable food systems that promote sustainable management and use of resources are required to ensure the sustainable development of aquaculture. In this context, aquaponic farming is a production technique that integrates aquaculture with plant cultivation, utilizing the aquaculture water as a nutrient solution. This technique encompasses two plant culture methods: hydroponics (aquaponics), where plants draw nutrients directly from aquaculture-derived water, and non-hydroponics (trans-aquaponics), which employs a combination of soil and nutrient-rich aquaculture water [13]. Aquaponic farming diversifies production systems and represents a pathway toward a more sustainable production system by recycling resources such as water and nutrients.

In recent years, aquaponics (Figure 1), a technology that couples tank-based animal aquaculture with hydroponics involving microbiological processes—using water from aquaculture for plant nutrition and irrigation [13]—has attracted the attention of researchers and entrepreneurs worldwide, as it is considered a sustainable system that can potentially improve food security in developed and developing countries in the face of drought, soil fertility loss, climate change, and urban growth [1,14,15].

Aquaponics integration into urban and industrial settings focusing on circular economy principles has been studied, particularly for the Global North [16,17]. However, even though these and other similar studies provide valuable insights, they often rely on controlled environments and commercial, high-tech aquaponic systems, which may not be directly applicable to conditions of small-scale rural aquaculture. In addition, implementing circular economy policies in the Global South, modeled after those in the Global North, can limit their ability to drive sustainable development and innovation [18]. Still, aquaponics has the potential to drive socioeconomic development in rural areas of developing countries, as it can increase and diversify production and incomes [19–21]. However, it is crucial to consider local contexts when designing aquaponic systems to promote sustainable development [15,22]. Moreover, aquaponics or aquaponic farming could serve as the foundation of an integrated system where not only the dissolved nutrients in the water are recycled, but also renewable resources, defined as the 'wastes' or by-products and outputs generated by its components (aquaculture and plant culture), are utilized and recycled via appropriate circular processes. This would result in a small-scale integrated circular aquaponic system (ICAq), defined here as aquaponics or aquaponic farming with additional modules that utilize material flows to increase the sustainability of the system by improving internal circularity. ICAq can be designed using some of the principles of ecological engineering (EE) and the circular economy (CE) so that the outputs of the aquaponic components would be the inputs of other ICAq components or circular entities.

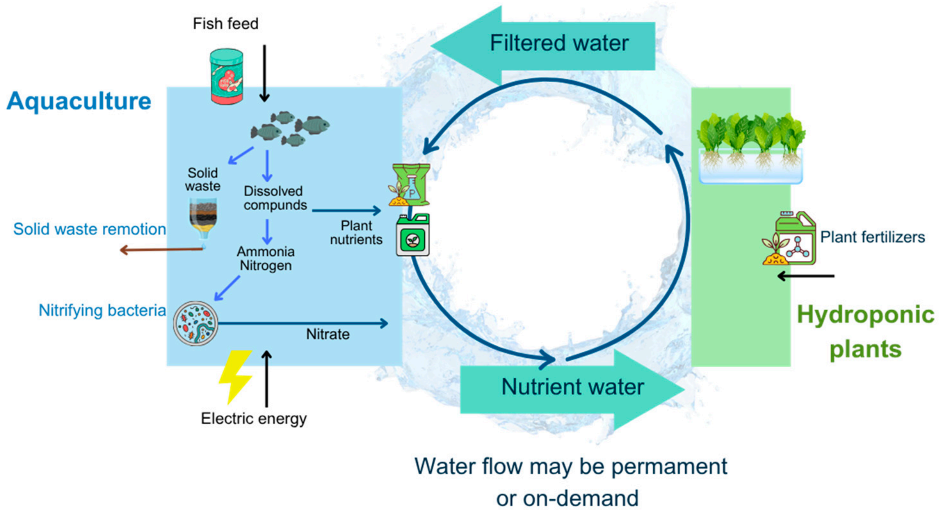

Figure 1. Basic aquaponic system scheme adapted from Baganz et al. [13]. The aquaponic system combines aquaculture with hydroponic or soilless plant cultivation. It involves nitrifying bacteria and reuses water and dissolved compounds from the recirculating aquaculture unit, which serve as nutrients for plants. In these systems, beyond fish and plants, the main inputs typically include fish feed, electrical energy, and often, plant fertilizers. Water flow between aquaculture and hydroponic plants may be permanent or on-demand depending on the system configuration.

The circular economy is based on various principles that can generally be grouped into four categories known as the 4R principles: reduce, reuse, recycle, and reverse logistics [23]. Specifically for the agribusiness sector, the United Nations Industrial Development Organization [24] mentions three principles: "(1) Pollution and waste are transformed to become regenerative, (2) Preserve value over time and design for durability, reuse, remanufacture and recycle in the technical cycle, prioritizing biological-based material before it returns to the natural system, and (3) Avoid the use of non-renewable resources and return valuable nutrients to the soil to support natural regeneration". As for ecological engineering (EE), Schönborn and Junge [25] state, "Ecological engineering integrates ecological principles, processes, and organisms with existing engineering practice to a holistic approach for problem-solving". In EE, design is the foundation for achieving the goals for developing new sustainable ecosystems with human and ecological value [26]. An EE design relies on a network of species to perform specific functions [27], and some designs are inspired by ancient human management practices, as seen in ecological aquaculture [27,28]. Thus, EE designs can draw inspiration from ecological wisdom or nature-based solutions [29].

The circular bioeconomy offers significant potential for enhancing both aquaculture [30] and agricultural systems [31], as evidenced by several reviews. In the realm of aquaponics, research on sustainable or circular bioeconomy products and processes with potential applications within the system or in aquaponic farming is available [32,33]. Recently, the integration of system-internal resource streams for aquaponics has been explored for fish feed [34]. Given that a significant portion of aquaculture is conducted on a small scale in the Global South, making actions to improve the sustainability of production are critically needed. This review aims to contribute to this effort. It proposes and provides an overview of causal links relating inputs and outputs of aquaponic systems through a series of circular processes previously studied in aquaculture, agriculture, or aquaponics, and which are suitable for small-scale application. This research also aims to provide insights that can inspire future studies to develop innovative solutions adapted to specific regional needs and to identify research needs for advancing circularity in small-scale rural aquaponics through integrated circular aquaponics.

2. Materials and Methods

Given the multidisciplinary approach of the review and the objectives of it, an ad hoc review methodology was proposed, and it is described in Figure 2.

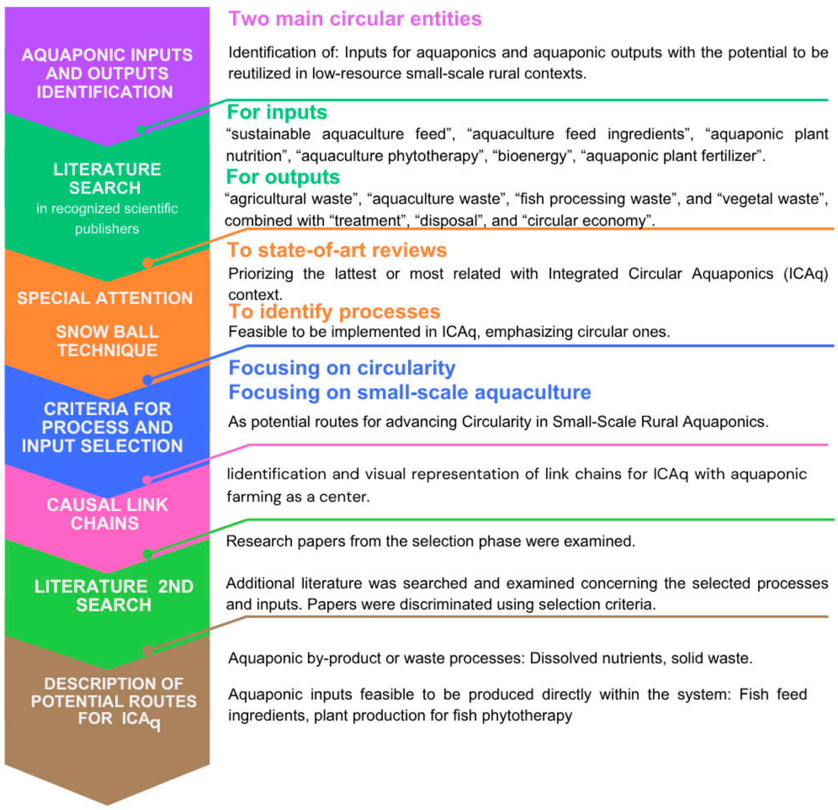

Figure 2. General scheme of research methodology proposed.

Initially, the concept of circular entities [35] was utilized to identify inputs from aquaponics and outputs or by-products with the potential to be reutilized in low-resource, small-scale rural contexts that could be potential routes to advancing circularity in small-scale rural aquaponics.

Following this identification, a literature search was conducted on the ISI Web of Knowledge and Google Scholar databases. For inputs, the search included the terms "sustainable aquaculture feed", "aquaculture feed ingredients", "aquaponic plant nutrition", "aquaculture phytotherapy," and "bioenergy." For by-products, the search terms included "agricultural waste", "aquaculture waste", "fish processing waste", and "vegetal waste", combined with "treatment", "disposal", and "circular economy". The search was limited to peer-reviewed articles, books, and book chapters of recognized scientific publishers such as Elsevier, Springer, MDPI, PLOS, Frontiers, Wiley, etc.

Since a wealth of information is available on specific topics related to aquaculture, agriculture, bioenergy, and waste or by-product disposal and treatment, special attention was given to the state-of-the-art reviews. Additionally, the snowball technique was employed to identify several processes described in the research and review papers, facilitating a literature review aimed at identifying possible circular processes for ICAq.

Processes and inputs selection as potential routes for advancing circularity in small-scale rural aquaponics through ICAq was performed through the literature examination using a multicriteria approach. The selection emphasized circularity and small-scale, on-farm feasibility. Specific criteria are described in Figure 3. This approach leveraged the authors' expertise in aquaponics and small-scale aquaculture (SSA) and adhered to previously defined SSA boundaries.

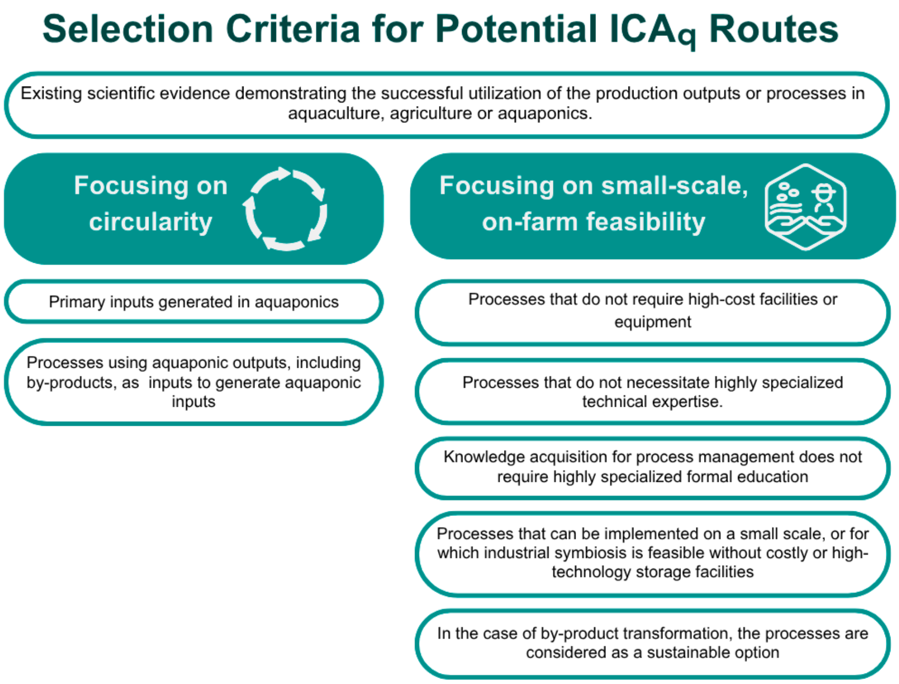

Figure 3. Multicriteria approach applied for processes and inputs selected as possible routes for advancing circularity in small-scale rural aquaponics through integrated circular aquaponics (ICAq).

Utilizing the identified processes, causal link chains for small-scale aquaponics and aquaponic farming production within the framework of the circular economy were established and visually represented. Considering the theoretical foundations of the circular economy (CE) and ecological economy (EE), the literature review of the processes was performed to examine the advances in each topic that could be relevant to the development of small-scale ICAq. To further support the review, additional literature on the selected processes and inputs was searched and examined. This involved applying the initial search criteria for process and input selection and specifically targeting up-to-date reviews and criteria-aligned studies.

The acquired information was structured as a narrative review. This review aimed to provide a comprehensive overview of identified processes for by-product or waste valorization and on-farm input production within ICAq. Areas where information was not found regarding the quantity of inputs or outputs generated, mass balances, or the reuse percentage of any compound, input, or element within ICAq or aquaponics were designated as research gaps. This also includes the lack of data on the technical-biological, productive, or economic effects, as well as the environmental or economic sustainability analyses resulting from the adoption of the described circular processes within the identified ICAq causal links.

3. Results

This section presents several options that, in conjunction with the CE and EE principles, could be employed to promote research and development of ICAq for rural small-scale aquaculture farms. Figure 4 summarizes several processes identified as options that can be implemented within ICAq. In this figure, causal links representing the possible resource flows and transformation processes that can convert products and by-products from the two primary aquaponic entities (recirculating aquaculture and aquaponic plant production) into inputs for the same system are presented.

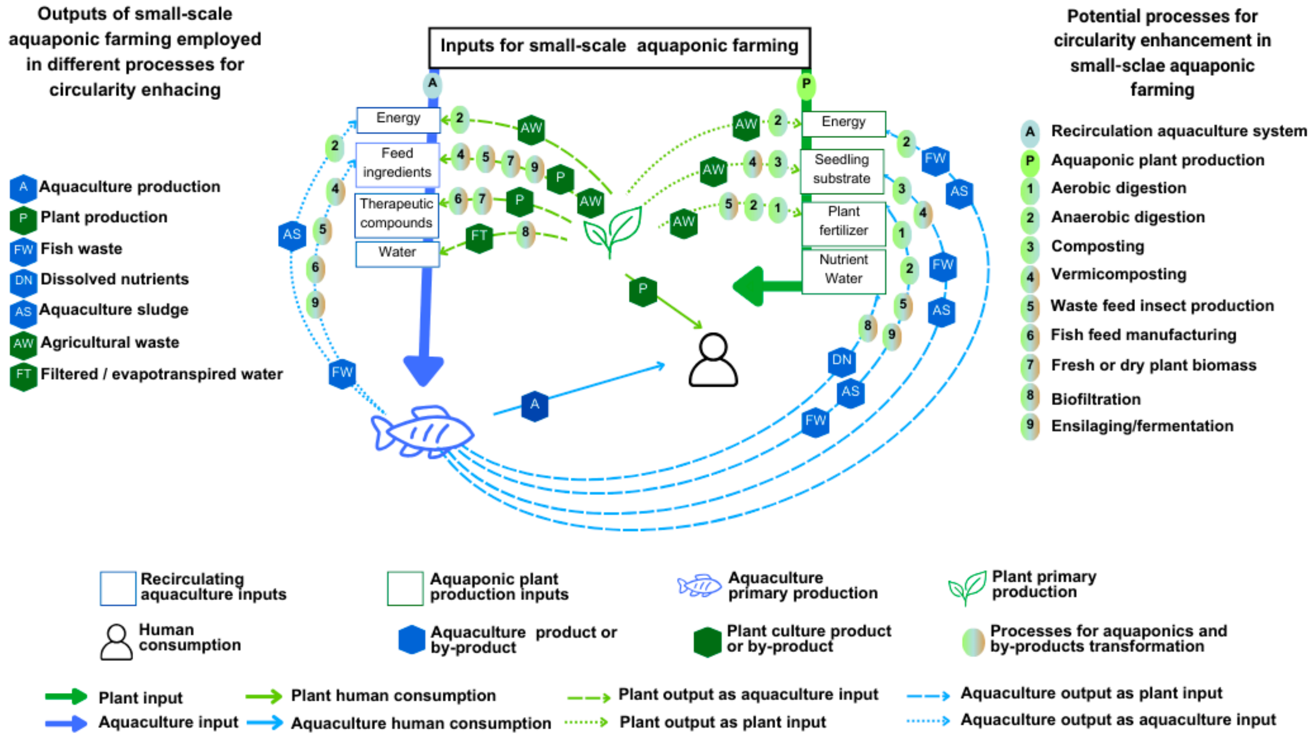

Figure 4. Potential processes to enhance circularity in rural small-scale aquaculture (SSA) farms through small-scale integrated circular aquaponics (ICAq) with aquaponic farming as a center. These processes represent an option for farms with restricted investment in assets and operational costs, farming dispersed over large areas, family or community labor, limited access to competitive markets, and inadequate access to formal education and technical resources.

For a more specific and in-depth analysis, the displayed processes could also represent a circular entity in which they are carried out. However, since the paper focuses on processes and given that circular entities analysis incorporates concepts such as energy flows and site allocation, which are not covered in this review, these processes are presented solely as concepts.

3.1. Dissolved Nutrients

In feed-based aquaculture, only 20 to 40% of the nitrogen and phosphorus supplied with the feed is recovered in the harvested biomass. For commonly fed aquaculture species, only an average of 30.9% and 19.4% of the feed protein (calculated by protein efficiency ratio) is recovered in the harvested biomass and processed fillets, respectively [36].

Options for the reuse of aquaculture wastewater included use for permanently coupled and on- demand coupled aquaponics, trans-aquaponics, and the cultivation of algae and daphnia [13,37,38]. Given the high protein content in fish feed, nitrogen (N) is typically the most abundant element in aquaculture wastewater, with most of it present as NO_3-N in recirculating systems [39]. Modern aquaponics systems originally emerged as an option for N recycling in recirculating aquaculture systems [40]. This principle was previously applied by the ancient Aztecs in the Chinampas [13], which is an example of using traditional ecological knowledge and wisdom. However, there is no evidence that the pioneers of modern aquaponics were aware of the Aztec Chinampas.

As the foundation of aquaponics technology, the reuse and recycling of N generated in recirculating aquaculture systems (RASs) has been one of the most studied topics in aquaponics. N removal in aquaponics systems occurs when the outputs of RASs are used in the hydroponic component of the system. This fact has been demonstrated by several authors, with different results depending on the system configuration, species, water composition, and location [41–43]. Wongkiew et al. [44] conducted a comprehensive review on this topic, detailing the effects of pH, dissolved oxygen, hydraulic loading rate, ammonia and nitrite concentrations, and carbon-to-nitrogen ratio (C:N) on nitrogen transformations in aquaponic systems and their components.

Efforts to improve nitrogen use efficiency (NUE) in both the plant and recirculating aquaculture system (RAS) components of aquaponic systems, in alignment with the recycling and narrowing resource flow cycles used in CE practices [45], have been carried out using various approaches. Zou et al. [46] evaluated two strategies: the incorporation of specific microorganisms to enhance nitrification and the modification of plant component design to increase the area for microorganism fixation. These authors reported that the second strategy was more efficient for improving NUE. In a different approach, Yang and Kim [47] assessed several feeding management practices in the RAS component, demonstrated their effects on nitrogen use efficiency, and reported that maintaining a constant quantity of feed throughout the culture cycle increased the NUE in aquaponic systems compared to an incremental feeding strategy. While these examples are not exhaustive, they illustrate that multiple options exist for enhancing the efficiency of nitrogen use. Other combinations of different methods should also be explored to further improve input use efficiency in aquaponic systems.

In aquaponics, phosphorus (P) is the second nutrient of interest when discussing wastewater remediation, given the potential risk of eutrophication when discharged into water bodies. Cerozi and Fitzsimmons [48–50] have studied the balance, availability, and methods to enhance its availability for plant uptake. Complementarily, Shaw et al. [51,52] demonstrated that the protein sources used in fish feed formulation impact the concentration of certain micronutrients that are important for aquaponics. They found a higher release of Ca and P in the RAS water when fish diets with higher animal protein content were used and a higher release of K, Mg, and B when increasing plant protein contribution [51]. In a second trial Shaw et al. [52] examined differences in dissolved nutrient excretion patterns of Nile tilapia (*Oreochromis niloticus*) reared in recirculating aquaculture systems (RASs) when fed diets containing black soldier fly meal (BSFM), poultry by-product meal (PM), poultry blood meal (PBM), or fishmeal (FM) as individual protein sources. Fish fed FM and PM showed better growth performance and higher dissolved nitrogen (N) and phosphorus (P) levels. In contrast, BSFM and PBM resulted in reduced fish performance. While the BSFM diet led to higher dissolved potassium (K), magnesium (Mg), and copper (Cu), the PBM diet was associated with the lowest overall dissolved nutrient levels in the water.

In this case, it has been shown that aquaponics aligns with the recycling and narrowing resource cycles used in the circular economy (CE), not just for N, but also for P and other micronutrients involved in plant nutrition. Further research on this subject is necessary. For example, the impact of inputs for fish feed produced within the system (ICAq) on dissolved nutrient concentration, mass balance, and circularity indicators, among others, needs to be investigated.

3.2. Aquaponics Solid Waste: Aquaculture Sludge, Fish Waste, Agricultural Waste

In aquaponics, solid waste is produced in both the RAS and the plant components. To the best of the authors' knowledge, research on the agricultural wastes (AWs) produced in the plant component of aquaponics or trans-aquaponics is scarce. Agricultural waste is rich in cellulose, lignin, and hemicellulose (lignocellulosic biomass), and its treatment and disposal currently pose a global issue since the vast majority is either burned or buried in soil for landfill [31]. Ganesh et al. [53] and Koul et al. [31] reviewed several treatments for reusing agricultural vegetable and fruit waste and proposed their use to produce biofuel, biofertilizers, biobricks, bio-coal, bioplastics, paper, industrial enzymes, organic acids, adsorbent materials, and bioactive compounds. From these, some treatments to produce biofuel (anaerobic digestion) and fertilizers (anaerobic digestion and composting) are recognized as viable technologies for rural areas and can be used in ICAq. However, considerable variability exists across farms, biodigesters and composting methods regarding expenses, revenue, opportunities, environmental constraints [54–56], and specific contexts must be considered to evaluate their environmental and economic impact. Aquaculture solid waste mainly consists of aquaculture processing waste (APW), sludge (AS), and, eventually, dead organisms due to parasites, diseases, faulty equipment, or other unexpected events [57]. Depending on the level of processing or type of fish, 30–70% of the original fish is APW [58] while the composition and quantity of AS vary among different types of systems (pond, raceway, recirculating), species, and food provided [59,60].

The organic matter resulting from APW and dead organisms consists of fish tissue such as heads, scales, viscera, tails, and backbones, being thus high in protein and lipid content, and highly perishable [57]. Some of the proposed uses include fertilizers, fish silage, and biogas production [58].

In aquaculture recirculating systems, aquaculture-suspended solids represent 25% of the feed provided, while the sludge quantity and composition depend on the efficiency rate of removal devices [61]. AS is characterized by a low content of total solids (TSs), varying from 1.5% to 3% [57,61]. However, AS is rich in proteins and lipids, with a volatile solid (VS) content ranging from 17% to 92%, depending on the fish species and feed composition [57,62]. When inadequately treated or disposed of in the environment, these wastes may pose social, economic, and environmental issues [63].

Incineration and/or landfills, which are non-sustainable methods, remain the primary means of solid waste management for food and aquaculture [64]. The discharge of sludge into the environment is a common practice for pond culture in several developing countries [57,65].

The appropriate method for sludge treatment depends on the sludge type [66], which is influenced by the characteristics of the aquatic culture. For example, Nhut et al. [64] reported that the sludge dry matter produced per kilogram of fish was six times higher in ponds than in RASs. However, solid waste from RASs had a much higher concentration of nutrients, thus being better for compost and anaerobic digestion than that from ponds. Other factors that define the sludge treatment include the economic, social, and climatic conditions on site [66]. Thus, for rural small-scale ICAq, the specific context must be considered and evaluated when implementing processes to enhance circularity.

3.2.1. Composting, Ensilaging, and Organic Fertilizer

A relatively simple and cost-effective method for reusing AS and AWs is to apply them directly to the soil, where they act as a fertilizer after successive applications, particularly in combination with the mineralization of nutrients [67,68]. In developing countries, windrow composting of APW and AS is often employed as a low-cost method that facilitates the recovery of several nutrients within 40–55 days, allowing the resulting compost to be used as fertilizer [60,63]. Composting requires a C:N ratio of approximately 30; therefore, when composting low C:N ratio materials, such as AS and APW, co-composting with high C:N ratio materials such as agricultural waste can help achieve the optimal C:N ratio [67,69].

In ICAq, incorporating locally produced waste as a C source to balance the C:N ratio in the composting process increases the efficiency of resource utilization and localization. Additionally, using the resulting compost as a substrate medium for seedlings is considered a promising approach to waste reuse [70]. Other proposed options include vermicomposting with *Eisenia andrei* earthworms and black soldier fly (*Hermetia illucens*) larvae [71,72]. These options also provide the added advantage of protein production, which can serve as a nitrogen source for fish feed in ICAq as discussed later in this work. In the case of vermicomposting with *E. andrei,* after an 18-week experiment composting 200 g of RAS sludge and shredded wheat straw in various proportions, the species showed an original stock survival rate ranging from 40% to 70%, depending on the substrate mixture percentage, and the juvenile yield varied between 256 and 309 individuals, stabilizing by week 12; also, the original sludge and final vermicomposts were found suitable for use in agriculture [71]. Vermicompost of bread and aquaculture waste with *H. illucens* larvae increased the larvae size by 35% and body protein content by 60% (45%DM) within 11 to 12 days of treatment, but inclusion of only 15% aquaculture waste is recommended since the addition of aquaculture waste in the treatments was negatively correlated to larvae survival [72].

Ensilaging is another process considered feasible for small-scale units [12,73,74]. Production of fish silage involves homogenizing fish waste, followed by preservation by adding an organic acid or by adding a fermentable substrate and a bacterial culture to attain a pH below 4, with an ideal target of approximately 3.5. Fish silage includes a complete hydrolysis of the product due to the proteolytic enzymes from the fish gut and it can be stored for at least 6 months or even years [74]. It allows for the recovery of nutrients from fish processing waste (FPW) and thus APW, with potential use as an organic fertilizer to replace commercial options [75]. This process requires adding a carbon source, such as AW, and is considered one of the simplest, cheapest, and most efficient preservation methods for raw fish [12]. However, for acidic silage, safety measures must be taken, use of protective glasses/safety face shields, acid resistant gloves, rubber boots, and protective clothing is recommended, and good ventilation in storage deposits is necessary for workers' safety for both ensilaging methods [74,76]. Furthermore, besides serving as a fertilizer, fish silage can provide easily digestible and absorbed ingredients or additives for aquafeed and may be more valuable as an animal feed ingredient [73,77].

In aquaponics, trials to evaluate the use of APW, AWs, or AS silage as fertilizer for plant production and fish feed ingredients are needed. ICAq can benefit from co-composting and ensilaging of APW, AS, and AWs as sources of nitrogen (N) and carbon (C) for seedling production. Co-composting can be conducted on-farm, extending the resource value of the fish and plants produced, or it can follow an industrial symbiosis strategy via enterprise agreements [45].

In ICAq, if trans-aquaponic systems co-exist with aquaponics, the use of organic fertilizers produced from outputs of the aquaponic system through processes such as composting, vermicomposting, or silaging, for non-hydroponic plant fertilization, can increase farm circularity. This aligns with the circular economy principle of returning valuable nutrients to the soil for the agribusiness sector as proposed by UNIDO [24].

3.2.2. Aerobic and Anaerobic Digestion Inputs and Outputs for Aquaponic Circular Farming

Two methods for treating AS and/or APW that allow an integrated biological process with multiple uses for their by-products are anaerobic (AnD) and aerobic digestion (AD). Anaerobic digestion has been used for stabilizing and reducing wastewater sludge and APW, being considered a straightforward method to decrease by-products and produce biogas [57]. Anaerobic digestion outputs are liquid digestate (centrate), solid digestate, and methane [78]. In ICAq, all these outputs (or by-products) could be used to preserve their value over time and throughout the process. In this regard, Choudhury et al. [79] reviewed the challenges of resource recovery opportunities from land-based aquaculture waste and seafood processing by-products and concluded that AnD, together with aquaponics, could further enhance the value of the waste streams from aquaculture facilities. According to their finds, outputs of anaerobic digestion of aquaculture by-products are influenced by a variety of factors. These include the type of feed used (e.g., algal slurry, animal processing waste), the total solid content (%VS) in the digester feed, and the reactor type and scale. Additionally, co-digestion with other substrates like sewage solids, manure, or food waste, and the presence of inhibitory factors, also contribute to the variability in results. For example, a methane production of RAS aquaculture sludge AnD in lab-scale batch reactors of 76.0 mL CH_4/g VS_{fed}, when feeding with 100% of weeber aquaculture sludge, has been reported; in contrast, the methane yield of turbot RAS sludge was ~330 mL CH_4/g VS_{fed} according to the Automatic Methane Potential Test System (AMPTS II), and salmon and trout sludge produces up to 519 mL/g VS_{fed} [80–82]. For fish waste, according to the data reviewed by Choudhury et al. [79], methane yield from AnD ranged from 261 CH_4/g VS_{fed} when fish scales were used to 933 mL CH_4/g VS_{fed} when intestines (viscera) were used. On the other hand, studies linked to aquaponics show that centrate anaerobic digestion of recirculating aquaculture AS can recover between 26–71% of phosphorus (P), potassium (K), and calcium (Ca). According to Goddek et al. [83], this process yielded centrate with concentrations ranging from approximately 50–60 ppm of total ammoniacal nitrogen (TAN), 20–50 ppm of P, and 20–40 ppm of K when catfish sludge was used and 230 ppm of TAN and 50 ppm of P and K when tilapia sludge was used. Similarly, Goddek et al. [84] reported concentrations of ~60 ppm pf NH_4, ~2 ppm of PO_4, and ~14 ppm of K in AnD centrate of Nile tilapia culture fed with Hokovit Tilapia Vegi feed.

Recovering nutrients from fish sludge through AnD and reintroducing them into plant production as liquid fertilizer has become attractive, as this practice enhances system sustainability [85]. However, this practice is still controversial since the main source of N for plants is nitrate (N-NO_3), and total ammonia nitrogen (TAN) could be toxic for them. In the AnD of aquaculture sludge, N-NO_3 is lost while TAN increases in both the effluent and solid digestate [84,86]. Nevertheless, several authors have evaluated the use of the centrate of anaerobic sludge digestion for aquaponic plant production with varying results. Goddek et al. [84] reported better lettuce production using the centrate compared to production with a conventional hydroponic solution. In contrast, Lobanov et al. [87] reported lower performance for lettuce produced with centrate compared with a conventional hydroponic solution, and Delaide et al. [88] indicated toxicity symptoms in plants fertilized with centrate from anaerobic sludge digestion.

On the other hand, in ICAq, the centrate from aquaculture processing waste (APW) and anaerobic digestion (AnD) is rich in TAN and can be reused for the production of microalgae or duckweed. This approach has been evaluated successfully for the use of the anaerobic digestion centrate derived from food waste, wastewater treatment, poultry, and dairy residues, among others [78,89,90]. Aerobic digestion (AD) of AS has also been studied to produce liquid plant fertilizer using the centrate [91,92]. The most commonly reported N compound in the centrate resulting from AD is nitrate nitrogen, NO_3-N [86,91]. The liquid centrate from aerobic digestion of aquaculture sludge is a good option for use as a hydroponic solution for lettuce cultivation, as the production levels are comparable to those obtained with standard hydroponic solutions [88]. Nevertheless, according to Delaide [88], K, P, and Mn deficiency can be observed when using the centrate from the aerobic digestion of pikeperch aquaculture sludge. Similarly, Goddek et al. [84] reported that the lettuce production was lower using the centrate of aerobic AS digestion compared to the centrate of anaerobic digestion of aquaculture sludge. Additionally, according to Khiari et al. [33], in the digestion process of fish sludge, under aerobic conditions, controlled pH of 5.5, 6.0, and 6.5, and temperatures of 30, 35, and 40 °C, only ammonification occurs, resulting in the production of ammonium nitrogen (NH_4-N). In contrast, during aerobic digestion without pH control, nitrification occurs, producing nitrate nitrogen (NO_3-N) when the temperature is <40 °C.

The circularity concerning the use of anaerobic and aerobic digestion in aquaponics is advancing for fertilizer production. Zhu et al. [33] demonstrated that a permanently coupled aquaponic system integrated with an upflow anaerobic sludge blanket (UASB) reactor increases nitrogen and phosphorus recovery, as well as plant aerial productivity, compared to both a permanently coupled system and an on-demand coupled system. Similarly, focusing on aerobic digestion, Madady et al. [93] proposed an aquaponic system coupled with an aerobic digestion bioreactor (ADBR), from which the fertilizer obtained was applied to the aquaponic system. This application increased the concentrations of PO_4^{3-}, K, Fe, Zn, Cu, and Mn in the water compared to a conventional aquaponic system. Furthermore, the same study reported improved performance of tilapia and mint cultures in the aquaponic system integrated with the ADBR for specific variables, such as the feed conversion ratio for tilapia and the total fresh weight, aerial fresh weight, and number of leaves for mint. In both studies, fish sludge waste was utilized for digestion. Further research is needed for aquaponics to evaluate the co-digestion of aquaculture sludge, as well as fish processing and agricultural waste generated in the system. Additionally, research is necessary regarding economic feasibility, mass balances, material flow, sustainability indicators, and fertilizer production capacity in both small-scale aquaponics (SSA) and integrated circular aquaculture (ICAq) contexts.

3.2.3. Aquaponics and Waste-to-Energy Technologies

In aquaponics, electric energy is a fundamental input for the whole system, involving two main circular entities, the RAS and the hydroponics. Aquaponics is characterized by the demand for electric energy, which is essential primarily for water recirculation and aeration. Depending on the location, additional electric energy may be required for heating, artificial illumination for plant growth, and controlling parameters and climatic conditions [94,95]. The use of electric energy in aquaponic systems is the factor that produces major environmental impact [96] and, in some cases, represents the first or second highest operational cost [97,98]. Given the importance of electric power consumption, the use of solar and geothermal energy has been proposed as alternative sources [99,100]. Similarly, the incorporation of waste-to-energy technologies could lead to more sustainable food production in aquaponics and should be considered in ICAq design. These approaches align with the avoidance principles regarding the use of nonrenewable energy proposed by UNIDO [24] and the suggestion from Schönborn and Junge [25] to avoid harmful constituents and outputs in the design.

Waste-to-energy production technologies allow the transformation of waste into useful energy forms [101]. The AWs, APW, and AS could be used to generate bioenergy (modern bioenergy), which, along with sun and wind energy, is considered one of the forms of renewable energy that can contribute to achieving the SDGs of affordable and clean energy. This renewable energy refers to the energy derived from biofuels, which are fuels produced directly or indirectly from biomass [102]. The utilization of aquaponic wastes for bioenergy production could help close the resource loops for food production in ICAq.

There are several technologies to transform waste into bioenergy, which can be divided into four conversion methods: biochemical, physicochemical, chemical, and physical. A complete review of these methods, including their applicability to various types of waste (biomass), their advantages, disadvantages, scale-up, economics, feasibility, and status, was published by Banerjee [103]. Additionally, Saravanan [104] summarized the bioproducts derived from different biowastes, their elemental analysis, conversion process, and energy content. Each of the waste-to-energy technologies is suitable for transforming different types of biomass [103,104]. Based on our findings and specifically for aquaponics, evidence regarding biogas production from anaerobic digestion using aquaculture sludge or aquaculture processing waste is available and might be the best match. Therefore, an inventory and characterization of the biomass generated as waste in aquaponics or aquaponic farming systems is essential to determine which waste-to-energy technology is appropriate for each case. Concurrently, research is necessary to determine which waste-to-energy technologies are best suited for specific aquaponic waste streams, thereby fostering the circularity essential for developing integrated circular aquaponics (ICAq) systems.

Indeed, a waste-to-energy technology that has been studied for aquaponics is AnD; however, these studies were conducted focusing on the fertilizer potential or nutrient recovery from aquaponic fish or plant wastes [84,86,88].

Fish sludge AnD has been pointed out as a promising biogas (methane)-producing technology [105]. Additionally, in aquaponics, the anaerobic digestion of plant waste was efficient in reducing pollution burden, producing high-quality biogas, and recovering nutrients [106]. However, as indicated by Choudhury et al. [79], several challenges need to be addressed for fish sludge AnD, such as low solid concentrations, low carbon/nitrogen ratio, and high lipid content in the waste streams. In the case of plant waste, AnD presents challenges like low biogas yield, poor buffering capacity, low-quality end products, and potential variability [107]. In this sense, one of the suggested techniques for improving biogas production from both agricultural and inland aquaculture waste is co-digestion [105,107]. The co-digestion of waste derived from aquatic animals and plants has been successfully tested to increase methane generation [108].

Thus, the co-digestion of agricultural and fish waste could improve the circularity in ICAq, as its bioproducts might be used to meet several energy and fertilizer requirements. Additionally, since the co-digestion inputs are naturally present in aquaponics and/or aquaponic farms, the on-site anaerobic co-digestion of plant and fish wastes would embody some principles of circular economy and ecological engineering design. This approach has been explored theoretically by Yogev et al. [109] for aquaponic production. This study suggests the need for a system capable of producing 3.4 tons of fish annually and approximately 35 tons of tomatoes per year to generate sufficient fish sludge and agricultural waste for an anaerobic digester to yield 70 kWh/day of biogas, thereby powering the system.

Biogas production through anaerobic digestion of agricultural and aquaculture waste has been identified as an economically viable alternative for biogas production [110] and may involve small-scale farms and even households, offering an alternative for bioenergy production in rural areas [54]. However, several issues previously identified concerning biogas technology in the rural small-scale context, such as the need for technical improvements, potential lack of social acceptance, and high investment costs, must be considered [55]. Additionally, other factors, including technical training, policy enforcement, public–private partnership funding, and record keeping, need to be taken into account for successful biogas implementation [111]. Consideration of strategies such as industrial symbiosis may also be relevant, depending on the context.

3.3. Production of Aquaculture Feed Ingredients for Small-Scale Aquaculture

Aquaculture feed has a crucial role in industry growth [112]. However, aquaculture feeds are the main source of pollution in aquaculture effluents and account for about half of the variable costs in aquaculture production [113]. In rural small-scale aquaculture, access to formulated commercial feed at competitive prices has been identified as one of the main obstacles to self-sustainability, leading to a common reliance on supplementary and artisanal feed [9,11]. For small-scale producers, another pathway to achieving more sustainable aquaculture feed production is through the concept of self-sufficient fish feed. This approach aims to manufacture fish feed using locally available materials derived from natural wastes and by-products [113,114]. The use of feed ingredients produced in the ICAq by recycling and narrowing resource flow cycles could improve the circularity of fish and plant production and also boost nutrient availability for aquaponic plant cultivation [34]. Strategies for implementing these practices could include industrial symbiosis or extending resource value [45], depending on the scale and other specific conditions. For rural small-scale aquaculture, field schools for feed formulation present an option to enhance fish production and generate income [11].

Regarding ingredients for the aquafeed formulation, a suitable option for ICAq could be the utilization of aquaponics waste to produce insect meals, which can serve as an indirect replacement for fishmeal. The intensive production of insects provides an opportunity to break down organic waste and generate insect biomass, such as *Hermetia illucens* and *Tenebrio molitor* [115] that could be used as a protein source for fish feed. Insect production has been successfully tested using both agricultural and fish wastes [116,117]. Furthermore, the combination of these types of waste could be ideal for enhancing insect production [118].

Several reviews exploring this subject are available, for example, a systematic review and meta-analysis of the production performance of aquaculture species fed dietary insect meals published by Tran et al. [119]. In this work, larval defatted mealworm (*Tenebrio molitor*) and pupal full-fat silkworm *Bombyx mori* were identified as having the potential to increase the specific growth rate (SGR) and decrease the feeding conversion rate (FCR) for aquatic animals. In another review by Maulu et al. [120], *Tenebrio molitor* and *Hermetia illucens* were identified as species with high potential to replace fishmeal in aquafeed. A specific review on the use of *T. molitor* as aquafeed has been written by Shafique et al. [121] while another focused on *H. illucens* was published by Mohan et al. [122].

Specifically for aquaponics, Maranga et al. [123] evaluated diets containing *H. illucens* larvae as a substitute for fishmeal in feed to *Clarias gariepinus*. According to their findings, *H. illucens* larva meal has the potential to substitute fishmeal for *C. gariepinus* up to 75%. Additionally, it has been demonstrated that the use of *H. illucens* in fish feed has no negative effects and may even enhance the growth of *L. sativa* and *Ocimum basilicum* in on-demand aquaponic systems [124,125]. All these studies could be beneficial for future ICAq trials.

Moreover, recent examples of the production of insect meals using fish and agricultural waste, as well as the use of insects as feed ingredients, are presented in Table 1. However, it is important to highlight that insect meal production is considered a high-cost product, and some of the processing methods to obtain meal require sophisticated techniques, resources, and knowledge. In their review, Maulu et al. [120] list several processing methods to obtain insect meal, including boiling, air-drying, hydrolysis, grinding, and milling, which can be explored for ICAq. The use of insects as aquafeed ingredients in ICAq requires further research on insect production, decontamination, processing methods, and performance as aquafeed.

Another option for fishmeal substitution, in a small-scale rural context, could involve the use of suitable plants for aquaculture feed [32]. Some examples include water spinach (*Ipomoea aquatica*), duckweed (*Lemna* spp.), and water hyacinth (*Eichhornia crassipes*), which have been cultivated in aquaponics systems [60,126]. Table 1 shows recent studies related to macrophytes used for fish feeding. A comprehensive review of macrophytes as fish feed ingredients has been conducted by Naseem et al. [127], and research on macrophyte composition focusing on aquaculture feed ingredients has been developed by Ma et al. [128]. Specifically focusing on aquatic plants, a detailed review by Hossain et al. [129] summarized studies on the composition of aquatic plants and algae in aquaculture, their direct use as fish feed, and their application as feed ingredients, presenting relevant findings.

For some specific cases, the use of fermented plant ingredients in aquafeed can improve growth and health performance when comparing with non-fermented plant protein sources by providing probiotic benefits, enhancing nutrient availability and feed bioavailability, increasing the palatability and digestibility, and even eliminating anti-nutritional compounds found in dietary feed ingredients [130]. For example, replacing 45% of fishmeal with fermented soybean meal (using various bacteria) in feed significantly increased the specific growth rate (SGR) of juvenile turbot compared to replacing the same percentage of fishmeal with unfermented soybean meal. In this case, the SGR improved from 2.91 using unfermented soymeal to a range of 3.20–3.41 using fermented soymeal. This improved SGR was similar to the 3.35 SGR achieved with a pure fishmeal diet [131]. Similarly, including 30% of fermented *Azolla pinnata*, an aquatic macrophyte, in juvenile Nile tilapia diets diminished the feeding conversion rate (FCR) from 1.56 to 1.42 and increased the SGR from 1.38 to 1.52 [132]. Siddik et al. [130] presented a complete review on the subject; their review summarizes the various methods of fermentation and explores the key characteristics of fermented feed ingredients, the critical factors influencing fermentation, and the nutritional quality of these ingredients for aquaculture production. The study discussed the various methods of fermentation, key characteristics of fermented feed ingredients, critical factors influencing fermentation, and the nutritional quality of these ingredients for aquaculture production. Additionally, a systematic review and meta-analysis of replacement of fishmeal with fermented plant proteins in the aquafeed industry revealed that in general, this substitution is safe and represents a route to promote aquaculture sustainability. However, the study also revealed that the feed conversion ratio (FCR) values were poorer compared to diets containing fishmeal [133].

Prior studies offer valuable insights into the use of fish feed inputs that can be feasibly produced within aquaponic systems for reuse in those same systems, thereby increasing circularity. However, further research is necessary to address mass balance, system design, nutrient use efficiency, circularity, economic viability, and other related subjects concerning the production of insects and macrophytes and fermented ingredients, as well as their subsequent reintroduction into the aquaponic system as feed ingredients.

It has been suggested that the use of FPW or APW as ingredients, processed in various forms, can enhance the sustainability of aquafeed [134]. Sustainable fishmeal made from FPW represents about 30% of the fishmeal produced globally [135]. In aquaponics, successful intraspecies fish processing meal, in combination with ingredients such as poultry by-products meal and insect meal, has been demonstrated as a viable option to substitute commercial diets, and even to improve fish production performance as well as the nutrient profile in the water [34]. However, the FPW meal is not suitable for small-scale operations due to the large quantity of material required and the high investment costs needed to make it profitable [12].

Conversely, the use of fish silage, which is a mixture rich in hydrolyzed proteins, lipids, vitamins, minerals, and other nutrients, offers a relatively simple and economical alternative in situations where a fishmeal plant is not economically viable, such as small-scale operations. It is also an option in areas that are distant from fishmeal production plants [12,74]. The silage process can be achieved through the addition of acids, endogenous enzymes, or fermenting agents to the raw material, which, in this case, are FPW, AS, or AW [57].

Fish silage for animal feeding has been widely studied [136–138]. Maksimenko et al. [73] elaborated a review on the use of ensiling technology for fish waste as an aquafeed ingredient. These authors conclude that the use of fish silage as aquafeed has advantages like improving feed acceptance, stimulating nonspecific immunity, and enhancing growth rates, while also highlighting the combined use of AW and FWP as an opportunity to add value sustainably. Additionally, they present a structured compilation of research conducted to test fish silage as an aquafeed ingredient while also proposing to encourage the application of fish waste silage among smallholder producers to mitigate the improper disposal of organic matter and prevent environmental contamination [77].

Nevertheless, considerations regarding the availability of raw materials, as well as socioeconomic and environmental conditions, are important to evaluate the use of fish silage as aquafeed for aquaponics or aquaponic farming. Additionally, it is essential to verify and adhere to local regulations concerning intra-species use, as this practice is banned in some regions. Where it is not banned, safety procedures and controls of processed animal proteins must be considered and standardized [139]. In this regard, combining AW and FPW ensilage as aquaculture feed might be an option for small-scale aquaponics or aquaponic farming, but special attention must be given to safety regulations. To the best of our knowledge, there are no reports on the use of FPW or AW as feed ingredients in aquaponics; thus, further information is needed to evaluate the performance of FPW, AS, and AW, and their potential use as aquafeed or organic fertilizer in aquaponic systems. Some recent studies on silage as aquafeed relevant to aquaponics are presented in Table 1.

Table 1. Examples of recent studies (not covered by the aforementioned reviews) about the production of aquaculture feed ingredients with potential application in rural ICAq.

Process	Plant Specie	Animal Species	Key Findings	References
Production of insect meal with fish and agricultural waste		*Hermetia illucens*	*H. illucens* larvae (BSF) can be reared on agricultural and fish waste and when produced on by-products or waste rich in provitamin A carotenoids could be a sustainable strategy to recycle a fraction of vitamin A back into the food chain; the combination of fish and plant waste (fruit, vegetable, and rice) can be utilized for better mass production of BSF.	[116,118,140,141]

Table 1. *Cont.*

Process	Plant Specie	Animal Species	Key Findings	References
Use of macrophytes as feed ingredients	*Lemna* spp., *Spirodela polyrhiza*	*Oncorhynchus mykiss*, *Cyprinus carpio*, *Oreochromis niloticus*	For *O. mykiss* culture 20% fed protein regular sources (fishmeal and soybean meal) can be substituted with *Lemna minor* without negative effects on the growth performance; *C. carpio* performs better when feeding with diets with partial replacement of soybean meal with *Lemna minor* and *S. polyrhiza;* the inclusion of 15% of *L. minor* as protein source for *O. niloticus* feed provides a similar performance when compared with an isonitrogenous control diet.	[142–145]
	Ipomoea aquatica	*Heteropneustes fossilis*, *Oreochromis niloticus*	*I. aquatica* can replace up to 25% of fishmeal without affecting *O. niloticus* performance; 20% dietary inclusion of *I. aquatica* can be used to increase fatty acids in *O. niloticus*. Fermented *I. aquatica* at 50% inclusion is an adequate protein supplement for *H. fossilis* feed.	[146–148]
	Eichhornia crassipes	*Sander lucioperca*	Diets containing 1.5% of *Eichhornia crassipes* leaves powder (WLP) increased the growth performance of *S. lucioperca* when compared with diets without WLP.	[149]
Ensilage/fermentation	Cassava waste, peel of *Annanas comosus*, molasses, and corn stubble	*Colossoma macropomum*, mix of several species of fish waste, *Oreochromis niloticus*	*C. macropomum* viscera and cassava waste silage are well digested by *C. macropomum;* silage of fish, molasses, fruit, and agricultural waste with *Lactobacillus* B2 reaches stabilization within 14 days and presents high nutrient content; trials on animal feed are still needed. Production of Nile tilapia processing waste silages with 192 h of hydrolysis proved to be viable. Fermented silage processing revealed a better apparent digestibility coefficient than acid silage.	[77,137,150]

As an alternative protein source, additional benefits can be obtained by incorporating insects and macrophytes, silage, or fermented ingredients into fish feed. The nutritional composition of fish, particularly the increase in fatty acids, may improve with the inclusion of macrophytes and/or insects in fish feed [144,145,147]. However, it is necessary to conduct tests on specific combinations of different species, as improvements in fish quality are not always guaranteed [120,142]. Additional benefits from incorporating insect production into aquaponics systems have been observed for RAS and plant components. The use of larvae frass tea (a by-product of insect production) has been shown to improve the nutritional quality of aquaponic vegetable products without compromising fish production or water quality when added to the systems [151]. Furthermore, larvae frass tea enhances the production of fish (*Ictalurus punctatus*) and plants (*Stevia rebaudiana, Lavaridula angustifolia*) when included in fish feed [152]. In the case of silage or fermented ingredients for aquafeed, these can improve fish growth and health performance by providing probiotic benefits, enhancing nutrient availability and bioavailability of feed, increasing the palatability and digestibility, and even eliminating anti-nutritional compounds in dietary feed ingredients [130].

However, research on insect cultivation using aquaponic waste and plant production as aquaculture feed must be undertaken to assess their technical, environmental, and economic viability. Aschenbruck et al. [153] investigated the supply of *H. illucens* larvae needed for *O. niloticus* feeding under controlled environmental conditions in developed countries. Similar studies could be useful for developing countries, with adaptations made according to the seasonal variations, as climate control is generally not available. This evaluation will help determine their utility in enhancing the circularity of aquaponics and advancing into ICAq.

3.4. Fish Welfare and Plant Production for Phytotherapy

Information regarding whether aquaponics has a beneficial effect on aquatic organisms at the physiological level is still scarce. Moreover, one of the main challenges connected with the cultivation of hydrobionts and plants in this culture system is the control of diseases and pathogenic microorganisms [154]. Differences in species, the design of aquaponic systems, water temperature and quality, initial sizes and stocking densities of fish, composition of feed, and feeding rates account for the varying results among studies [155]. The widespread lack of legislation regarding the use of antimicrobials, along with the prohibition of all therapeutic antimicrobials in aquaculture in Europe and the tendency to ban these substances in other regions of the world, has led to an increasing necessity for developing and evaluating new alternative tools in these systems. As a result, there is a priority for researchers to elucidate the effect of aquaponics on fish welfare, with results from some relevant studies presented in Table 2.

Table 2. Different studies evaluating the advantages of aquaponics on aquatic organisms' health.

Species (Animal and Plant)/Reference	Treatments	Analysis (Aquatic Organism)	Conclusion
Dicentrarchus labrax, *Beta vulgaris* [156]	Control, reared at 20 ppt salinity; aquaponics AFI, reared in freshwater (0 ppt), infected with *Amyloodinium ocellatum*; aquaponics, ASI, reared at 20 ppt salinity and infected with *A. ocellatum*	Growth: final body weight (g), survival rate (SR, %), hepatosomatic index (HSI, %), specific growth rate (SGR, %); histology: gills, liver, intestine; cortisol assay; molecular analysis (RNA): 18 s, IGF I, NPY, PPARa, IL-1, TNFa, GR	AFI is more similar to control. For *Dicentrarchus labrax*, an aquaponics system may be used as a solution against *A. ocellatum* infection.
Clarias gariepinus, *Cucumis sativus* [157]	Aquaponics, control	Growth: final length, final weight, FCR, SGR, daily growth rate (DGR, g/fish/day); stress responses: cortisol, blood glucose, and external injuries	Co-cultivation of fish and plants might offer benefits to the welfare of the fish by reducing skin injuries.
Cyprinus carpio L. [154]	Aquaponics without symbiotic, S0; aquaponics with commercial symbiotic (Bio Balance®), S1	Growth: SGR, FCR; physiological: HIS, viscerosomatic index (VSI, %); immunological: phagocytosis activity, bactericide activity, and content of hemoglobin	Positive effect of symbiotic on growth and feed utilization in carp fingerlings.

Table 2. *Cont.*

Species (Animal and Plant)/Reference	Treatments	Analysis (Aquatic Organism)	Conclusion
Clarias gariepinus [158]	PO_4^{3-}-P different concentrations in mg/L: P0 (control), P40, P80, P120	Growth and feed efficiency: final weight, total length, standard length, growth, fillet ratio, SGR, FCR, total feed intake (TFI); body and fillet composition: dry matter, ash, protein, fat, calcium, phosphorus, sodium, magnesium, potassium Apparent net nutrient utilization (ANNU); histology: gills; plasma metabolites: calcium, ammonia, blood glucose, plasma cortisol; behavior: agonistic behavior, group and individual air-breathing and swimming, and biting wounds	Concentrations ranging from 40 to 80 mg/L of PO_4^{3-}-P fall within safe levels for African catfish aquaculture. Elevated values (120 mg/L) affect fish welfare.
Carassius auratus, *Ipomoea aquatica*, *Lactuca sativa*, *Lemna minor*, *Amaranthus tricolor*, *Ceratophyllum demersum*, *Vallisneria spiralis*, and *C. demersum* [159]	Control, only fish (CK); aquaponics with *Ipomoea aquatica* (Ia), *Lactuca sativa* (Ls), *Lemna minor* (Lm), *Amaranthus tricolor* (At), *Ceratophyllum demersum* (Cd), *Vallisneria spiralis* (Vn), and *C. demersum-net* (Cd-ns)	Growth: weight gain rate (WGR, %), SGR (%), feeding ratio (FR, %), food conversion rate (FCR, %); blood chemistry: glucose (GLU), triglyceride (TG), cholesterol (CHOL), creatinine (CREA), urinary nitrogen (BUN), total proteins (TP), albumin (ALB), globulin (GLO) and A/G (calculated by dividing the ALB by the GLO), the activity of alkaline phosphatase (ALP), alanine aminotransferase (ALT), aspartate aminotransferase (AST)	Hydroponic plants were more advantageous for *C. auratus* under intensive conditions by providing more energy to resist environmental stress than the aquatic plants.
Penaeus vannamei, *Ipomoea aquatica*, *Chlorella pyrenoidosa* [160]	S0, aquaculture water without vegetation and chlorella; S1, aquaculture water with water spinach; S2, aquaculture water with chlorella; S3, aquaculture water with vegetation and chlorella	Growth: SR, SGR, weight gain rate (%); activities of the immune enzymes superoxide dismutase (SOD), catalase (CAT), glutathione reductase (GR), glutathione (GSH), glutathione S-transferase (GST), and peroxidase (POD) in the hepatopancreas	Aquaponic shrimp cultivation with water spinach and *Chlorella pyrenoidosa* maintains good water quality, which improves the immunity of *Penaeus vannamei.*
Nile tilapia (*Oreochromis niloticus*) [161]	With and without fertilizer; fertilizer: 580 ppm $CaNO_3$, 280 mg/L KNO_3, 490 mg/L $MgSO_4$, 270 mg/L K_2PO_4, and 48 mg/LNutrel C YaraVita™	Growth: gain weight and length; blood plasma stress indicators: cortisol, glucose, and triglycerides	Fish production parameters were not significantly different between treatments, nor were physiological indicators of fish stress (plasma cortisol, glucose, and triglycerides).
Carassius auratus, *Lactuca sativa* [162]	NC, control, no hypoxia, hypoxia; T0, plant water; T1, fish water; T2, fish and plant water	Growth: FW, SGR, relative growth rate (WGR, %); stress parameters: cortisol, serum glucose; antioxidant parameters: catalase and superoxide dismutase; gene expression profiles: HSP70, Prdx3	There is evidence that the hypoxia stress of crucian carp is reduced in aquaponics.

Nowadays, phytotherapy has emerged in aquaculture as an eco-friendly alternative to chemical drug therapies. It can be administered in several ways, including injection, bathing, orally, and as feed ingredients [163]. Active compounds in plants such as alkaloids, terpenoids, pigments, polyphenols, quinones, lectins, tannins, and polypeptides have demonstrated several of the following effects, including antibacterial, growth-promoting, immune-boosting, appetite-stimulating, and anti-stress properties for aquatic organisms in aquaculture [163–166]. Use of phytotherapy in aquaculture has been widely reviewed [163–166]. For example, a meta-analysis conducted by Chakroborty et al. [167] specifically examined 27 papers on medicinal plants used as feed additives in the Asian region. Their study evaluated 27 papers on medicinal plants as feed additives, revealing positive impacts on fish growth and immunity from plants such as garlic (*Allium sativum*) (allicin), rosemary (*Rosmarinus officinalis*), oregano (carvacrol), *I. batatas*, *Astragalus* sp., and *Psidium guajava*, among others.

A mini-review focusing on medicinal herbs successfully grown in aquaponics identified basil (*Ocimum basilicum*), coriander (*Coriandrum sativum*), parsley *(Petroselinum crispum*), spearmint (*Mentha spicata*), thyme (*Thymus vulgaris*), oregano (*Origanum vulgare*), and dill (*Anethum graveolens*) [168]. However, identification of medicinal plants with proved phytotherapeutic effects suitable for aquaponic culture and in this case suitable for ICAq is needed. Aquaponics has the potential to increase the levels of specific compounds in plants without affecting overall plant production [169–172]. Basil (*Ocimum basilicum*) has shown higher levels of protein, rosmarinic acid, myrcetin, phenolics, antioxidants, and antioxidant activity (on a dry basis) when cultured in aquaponics compared to soil cultivation [169,170]. Also, parsley (*Petroselinum crispum)* cultivated in aquaponics accumulates more resveratrol compared to soil-grown parsley [170]. In addition to herbs, aquaponically grown fruits, such as tomatoes (*Solanum lycopersicum*), exhibit improved antioxidant activity and increased content of specific compounds, such as lycopene and carotenoids, compared to those cultivated in traditional soil [170,173]. Specifically, regarding phytotherapeutic compounds, aquaponics has been demonstrated to have the potential to biostimulate or elicit medicinal plants, thereby increasing their bioactive compounds or antifungal properties [171,172].

Thus, for ICAq, the incorporation of a circular system to produce phytotherapeutic compounds or aquaculture medicinal plants on a farm could be economically advantageous. Depending on several factors such as the application method, the process for active compound extraction, farm size, location, investment capacity, etc., strategies for extending resource value or industrial symbiosis can be applied [45].

Several plants used for therapeutic purposes in aquaculture are also consumed by humans, either for their health benefits or simply as food, including ginger [174], garlic [175], and turmeric [175]. For small-scale or low-resource farms, these plants, along with their extracts or powders, must be purchased at market prices and transported to the farm. Therefore, implementing on-site production within a circular framework for cultivating plants with phytotherapeutic objectives—and, when feasible, producing plant extracts—can offer economic advantages. In this case, strategies for extending resource value could be applied based on factors such as climate suitability, plant culture, and the method of application or active compound extraction to integrate the output of one circular entity as the input for another.

Nevertheless, a higher phytochemical content in aquaponics plants is not always the case, as it varies among different plant species and specific compounds of interest [170,172]. Therefore, for ICAq development, additional studies evaluating the production of diverse medicinal plants used in aquaculture and the concentration of their active com-pounds are needed.

Moreover, the challenges identified in using medicinal plants or plant extracts as phytotherapy for aquaculture must be considered for ICAq. Factors such as plant origin, identification, chemical composition, standardization of tests, identification, and the use of a specific quantity of active molecules, as well as their comparison against a control, must be assessed [165,176]. Additionally, measuring the toxicological effects of herbal remedies in aquaculture requires further investigation to establish safe concentrations or dosages for administration [163]. In the context of aquaponics, aquaponic farming, and ICAq, it is crucial to identify and quantify active compounds from plants with potential applications in aquaculture phytotherapy, as well as to determine the factors affecting their synthesis and accumulation.

3.5. General Considerations for ICAq Research and Implementation

In rural small-scale aquaculture (SSA), aquaponics and aquaponic farming can enhance circularity and/or diversification by integrating one or more of the several circular processes presented in this review. This diversification can lead to increased income stabilization and improved food availability while enhancing environmental sustainability [177,178]. However, at the rural and small-scale levels, food security might be achieved more effectively through the purchase of food items using surplus income generated from fish and crop sales, rather than by increasing personal consumption [178]. Similarly, the integration of on-farm circular processes in ICAq has the potential to enhance the economic performance of the farm by reducing the costs of self-produced inputs. However, it is important to note that higher levels of regional economic benefits may be obtained compared to on-farm economic benefits [177]. Therefore, the integration of one or several on-farm circular processes in SSA, AF, or SSAA farming must be evaluated for its economic viability at the farm level, and process combinations must be assessed.

In this regard, studies focusing on the design and modeling of aquaponics systems within the context of the circular economy have been conducted [35,179,180], which could provide valuable tools for the integration of one or several of the options presented. The model developed by Baganz et al. [35] enables the management of data for circular entities, facilitating the organization of their resource allocation and use within the circular city while considering both material and energy flows. Based on site resource inventory [35], an assessment of inputs and outputs for the design and modeling of ICAq in different and specific contexts can be conducted.

Additionally, developing a framework for the integration of nature-based solutions (NBSs) to address circular economy challenges [181] could be an option to facilitate the incorporation of the potential circular processes described. Models of rural small-scale aquaponic farming must account for seasonal environmental variations due to the lack of climate control [11]. Leveraging ecological wisdom, traditional knowledge, and participatory action can also serve as a strategy for designing and developing integrated aquaculture, ICAq [28,182].

Ultimately, to advance circularity in aquaponics, particularly focusing on small-scale rural applications and the circularity evaluation of integrated culture aquaponics (ICAq), establishing pertinent indicators is vital. Even though research on waste or by-products is available for agriculture and aquaculture, further research on the circular use of aquaponic and IACq waste is needed. Building upon the work of Chary et al. [183], who grouped and summarized farm-level nutrient circularity indicators for integrated aquaculture, a dedicated set of circularity indicators for ICAq, including material, resource, economic, and social aspects, remains necessary (Figure 5).

The future perspectives identified in the article primarily focus on the critical need to advance circularity within small-scale aquaponic systems. Key areas for future investigation include conducting detailed studies to quantify and characterize aquaponic by-products, thereby defining their properties and potential circular uses. Another crucial area is the evaluation of the actual impact and performance of circular inputs generated within integrated circular aquaponics (ICAq) systems on overall production, product quality, and system health. Additionally, demonstrating the technical and economic feasibility of implementing the proposed circular processes in the context of small-scale aquaculture (SSA) is highlighted as essential. Furthermore, the establishment of relevant and adapted circularity indicators specifically for ICAq evaluation is emphasized. These indicators should comprehensively cover material, resource, economic, and social aspects, enabling more precise measurement and comparison. Ultimately, the goal is to encourage innovative solutions that are tailored to specific regional needs and contexts.

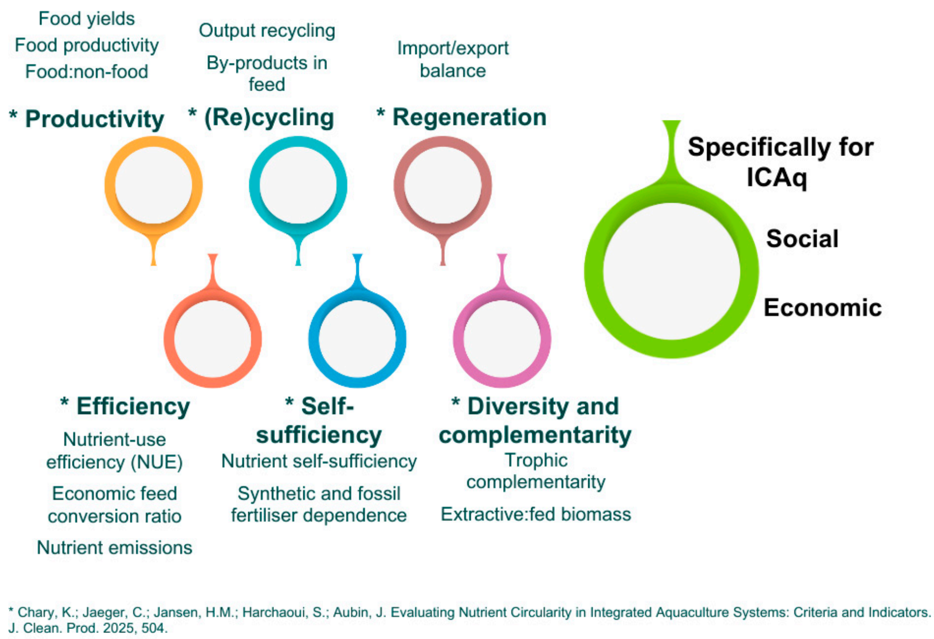

Figure 5. General criterion and selected circularity indicators proposed by Chary et al. [183] to evaluate nutrient circularity in integrated aquaculture systems. Specifically, for ICAq, social and economic criteria are recommended. Therefore, a dedicated set of circularity indicators for ICAq remains necessary.

4. Conclusions

Aquaponic components offer a variety of possibilities for the development of circular food systems. The diverse inputs required and outputs generated in these components present an opportunity to design, redesign, and research production systems within the framework of the circular economy and sustainable value chains.

We propose the term ICAq to refer to a circular production system based on aquaponics or aquaponic farming, in which several processes, beyond aquaponics itself, can be implemented within the farm to increase circularity. The development of ICAq might include the production of fish, plants, compost, fertilizers, energy, fish feed ingredients or additives, and fish therapeutic compounds.

Enhancing circularity of SSA by establishing small-scale integrated circular aquaponics (ICAq) systems bears the potential to promote sustainable rural development, considering the SSA boundary conditions of limited investment, family labor, low levels of formal education among farmers, and the relative isolation of other industries due to their dispersion over large areas, as well as limited access to competitive markets for inputs and products.

Processing technologies that can be implemented in ICAq systems have been studied and are continually evolving for specific industries such as aquaculture, agriculture, phytochemical production, energy generation, and waste treatment. Given the multidisciplinary nature of aquaponics and aquaponic farming and the proposed ICAq, research and implementation of circular systems based on aquaponics should leverage the existing knowledge and research from each discipline.

Study Limitations and Future Perspectives

Given aquaponics' inherent multidisciplinary nature, along with the extensive literature available on agriculture and aquaculture waste treatment, aquafeed advancements, and related processes, and a specific focus on small-scale aquaculture, this review adopted an ad hoc methodology. The comprehensive scope of the review, combined with this methodology and the vast amount of information, necessitated a careful selection of articles.

While this selection process inherently involves some author subjectivity, it ultimately ensures a focused and relevant synthesis. The review then provides a general overview of these processes, offering valuable insights for future studies. However, for a more in-depth understanding and application of these processes within the context of aquaponics or ICAq, further investigation is recommended.

The future perspectives identified in this article primarily focus on the critical needs to advance circularity within small-scale aquaponic systems. Key areas for future investigation include conducting detailed studies to quantify and characterize aquaponic by-products, thereby defining their properties and potential circular uses. Another crucial area is the evaluation of the actual impact and performance of circular inputs generated within integrated circular aquaponics systems on overall production, product quality, and system health. It is essential to demonstrate the technical and economic feasibility of implementing the proposed circular processes in the context of small-scale aquaculture. Furthermore, the establishment of relevant and adapted circularity indicators specifically for ICAq, encompassing material, resource, economic, and social aspects, is emphasized for evaluation. Finally, developing ICAq systems that are tailored to specific regional needs and contexts is highly encouraged.

Author Contributions: Conceptualization, L.S., F.J.M.-C., G.B., D.B., A.H.-P., E.C. and M.C.P.; methodology, L.S.; investigation, L.S.; writing—original draft preparation, L.S. and A.H.-P.; writing—review and editing, F.J.M.-C., G.B., D.B., A.H.-P., E.C. and M.C.P.; visualization, L.S. and E.C.; supervision, F.J.M.-C. and M.C.P.; project administration, L.S.; funding acquisition F.J.M.-C. and M.C.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Mexico National Council of Humanities, Sciences, and Technologies (CONAHCYT) through a postdoctoral research grant to develop the project "Implementación de sistemas agro-acuícolas con cultivo de vegetales de alto valor económico para promover la sostenibilidad ambiental y económica de sistemas de producción acuícola a pequeña escala," as well as Project CONAHCYT-PRONACES 317100, by the São Paulo Research Foundation (FAPESP), under grants 2018/23658-5 and 2017/50431-9, and by the Brazilian National Council for Scientific and Technological Development (CNPq) under grant 307389/2021-9.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SSA	rural small-scale aquaculture
ICAq	small-scale integrated circular aquaponics
SSFs	small-scale fisheries
FAO	Food and Agriculture Organization
EE	ecological engineering
CE	circular economy
RAS	recirculating aquaculture system
NUE	nitrogen use efficiency
AWs	agricultural wastes
APW	aquaculture processing waste
AS	aquaculture sludge
TSs	total solids
VS	volatile solid content
FPW	fish processing waste

AnD	anaerobic digestion
AD	aerobic digestion
TAN	total ammonia nitrogen
ADBR	aerobic digestion bioreactor
SDGs	sustainable development goals

References

1. FAO. *The State of World Fisheries and Aquaculture 2024. Blue Transformation in Action*; FAO: Rome, Italy, 2024; ISBN 978-92-5-138763-4.
2. Garlock, T.; Asche, F.; Anderson, J.; Bjørndal, T.; Kumar, G.; Lorenzen, K.; Ropicki, A.; Smith, M.D.; Tveterås, R. A Global Blue Revolution: Aquaculture Growth Across Regions, Species, and Countries. *Rev. Fish. Sci. Aquac.* **2020**, *28*, 107–116. [CrossRef]
3. FAO. *Guidelines for Sustainable Aquaculture*; FAO: Rome, Italy, 2025; ISBN 978-92-5-139497-7.
4. FAO. *International Year of Artisanal Fisheries and Aquaculture 2022*; Final Report; FAO: Rome, Italy, 2023.
5. FAO. *The International Year of Artisanal Fisheries and Aquaculture 2022*; FAO: Rome, Italy, 2019.
6. Edwards, P. Review of Small-Scale Aquaculture: Definitions, Characterization, Numbers. In *Enhancing the Contribution of Smallscale Aquaculture to Food Security, Poverty Alleviation and Socio-Economic Development*; Bondad-Reantaso, M.G., Subasinghe, R., Eds.; FAO: Rome, Italy, 2013; pp. 37–61.
7. Short, R.E.; Gelcich, S.; Little, D.C.; Micheli, F.; Allison, E.H.; Basurto, X.; Belton, B.; Brugere, C.; Bush, S.R.; Cao, L.; et al. Harnessing the Diversity of Small-Scale Actors Is Key to the Future of Aquatic Food Systems. *Nat. Food* **2021**, *2*, 733–741. [CrossRef] [PubMed]
8. Bondad-Reantaso, M.G.; Prein, M. *Measuring the Contribution of Small-Scale Aquaculture an Assessment*; FAO: Rome, Italy, 2009.
9. Flores-Nava, A. *Diagnóstico de La Acuicultura de Recursos Limitados (AREL) y de La Acuicultura de La Micro y Pequeña Empresa (AMYPE) En América Latina*; FAO: Rome, Italy, 2013; ISBN 978-92-5-307462-4.
10. Martínez-Cordero, F.J.; Delgadillo Tiburcio, S.; Sánchez-Zazueta, E.; Cai, J. *Tilapia Aquaculture in Mexico: Assessment with a Focus on Social and Economic Performance*; FAO Fisheries and Aquaculture Circular No. 1219; FAO: Rome, Italy, 2021.
11. Das, S.K.; Mandal, A. Diversification in Aquaculture Resources and Practices for Smallholder Farmers. In *Agriculture, Livestock Production and Aquaculture: Advances for Smallholder Farming Systems: Volume 1*; Springer International Publishing: Cham, Switzerland, 2022; Volume 1, pp. 263–286; ISBN 978-3-030-93258-9.
12. Islam, A.H.M.S. Dynamics and Determinants of Participation in Integrated Aquaculture–Agriculture Value Chain: Evidence from a Panel Data Analysis of Indigenous Smallholders in Bangladesh. *J. Dev. Stud.* **2021**, *57*, 1871–1892. [CrossRef]
13. Baganz, G.; Junge, R.; Portella, M.C.; Goddek, S.; Keesman, K.J.; Baganz, D.; Staaks, G.; Shaw, C.; Lohrberg, F.; Kloas, W. The Aquaponic Principle—It Is All about Coupling. *Rev. Aquac.* **2022**, *14*, 252–264. [CrossRef]
14. Fernández-Cabanás, V.M.; Suárez-Cáceres, G.P.; Pérez-Urrestarazu, L.; Lobillo-Eguíbar, J.; Gross, J.A. Contribution of Household Aquaponic Production to a Low Price Healthy Mediterranean Diet in an Economically Depressed Community. *Agronomy* **2023**, *13*, 498. [CrossRef]
15. Obirikorang, K.A.; Sekey, W.; Gyampoh, B.A.; Ashiagbor, G.; Asante, W. Aquaponics for Improved Food Security in Africa: A Review. *Front. Sustain. Food Syst.* **2021**, *5*, 705549. [CrossRef]
16. Baganz, G.F.M.; Timpe, A.; Baganz, D.; Staaks, G.; Hunger, B.; Kloas, W.; Lohrberg, F. City or Hinterland—Site Potentials for Upscaled Aquaponics in a Berlin Case Study. *npj Urban Sustain.* **2022**, *2*, 29. [CrossRef]
17. de Korte, M.; Bergman, J.; van Willigenburg, L.G.; Keesman, K.J. Towards a Zero-Waste Aquaponics-Centered Eco-Industrial Food Park. *J. Clean. Prod.* **2024**, *454*, 142109. [CrossRef]
18. Haswell, F.; Edelenbosch, O.Y.; Piscicelli, L.; van Vuuren, D.P. The Geography of Circularity Missions: A Cross-Country Comparison of Circular Economy Policy Approaches in the Global North and Global South. *Environ. Innov. Soc. Transit.* **2024**, *52*, 100883. [CrossRef]
19. Babatunde, A.; Deborah, R.A.; Gan, M.; Simon, T. Economic Viability of a Small Scale Low-Cost Aquaponic System in South Africa. *J. Appl. Aquac.* **2023**, *35*, 285–304. [CrossRef]
20. Bich, T.T.N.; Tri, D.Q.; Yi-Ching, C.; Khoa, H.D. Productivity and Economic Viability of Snakehead Channa Striata Culture Using an Aquaponics Approach. *Aquac. Eng.* **2020**, *89*, 102057. [CrossRef]
21. Yahya, F.; El Samrani, A.; Khalil, M.; Abdin, A.E.-D.; El-Kholy, R.; Embaby, M.; Negm, M.; De Ketelaere, D.; Spiteri, A.; Pana, E.; et al. Decentralized Wetland-Aquaponics Addressing Environmental Degradation and Food Security Challenges in Disadvantaged Rural Areas: A Nature-Based Solution Driven by Mediterranean Living Labs. *Sustainability* **2023**, *15*, 15024. [CrossRef]
22. Adeleke, B.; Cassim, S.; Taylor, S. Pathways to Low-Cost Aquaponic Systems for Sustainable Livelihoods and Economic Development in Poor Communities: Defining Critical Success Factors. *Aquac. Int.* **2022**, *30*, 1575–1591. [CrossRef]
23. Uvarova, I.; Atstaja, D.; Volkova, T.; Grasis, J.; Ozolina-Ozola, I. The Typology of 60R Circular Economy Principles and Strategic Orientation of Their Application in Business. *J. Clean. Prod.* **2023**, *409*, 137189. [CrossRef]

24. UNIDO Circular Economy and Agribusiness Development. Available online: https://www.unido.org/sites/default/files/files/2022-03/Circular%20economy%20and%20agribusiness%20development.pdf (accessed on 13 December 2021).
25. Schönborn, A.; Junge, R. Redefining Ecological Engineering in the Context of Circular Economy and Sustainable Development. *Circ. Econ. Sustain.* **2021**, *1*, 375–394. [CrossRef]
26. Mitsch, W.J.; Jørgensen, S.E. Ecological Engineering: A Field Whose Time Has Come. *Ecol. Eng.* **2003**, *20*, 363–377. [CrossRef]
27. Kangas, P.C. *Ecological Engineering: Principles and Practice*; Lewis Publishers: Boca Raton, FL, USA, 2004; ISBN 978-1-56670-599-8.
28. Costa-Pierce, B. The Principles and Practices of Ecological Aquaculture and the Ecosystem Approach to Aquaculture. *World Aquac.* **2021**, *52*, 25–31.
29. European Commission: Directorate-General for Research and Innovation. *Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-Naturing Cities: Final Report of the Horizon 2020 Expert Group on 'Nature-Based Solutions and Re-Naturing Cities': (Full Version)*; European Commission: Luxembourg, 2015; ISBN 978-92-79-46050-0.
30. Das, S.K.; Mondal, B.; Sarkar, U.K.; Das, B.K.; Borah, S. Understanding and Approaches towards Circular Bio-Economy of Wastewater Reuse in Fisheries and Aquaculture in India: An Overview. *Rev. Aquac.* **2023**, *15*, 1100–1114. [CrossRef]
31. Koul, B.; Yakoob, M.; Shah, M.P. Agricultural Waste Management Strategies for Environmental Sustainability. *Environ. Res.* **2022**, *206*, 112285. [CrossRef] [PubMed]
32. Goyal, S.; Ott, D.; Liebscher, J.; Höfling, D.; Müller, A.; Dautz, J.; Gutzeit, H.O.; Schmidt, D.; Reuss, R. Sustainability Analysis of Fish Feed Derived from Aquatic Plant and Insect. *Sustainability* **2021**, *13*, 7371. [CrossRef]
33. 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]
34. Shaw, C.; Knopf, K.; Klatt, L.; Marin Arellano, G.; Kloas, W. Closing Nutrient Cycles through the Use of System-Internal Resource Streams: Implications for Circular Multitrophic Food Production Systems and Aquaponic Feed Development. *Sustainability* **2023**, *15*, 7374. [CrossRef]
35. Baganz, G.; Proksch, G.; Kloas, W.; Lorleberg, W.; Baganz, D.; Staaks, G.; Lohrberg, F. Site Resource Inventories-A Missing Link in the Circular City's Information Flow. *Adv. Geosci.* **2020**, *54*, 23–32. [CrossRef]
36. Boyd, C.E.; McNevin, A.A.; Tucker, C.S. Resource Use and the Environment. In *Aquaculture Farming Aquatic Animals and Plants*; Lucas, J.S., Southgate, P.C., Tucker, C.S., Eds.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2019; pp. 93–112.
37. Fruscella, L.; Kotzen, B.; Paradelo Perez, M.; Milliken, S. Investigating the Effects of Fish Effluents as Organic Fertilisers on Basil (*Ocimum basilicum*). *Appl. Sci.* **2025**, *15*, 1563. [CrossRef]
38. Kurniawan, S.B.; Ahmad, A.; Imron, M.F.; Abdullah, S.R.S.; Othman, A.R.; Hasan, H.A. Achieving a Biocircular Economy in the Aquaculture Sector Through Waste Valorization. *Toxics* **2025**, *13*, 131. [CrossRef] [PubMed]
39. Lunda, R.; Roy, K.; Másílko, J.; Mráz, J. Understanding Nutrient Throughput of Operational RAS Farm Effluents to Support Semi-Commercial Aquaponics: Easy Upgrade Possible beyond Controversies. *J. Environ. Manag.* **2019**, *245*, 255–263. [CrossRef] [PubMed]
40. Naegel, L.C.A. Combined Production of Fish and Plants in Recirculating Water. *Aquaculture* **1977**, *10*, 17–24. [CrossRef]
41. Alarcón-Silvas, S.G.; León-Cañedo, J.A.; Fierro-Sañudo, J.F.; Ramírez-Rochín, J.; Fregoso-López, M.G.; Frías-Espericueta, M.G.; Osuna-Martínez, C.C.; Páez-Osuna, F. Water Quality, Water Usage, Nutrient Use Efficiency and Growth of Shrimp *Litopenaeus Vannamei* in an Integrated Aquaponic System with Basil *Ocimum basilicum*. *Aquaculture* **2021**, *543*, 737023. [CrossRef]
42. Körner, O.; Bisbis, M.B.; Baganz, G.F.M.; Baganz, D.; Staaks, G.B.O.; Monsees, H.; Goddek, S.; Keesman, K.J. Environmental Impact Assessment of Local Decoupled Multi-Loop Aquaponics in an Urban Context. *J. Clean. Prod.* **2021**, *313*, 127135. [CrossRef]
43. Silva, L.; Hernandez, M.; Escalante, E.; Valdés, D.; Gasca, E. Evaluation of a Semi-Intensive Aquaponics System, with and without Bacterial Biofilter in a Tropical Location. *Sustainability* **2017**, *9*, 592. [CrossRef]
44. 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]
45. Bocken, N.M.P.; de Pauw, I.; Bakker, C.; van der Grinten, B. Product Design and Business Model Strategies for a Circular Economy. *J. Ind. Prod. Eng.* **2016**, *33*, 308–320. [CrossRef]
46. Zou, Y.; Hu, Z.; Zhang, J.; Xie, H.; Liang, S.; Wang, J.; Yan, R. Attempts to Improve Nitrogen Utilization Efficiency of Aquaponics through Nitrifies Addition and Filler Gradation. *Environ. Sci. Pollut. Res.* **2016**, *23*, 6671–6679. [CrossRef] [PubMed]
47. Yang, T.; Kim, H.J. Nutrient Management Regime Affects Water Quality, Crop Growth, and Nitrogen Use Efficiency of Aquaponic Systems. *Sci. Hortic.* **2019**, *256*, 108619. [CrossRef]
48. Cerozi, B.d.S.; Fitzsimmons, K. Use of *Bacillus* Spp. to Enhance Phosphorus Availability and Serve as a Plant Growth Promoter in Aquaponics Systems. *Sci. Hortic.* **2016**, *211*, 277–282. [CrossRef]
49. Cerozi, B.d.S.; Fitzsimmons, K. The Effect of pH on Phosphorus Availability and Speciation in an Aquaponics Nutrient Solution. *Bioresour. Technol.* **2016**, *219*, 778–781. [CrossRef] [PubMed]

50. Cerozi, B.d.S.; Fitzsimmons, K. Effect of Dietary Phytase on Phosphorus Use Efficiency and Dynamics in Aquaponics. *Aquac. Int.* **2017**, *25*, 1227–1238. [CrossRef]
51. Shaw, C.; Knopf, K.; Roy, K.; Ulrichs, C.; Kloas, W. Animal versus Plant Protein Sources in Marine Ingredient-Free Aquaponic Diets: A Case Study on Nutrient Release, and Retention of African Catfish (*Clarias gariepinus*) Reared in RAS. *Aquaculture* **2024**, *584*, 740641. [CrossRef]
52. Shaw, C.; Knopf, K.; Kloas, W. Fish Feeds in Aquaponics and Beyond: A Novel Concept to Evaluate Protein Sources in Diets for Circular Multitrophic Food Production Systems. *Sustainability* **2022**, *14*, 4064. [CrossRef]
53. Ganesh, K.S.; Sridhar, A.; Vishali, S. Utilization of Fruit and Vegetable Waste to Produce Value-Added Products: Conventional Utilization and Emerging Opportunities—A Review. *Chemosphere* **2022**, *287*, 132221. [CrossRef] [PubMed]
54. Ferrer, I.; Lansing, S.; Martí-Herrero, J. (Eds.) *Biogas for Rural Areas*; MDPI: Basel, Switzerland, 2022.
55. Garfí, M.; Martí-Herrero, J.; Garwood, A.; Ferrer, I. Household Anaerobic Digesters for Biogas Production in Latin America: A Review. *Renew. Sustain. Energy Rev.* **2016**, *60*, 599–614. [CrossRef]
56. Mohee Romeela Waste Management Opportunities for Rural Communities. *Composting as an Effective Waste Management Strategy for Farm Households and Others*; FAO: Rome, Italy, 2007.
57. Wu, Y.; Song, K. Source, Treatment, and Disposal of Aquaculture Solid Waste: A Review. *J. Environ. Eng.* **2021**, *147*, 03120012. [CrossRef]
58. Ahuja, I.; Dauksas, E.; Remme, J.F.; Richardsen, R.; Løes, A.-K. Fish and Fish Waste-Based Fertilizers in Organic Farming—With Status in Norway: A Review. *Waste Manag.* **2020**, *115*, 95–112. [CrossRef] [PubMed]
59. Koyama, M.; Nagao, N.; Syukri, F.; Rahim, A.A.; Toda, T.; Tran, Q.N.M.; Nakasaki, K. Ammonia Recovery and Microbial Community Succession during Thermophilic Composting of Shrimp Pond Sludge at Different Sludge Properties. *J. Clean. Prod.* **2020**, *251*, 119718. [CrossRef]
60. Van Tung, T.; Tran, Q.B.; Phuong Thao, N.T.; Vi, L.Q.; Hieu, T.T.; Le, S.; Tuan, N.Q.; Sonne, C.; Lam, S.S.; Hai, L.T.; et al. Recycling of Aquaculture Wastewater and Sediment for Sustainable Corn and Water Spinach Production. *Chemosphere* **2021**, *268*, 129329. [CrossRef] [PubMed]
61. Ebeling, J.M.; Timmons, M.B. *Recirculating Aquaculture Systems. Aquaculture Production Systems*; Cayuga Aqua Ventures: Ithaca, NY, USA, 2010.
62. Piedrahita, R.H. Reducing the Potential Environmental Impact of Tank Aquaculture Effluents through Intensification and Recirculation. *Aquaculture* **2003**, *226*, 35–44. [CrossRef]
63. Lopes, I.G.; Braos, L.B.; Cruz, M.C.P.; Vidotti, R.M. Valorization of Animal Waste from Aquaculture through Composting: Nutrient Recovery and Nitrogen Mineralization. *Aquaculture* **2021**, *531*, 735859. [CrossRef]
64. Araujo, J.; Sica, P.; Costa, C.; Márquez, M.C. Enzymatic Hydrolysis of Fish Waste as an Alternative to Produce High Value-Added Products. *Waste Biomass Valorization* **2021**, *12*, 847–855. [CrossRef]
65. Kim, N.T.Q.; Van Hien, H.; Doan Khoi, L.N.; Yagi, N.; Lerøy Riple, A.K. Quality Management Practices of Intensive Whiteleg Shrimp (*Litopenaeus vannamei*) Farming: A Study of the Mekong Delta, Vietnam. *Sustainability* **2020**, *12*, 4520. [CrossRef]
66. Jasmin, M.Y.; Syukri, F.; Kamarudin, M.S.; Karim, M. Potential of Bioremediation in Treating Aquaculture Sludge: Review Article. *Aquaculture* **2020**, *519*, 734905. [CrossRef]
67. Lenz, G.L.; Loss, A.; Lourenzi, C.R.; de Alcantara Lopes, D.L.; de Matos Siebeneichler, L.; Brunetto, G. Common Chicory Production in Aquaponics and in Soil Fertilized with Aquaponic Sludge. *Sci. Hortic.* **2021**, *281*, 109946. [CrossRef]
68. Bakali, M.E.; Mustapha, A. Phosphorus Waste Production in Fish Farming a Potential for Reuse in Integrated Aquaculture Agriculture. *Int. J. Environ. Agric. Res.* **2021**, *7*, 5–13. [CrossRef]
69. Gonawala, S.S.; Jardosh, H. Organic Waste in Composting: A Brief Review. *Int. J. Curr. Eng. Technol.* **2018**, *8*, 36–38. [CrossRef]
70. Danaher, J.J.; Rakocy, J.E.; Shultz, R.C.; Bailey, D.S.; Pantanella, E. Dewatering and Composting Aquaculture Waste as a Growing Medium in the Nursery Production of Tomato Plants. *Acta Hortic.* **2011**, *891*, 223–229. [CrossRef]
71. Kouba, A.; Lunda, R.; Hlaváč, D.; Kuklina, I.; Hamáčková, J.; Randák, T.; Kozák, P.; Koubová, A.; Buřič, M. Vermicomposting of Sludge from Recirculating Aquaculture System Using *Eisenia andrei*: Technological Feasibility and Quality Assessment of End-Products. *J. Clean. Prod.* **2018**, *177*, 665–673. [CrossRef]
72. Lopes, I.G.; Lalander, C.; Vidotti, R.M.; Vinnerås, B. Using *Hermetia illucens* Larvae to Process Biowaste from Aquaculture Production. *J. Clean. Prod.* **2020**, *251*, 119753. [CrossRef]
73. Maksimenko, A.; Belyi, L.; Podvolotskaya, A.; Son, O.; Tekutyeva, L. Exploring Sustainable Aquafeed Alternatives with a Specific Focus on the Ensilaging Technology of Fish Waste. *Fermentation* **2024**, *10*, 258. [CrossRef]
74. Toppe, J.; Olsen, R.L.; Peñarubia, O.R.; James, D.G. *Production and Utilization of Fish Silage a Manual on How to Turn Fish Waste into Profit and a Valuable Feed Ingredient or Fertilizer*; FAO: Rome, Italy, 2018.
75. Karim, N.U.; Lee, M.A.M.F.; Arshad, A.M. The Effectiveness of Fish Silage as Organic Fertilizer on Post-Harvest Quality of Pak Choy (*Brassica rapa* L. Subsp. Chinensis). *Eur. Int. J. Sci. Technol.* **2015**, *4*, 163–174.
76. Toppe, J.; Olsen, R.L. *Fish Silage Production by Fermentation*; FAO: Rome, Italy, 2024; ISBN 978-92-5-138787-0.

77. Neira, L.M.; Gonçalves, A.M.; Buzollo, H.; de Sandre, L.C.G.; do Nascimento, T.M.T.; Coutinho, J.J.O.; Pizauro Junior, J.M.; Carneiro, D.J. Effect of Acid and Fermented Silage Hydrolysis Time on Protein Fractionation and Digestibility for Nile Tilapia. *Anim. Feed Sci. Technol.* **2024**, *318*, 116126. [CrossRef]
78. Morales-Amaral, M.d.M.; Gómez-Serrano, C.; Acién, F.G.; Fernández-Sevilla, J.M.; Molina-Grima, E. Production of Microalgae Using Centrate from Anaerobic Digestion as the Nutrient Source. *Algal Res.* **2015**, *9*, 297–305. [CrossRef]
79. Choudhury, A.; Lepine, C.; Witarsa, F.; Good, C. Anaerobic Digestion Challenges and Resource Recovery Opportunities from Land-Based Aquaculture Waste and Seafood Processing Byproducts: A Review. *Bioresour. Technol.* **2022**, *354*, 127144. [CrossRef] [PubMed]
80. Wu, Y.; Song, K. Process Performance of Anaerobic Co-Digestion of Waste Activated Sludge and Aquaculture Sludge. *Aquac. Eng.* **2020**, *90*, 102090. [CrossRef]
81. Zhang, X.; Hu, J.; Spanjers, H.; Van Lier, J.B. Performance of Inorganic Coagulants in Treatment of Backwash Waters from a Brackish Aquaculture Recirculation System and Digestibility of Salty Sludge. *Aquac. Eng.* **2014**, *61*, 9–16. [CrossRef]
82. Choudhury, A.; Lepine, C.; Good, C. Methane and Hydrogen Sulfide Production from the Anaerobic Digestion of Fish Sludge from Recirculating Aquaculture Systems: Effect of Varying Initial Solid Concentrations. *Fermentation* **2023**, *9*, 94. [CrossRef]
83. Goddek, S.; Delaide, B.P.L.; Joyce, A.; Wuertz, S.; Jijakli, M.H.; Gross, A.; Eding, E.H.; Bläser, I.; Reuter, M.; Keizer, L.C.P.; et al. Nutrient Mineralization and Organic Matter Reduction Performance of RAS-Based Sludge in Sequential UASB-EGSB Reactors. *Aquac. Eng.* **2018**, *83*, 10–19. [CrossRef]
84. Goddek, S.; Schmautz, Z.; Scott, B.; Delaide, B.; Keesman, K.; Wuertz, S.; Junge, R. The Effect of Anaerobic and Aerobic Fish Sludge Supernatant on Hydroponic Lettuce. *Agronomy* **2016**, *6*, 37. [CrossRef]
85. Zhang, H.; Gao, Y.; Shi, H.; Lee, C.T.; Hashim, H.; Zhang, Z.; Wu, W.-M.; Li, C. Recovery of Nutrients from Fish Sludge in an Aquaponic System Using Biological Aerated Filters with Ceramsite plus Lignocellulosic Material Media. *J. Clean. Prod.* **2020**, *258*, 120886. [CrossRef]
86. Monsees, H.; Keitel, J.; Paul, M.; Kloas, W.; Wuertz, S. Potential of Aquacultural Sludge Treatment for Aquaponics: Evaluation of Nutrient Mobilization under Aerobic and Anaerobic Conditions. *Aquac. Environ. Interact.* **2017**, *9*, 9–18. [CrossRef]
87. Lobanov, V.P.; Combot, D.; Pelissier, P.; Labbé, L.; Joyce, A. Improving Plant Health Through Nutrient Remineralization in Aquaponic Systems. *Front. Plant Sci.* **2021**, *12*, 683690. [CrossRef] [PubMed]
88. Delaide, B.; Panana, E.; Teerlinck, S.; Bleyaert, P. Suitability of Supernatant of Aerobic and Anaerobic Pikeperch (*Sander lucioperca* L.) Sludge Treatments as a Water Source for Hydroponic Production of Lettuce (*Lactuca sativa* L. Var. Capitata). *Aquac. Int.* **2021**, *29*, 1721–1735. [CrossRef]
89. Rajagopal, R.; Mousavi, S.E.; Goyette, B.; Adhikary, S. Coupling of Microalgae Cultivation with Anaerobic Digestion of Poultry Wastes: Toward Sustainable Value Added Bioproducts. *Bioengineering* **2021**, *8*, 57. [CrossRef]
90. Rude, K.; Yothers, C.; Barzee, T.J.; Kutney, S.; Zhang, R.; Franz, A. Growth Potential of Microalgae on Ammonia-Rich Anaerobic Digester Effluent for Wastewater Remediation. *Algal Res.* **2022**, *62*, 102613. [CrossRef]
91. Delaide, B.; Goddek, S.; Keesman, K.J.; Jijakli, M.H.M. A Methodology to Quantify the Aerobic and Anaerobic Sludge Digestion Performance for Nutrient Recycling in Aquaponics. *Biotechnol. Agron. Soc. Environ.* **2018**, *22*, 106–112. [CrossRef]
92. Khiari, Z.; Kaluthota, S.; Savidov, N. Aerobic Bioconversion of Aquaculture Solid Waste into Liquid Fertilizer: Effects of Bioprocess Parameters on Kinetics of Nitrogen Mineralization. *Aquaculture* **2019**, *500*, 492–499. [CrossRef]
93. Madady, M.H.; Sarkheil, M.; Zahedi, S.; Arouei, H. Application of Liquid Organic Fertilizer Produced from Fish Sludge in an Aquaponics System: Influences on Growth of Nile Tilapia (*Oreochromis niloticus*) and Peppermint (*Mentha* × *piperita* L.). *Aquac. Eng.* **2025**, *110*, 102541. [CrossRef]
94. Gillani, S.A.; Abbasi, R.; Martinez, P.; Ahmad, R. Review on Energy Efficient Artificial Illumination in Aquaponics. *Clean. Circ. Bioeconomy* **2022**, *2*, 100015. [CrossRef]
95. Goddek, S.; Körner, O. A Fully Integrated Simulation Model of Multi-Loop Aquaponics: A Case Study for System Sizing in Different Environments. *Agric. Syst.* **2019**, *171*, 143–154. [CrossRef]
96. Maucieri, C.; Forchino, A.A.; Nicoletto, C.; Junge, R.; Pastres, R.; Sambo, P.; Borin, M. Life Cycle Assessment of a Micro Aquaponic System for Educational Purposes Built Using Recovered Material. *J. Clean. Prod.* **2018**, *172*, 3119–3127. [CrossRef]
97. Silva, L.; Valdés-Lozano, D.; Escalante, E.; Gasca-Leyva, E. Dynamic Root Floating Technique: An Option to Reduce Electric Power Consumption in Aquaponic Systems. *J. Clean. Prod.* **2018**, *183*, 132–142. [CrossRef]
98. Tokunaga, K.; Tamaru, C.; Ako, H.; Leung, P. Economics of Small-Scale Commercial Aquaponics in Hawai'i. *J. World Aquac. Soc.* **2015**, *46*, 20–32. [CrossRef]
99. Khaoula, T.; Abdelouahid, R.A.; Ezzahoui, I.; Marzak, A. Architecture Design of Monitoring and Controlling of IoT-Based Aquaponics System Powered by Solar Energy. *Procedia Comput. Sci.* **2021**, *191*, 493–498. [CrossRef]
100. Thorarinsdottir, R.; Unnthorsson, R. Direct Use of Geothermal Resources for Circular Food Production. *Proceedings* **2018**, *2*, 497. [CrossRef]

101. Khan, I.; Kabir, Z. Waste-to-Energy Generation Technologies and the Developing Economies: A Multi-Criteria Analysis for Sustainability Assessment. *Renew. Energy* **2020**, *150*, 320–333. [CrossRef]
102. FAO. *Bioenergy and Food Security (BEFS) Assessment—Seychelles*; FAO: Rome, Italy, 2022.
103. Banerjee, N. Biomass to Energy—An Analysis of Current Technologies, Prospects, and Challenges. *Bioenergy Res.* **2023**, *16*, 683–716. [CrossRef]
104. Saravanan, A.; Karishma, S.; Senthil Kumar, P.; Rangasamy, G. A Review on Regeneration of Biowaste into Bio-Products and Bioenergy: Life Cycle Assessment and Circular Economy. *Fuel* **2023**, *338*, 127221. [CrossRef]
105. Mirzoyan, N.; Tal, Y.; Gross, A. Anaerobic Digestion of Sludge from Intensive Recirculating Aquaculture Systems: Review. *Aquaculture* **2010**, *306*, 1–6. [CrossRef]
106. Zhu, Z.; Yogev, U.; Keesman, K.J.; Gross, A. Onsite Anaerobic Treatment of Aquaponics Lettuce Waste: Digestion Efficiency and Nutrient Recovery. *Aquac. Int.* **2021**, *29*, 57–73. [CrossRef]
107. Kainthola, J.; Kalamdhad, A.S.; Goud, V.V. A Review on Enhanced Biogas Production from Anaerobic Digestion of Lignocellulosic Biomass by Different Enhancement Techniques. *Process Biochem.* **2019**, *84*, 81–90. [CrossRef]
108. Serrano, A.; Siles, J.A.; Chica, A.F.; Martín, M.Á. Agri-Food Waste Valorization through Anaerobic Co-Digestion: Fish and Strawberry Residues. *J. Clean. Prod.* **2013**, *54*, 125–132. [CrossRef]
109. Yogev, U.; Barnes, A.; Gross, A. Nutrients and Energy Balance Analysis for a Conceptual Model of a Three Loops off Grid, Aquaponics. *Water* **2016**, *8*, 589. [CrossRef]
110. Ximenes, J.; Siqueira, A.; Kochańska, E.; Łukasik, R.M. Valorisation of Agri-and Aquaculture Residues via Biogas Production for Enhanced Industrial Application. *Energies* **2021**, *14*, 2519. [CrossRef]
111. Patinvoh, R.J.; Taherzadeh, M.J. Challenges of Biogas Implementation in Developing Countries. *Curr. Opin. Environ. Sci. Health* **2019**, *12*, 30–37. [CrossRef]
112. FAO. *The State of World Fisheries and Aquaculture 2022*; FAO: Rome, Italy, 2022.
113. FAO. *Supporting Local Feed Self-Sufficiency for Inland Aquaculture in Indonesia*; FAO: Rome, Italy, 2020; pp. 1–14.
114. Prabakusuma, A.S.; Wardono, B.; Fahlevi, M.; Zulham, A.; Djoko Sunarno, M.T.; Syukur, M.; Aljuaid, M.; Saniuk, S.; Apriliani, T.; Pramoda, R. A Bibliometric Approach to Understanding the Recent Development of Self-Sufficient Fish Feed Production Utilizing Agri-Food Wastes and by-Products towards Sustainable Aquaculture. *Heliyon* **2023**, *9*, e17573. [CrossRef] [PubMed]
115. Chemello, G.; Biasato, I.; Gai, F.; Capucchio, M.T.; Colombino, E.; Schiavone, A.; Gasco, L.; Pauciullo, A. Effects of *Tenebrio molitor* Larvae Meal Inclusion in Rainbow Trout Feed: Myogenesis-Related Gene Expression and Histomorphological Features. *Ital. J. Anim. Sci.* **2021**, *20*, 1211–1221. [CrossRef]
116. Mangindaan, D.; Kaburuan, E.R.; Meindrawan, B. Black Soldier Fly Larvae (*Hermetia illucens*) for Biodiesel and/or Animal Feed as a Solution for Waste-Food-Energy Nexus: Bibliometric Analysis. *Sustainability* **2022**, *14*, 13993. [CrossRef]
117. Zarantoniello, M.; Zimbelli, A.; Randazzo, B.; Compagni, M.D.; Truzzi, C.; Antonucci, M.; Riolo, P.; Loreto, N.; Osimani, A.; Milanović, V.; et al. Black Soldier Fly (*Hermetia illucens*) Reared on Roasted Coffee by-Product and *Schizochytrium* sp. as a Sustainable Terrestrial Ingredient for Aquafeeds Production. *Aquaculture* **2020**, *518*, 734659. [CrossRef]
118. Paul, P.K.; Awal, M.R.; Choudhury, M.A.R.; Hasan, M.M.; Rahman, M.M.; Ahmed, T.; Rahman, M.M.; Mondal, M.F. Evaluation of Different Food Waste for Sustainable Mass Rearing of Black Soldier Fly (*Hermetia illucens* L) in Bangladesh. *J. Insects Food Feed* **2023**, *9*, 877–884. [CrossRef]
119. Tran, H.Q.; Nguyen, T.T.; Prokešová, M.; Gebauer, T.; Doan, H.V.; Stejskal, V. Systematic Review and Meta-Analysis of Production Performance of Aquaculture Species Fed Dietary Insect Meals. *Rev. Aquac.* **2022**, *14*, 1637–1655. [CrossRef]
120. Maulu, S.; Langi, S.; Hasimuna, O.J.; Missinhoun, D.; Munganga, B.P.; Hampuwo, B.M.; Gabriel, N.N.; Elsabagh, M.; Van Doan, H.; Abdul Kari, Z.; et al. Recent Advances in the Utilization of Insects as an Ingredient in Aquafeeds: A Review. *Anim. Nutr.* **2022**, *11*, 334–349. [CrossRef] [PubMed]
121. Shafique, L.; Abdel-Latif, H.M.R.; Hassan, F.U.; Alagawany, M.; Naiel, M.A.E.; Dawood, M.A.O.; Yilmaz, S.; Liu, Q. The Feasibility of Using Yellow Mealworms (*Tenebrio molitor*): Towards a Sustainable Aquafeed Industry. *Animals* **2021**, *11*, 811. [CrossRef] [PubMed]
122. Mohan, K.; Rajan, D.K.; Muralisankar, T.; Ganesan, A.R.; Sathishkumar, P.; Revathi, N. Use of Black Soldier Fly (*Hermetia illucens* L.) Larvae Meal in Aquafeeds for a Sustainable Aquaculture Industry: A Review of Past and Future Needs. *Aquaculture* **2022**, *553*, 738095. [CrossRef]
123. Maranga, B.; Kagali, R.; Mbogo, K.; Orina, P.; Munguti, J.; Ogello, E. Growth Performance of African Catfish (*Clarias gariepinus*) Fed on Diets Containing Black Soldier Fly (*Hermetia illucens*) Larvae Under Aquaponic System. *Aquac. Stud.* **2023**, *23*, AQUAST910. [CrossRef]
124. Jones, J.J.; Shaw, C.; Chen, T.W.; Staß, C.M.; Ulrichs, C.; Riewe, D.; Kloas, W.; Geilfus, C.M. Plant Nutritional Value of Aquaculture Water Produced by Feeding Nile Tilapia (*Oreochromis niloticus*) Alternative Protein Diets: A Lettuce and Basil Case Study. *Plants People Planet* **2024**, *6*, 362–380. [CrossRef]

125. Pinho, S.; Leal, M.M.; Shaw, C.; Baganz, D.; Baganz, G.; Staaks, G.; Kloas, W.; Körner, O.; Monsees, H. Insect-Based Fish Feed in Decoupled Aquaponic Systems: Effect on Lettuce Production and Resource Use. *PLoS ONE* **2024**, *19*, e0295811. [CrossRef] [PubMed]
126. Camargo-Castellanos, J.C.; Flores-García, L.; Herrera-Díaz, I.E.; Álvarez-González, C.A.; Albertos-Alpuche, P.J.; Martínez-Yáñez, R. System Management of *Lemna minor* in Aquaponics. *Aquac. Res.* **2022**, *53*, 974–988. [CrossRef]
127. Naseem, S.; Bhat, S.U.; Gani, A.; Bhat, F.A. Perspectives on Utilization of Macrophytes as Feed Ingredient for Fish in Future Aquaculture. *Rev. Aquac.* **2021**, *13*, 282–300. [CrossRef]
128. Ma, A.; Ma, O.; Sp, A. Preliminary Assessment of Water Spinach (*Ipomoea aquatica*) and Morning Glory (*Ipomoea asarifolia*) Leaves Meals as Non-Conventional Fish Feed Stuffs. *Int. J. Zool. Anim. Biol.* **2019**, *7*, 446–450. [CrossRef]
129. Hossain, M.M.; Rahman, M.H.; Tina, F.W.; Shahjahan, M. Present Scenario and Prospects of the Use of Aquatic Plants in Aquaculture: A Review. *Aquac. Int.* **2024**, *32*, 6791–6825. [CrossRef]
130. Siddik, M.A.B.; Julien, B.B.; Islam, S.M.M.; Francis, D.S. Fermentation in Aquafeed Processing: Achieving Sustainability in Feeds for Global Aquaculture Production. *Rev. Aquac.* **2024**, *16*, 1244–1265. [CrossRef]
131. Dan, Z.; Zhang, W.; Zheng, J.; Gong, Y.; Cui, K.; Mai, K.; Ai, Q. Effects of Fishmeal Substitution by Four Fermented Soybean Meals on Growth, Antioxidant Capacity and Inflammation Responses of Turbot Juveniles (*Scophthalmus maximus* L.). *Aquaculture* **2022**, *560*, 738414. [CrossRef]
132. Ismail, T.; Hegazi, E.; Nassef, E.; Habotta, O.A.; Gewaily, M.S. The Optimized Inclusion Level of Bacillus Subtilis Fermented Azolla Pinnata in Nile Tilapia (*Oreochromis niloticus*) Diets: Immunity, Antioxidative Status, Intestinal Digestive Enzymes and Histomorphometry, and Disease Resistance. *Fish Physiol. Biochem.* **2022**, *48*, 767–783. [CrossRef] [PubMed]
133. Mugwanya, M.; Dawood, M.A.O.; Kimera, F.; Sewilam, H. Replacement of Fish Meal with Fermented Plant Proteins in the Aquafeed Industry: A Systematic Review and Meta-analysis. *Rev. Aquac.* **2023**, *15*, 62–88. [CrossRef]
134. Cooney, R.; de Sousa, D.B.; Fernández-Ríos, A.; Mellett, S.; Rowan, N.; Morse, A.P.; Hayes, M.; Laso, J.; Regueiro, L.; Wan, A.H.; et al. A Circular Economy Framework for Seafood Waste Valorisation to Meet Challenges and Opportunities for Intensive Production and Sustainability. *J. Clean. Prod.* **2023**, *392*, 136283. [CrossRef]
135. Muniasamy, S.; Rajasekaran, B.; Subramaniam, B.; Muniasamy, S.; Pailan, G.H. Utilization of Fish Waste and By-Products for Fish Meal Production as a Potential Feed Ingredient, Fish Waste to Valuable Products: Recent Applications and Research Update. In *Fish Waste to Valuable Products*; Maqsood, S., Naseer, M.N., Benjakul, S., Zaidi, A.A., Eds.; Springer: Berlin/Heidelberg, Germany, 2024; pp. 301–316.
136. Madage, S.S.K.; Medis, W.U.D.; Sultanbawa, Y. Fish Silage as Replacement of Fishmeal in Red Tilapia Feeds. *J. Appl. Aquac.* **2015**, *27*, 95–106. [CrossRef]
137. Santana, T.M.; Dantas, F.d.M.; Monteiro Dos Santos, D.K.; Kojima, J.T.; Pastrana, Y.M.; De Jesus, R.S.; Gonçalves, L.U. Fish Viscera Silage: Production, Characterization, and Digestibility of Nutrients and Energy for Tambaqui Juveniles. *Fishes* **2023**, *8*, 111. [CrossRef]
138. Vidotti, R.M.; Viegas, E.M.M.; Carneiro, D.J. Amino Acid Composition of Processed Fish Silage Using Different Raw Materials. *Anim. Feed Sci. Technol.* **2003**, *105*, 199–204. [CrossRef]
139. Woodgate, S.L.; Wan, A.H.L.; Hartnett, F.; Wilkinson, R.G.; Davies, S.J. The Utilisation of European Processed Animal Proteins as Safe, Sustainable and Circular Ingredients for Global Aquafeeds. *Rev. Aquac.* **2022**, *14*, 1572–1596. [CrossRef]
140. Dzepe, D.; Kuietche, H.M.; Magatsing, O.; Meutchieye, F.; Nana, P.; Tchuinkam, T.; Djouaka, R. From Agricultural Waste to Chicken Feed Using Insect-Based Technology. *J. Basic Appl. Zool.* **2023**, *84*, 18. [CrossRef]
141. Fabrikov, D.; Morote, E.; Montes, J.; Sánchez-Muros, M.J.; Barroso, F.G.; Rodríguez-Rodríguez, M.; González-Fernández, M.J.; Guil-Guerrero, J.L. Facing the Challenge of Discarded Fish: Improving Nutritional Quality of Two Insect Species Larvae for Use as Feed and Food. *J. Insects Food Feed* **2021**, *7*, 345–355. [CrossRef]
142. Fiordelmondo, E.; Ceschin, S.; Magi, G.E.; Mariotti, F.; Iaffaldano, N.; Galosi, L.; Roncarati, A. Effects of Partial Substitution of Conventional Protein Sources with Duckweed (*Lemna minor*) Meal in the Feeding of Rainbow Trout (*Oncorhynchus mykiss*) on Growth Performances and the Quality Product. *Plants* **2022**, *11*, 1220. [CrossRef] [PubMed]
143. Goswami, R.K.; Sharma, J.G.; Shrivastav, A.K.; Kumar, G.; Glencross, B.D.; Tocher, D.R.; Chakrabarti, R. Effect of *Lemna minor* Supplemented Diets on Growth, Digestive Physiology and Expression of Fatty Acids Biosynthesis Genes of *Cyprinus carpio*. *Sci. Rep.* **2022**, *12*, 3711. [CrossRef] [PubMed]
144. Opiyo, M.A.; Muendo, P.; Mbogo, K.; Ngugi, C.C.; Charo-Karisa, H.; Orina, P.; Leschen, W.; Glencross, B.D.; Tocher, D.R. Inclusion of Duckweed (*Lemna minor*) in the Diet Improves Flesh Omega-3 Long-Chain Polyunsaturated Fatty Acid Profiles but Not the Growth of Farmed Nile Tilapia (*Oreochromis niloticus*). *Anim. Feed Sci. Technol.* **2022**, *292*, 115442. [CrossRef]
145. Shrivastav, A.K.; Kumar, G.; Mittal, P.; Tocher, D.R.; Glencross, B.D.; Chakrabarti, R.; Sharma, J.G. Effect of Greater Duckweed *Spirodela polyrhiza* Supplemented Feed on Growth Performance, Digestive Enzymes, Amino and Fatty Acid Profiles, and Expression of Genes Involved in Fatty Acid Biosynthesis of Juvenile Common Carp *Cyprinus carpio*. *Front. Mar. Sci.* **2022**, *9*, 788455. [CrossRef]

146. Yousif, R.A.; Abdullah, O.J.; Ahmed, A.M.; Adam, M.I.; Mohamed Ahmed, F.A.; Idam, O.A. Effect of Replacing Fishmeal with Water Spinach (*Ipomoea aquatica*) on Growth, Feed Conversion and Carcass Composition for Nile Tilapia Fry (*Oreochromis niloticus*). *J. Aquat. Sci. Mar. Biol.* **2019**, *2*, 13–20. [CrossRef]
147. Chepkirui, M.; Orina, P.S.; Opiyo, M.; Muendo, P.; Mbogo, K.; Omondi, R. Fatty Acids Composition of Nile Tilapia (*Oreochromis niloticus*) Fingerlings Fed Diets Containing Different Levels of Water Spinach (*Ipomoea aquatica*). *J. Agric. Food Res.* **2021**, *5*, 100156. [CrossRef]
148. Nandi, S.K.; Suma, A.Y.; Rashid, A.; Kabir, M.A.; Goh, K.W.; Abdul Kari, Z.; Van Doan, H.; Zakaria, N.N.A.; Khoo, M.I.; Seong Wei, L. The Potential of Fermented Water Spinach Meal as a Fish Meal Replacement and the Impacts on Growth Performance, Reproduction, Blood Biochemistry and Gut Morphology of Female Stinging Catfish (*Heteropneustes fossilis*). *Life* **2023**, *13*, 176. [CrossRef] [PubMed]
149. Rufchaei, R.; Nedaei, S.; Hoseinifar, S.H.; Hassanpour, S.; Golshan, M.; Sayad Bourani, M. Improved Growth Performance, Serum and Mucosal Immunity, Haematology and Antioxidant Capacity in Pikeperch (*Sander lucioperca*) Using Dietary Water Hyacinth (*Eichhornia crassipes*) Leaf Powder. *Aquac. Res.* **2021**, *52*, 2194–2204. [CrossRef]
150. Ramírez-Ramírez, J.; Loya-Olguín, J.; Ulloa, J.; Rosas-Ulloa, P.; Gutiérrez-Leyva, R.; Silva-Carrillo, Y. Aprovechamiento de Desechos de Pescado y Cáscara de Piña Para Producir Ensilado Biológico. *Abanico Vet.* **2020**, *10*, 1–12. [CrossRef]
151. Romano, N.; Powell, A.; Islam, S.; Fischer, H.; Renukdas, N.; Sinha, A.K.; Francis, S. Supplementing Aquaponics with Black Soldier Fly (*Hermetia illucens*) Larvae Frass Tea: Effects on the Production and Composition of Sweetpotato Slips and Sweet Banana Peppers. *Aquaculture* **2022**, *555*, 738160. [CrossRef]
152. Romano, N.; Datta, S.N.; Pande, G.S.J.; Sinha, A.K.; Yamamoto, F.Y.; Beck, B.H.; Webster, C.D. Dietary Inclusions of Black Soldier Fly (*Hermetia illucens*) Larvae Frass Enhanced Production of Channel Catfish (*Ictalurus punctatus*) Juveniles, Stevia (*Stevia rebaudiana*), and Lavender (*Lavaridula angustifolia*) in an Aquaponic System. *Aquaculture* **2023**, *575*, 739742. [CrossRef]
153. Aschenbruck, T.; Esterhuizen, W.; Padmanabha, M.; Streif, S. Sustainability Analysis of Interconnected Food Production Systems via Theory of Barriers. *IFAC-PapersOnLine* **2020**, *53*, 15765–15770. [CrossRef]
154. Sirakov, I.; Velichkova, K.; Stoyanova, S.; Kaymakanova, M.; Slavcheva-Sirakova, D.; Atanasova, R.; Staykov, Y. Effect of Synbiotic Dietary Supplementation on Growth, Physiological and Immunological Parameters in Common Carp (*Cyprinus carpio* L.) Fingerlings and on Yield and Physiological Parameters in Lettuce (*Lactuca sativa* L.), Cultivated in Mesocosmos Aquaponic System. *Bulg. J. Agric. Sci.* **2018**, *24*, 140–149.
155. 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] [PubMed]
156. Nozzi, V.; Strofaldi, S.; Piquer, I.F.; Di Crescenzo, D.; Olivotto, I.; Carnevali, O. Amyloodinum Ocellatum in Dicentrarchus Labrax: Study of Infection in Salt Water and Freshwater Aquaponics. *Fish Shellfish Immunol.* **2016**, *57*, 179–185. [CrossRef] [PubMed]
157. Baßmann, B.; Brenner, M.; Palm, H.W. Stress and Welfare of African Catfish (*Clarias gariepinus* Burchell, 1822) in a Coupled Aquaponic System. *Water* **2017**, *9*, 504. [CrossRef]
158. Strauch, S.M.; Bahr, J.; Baßmann, B.; Bischoff, A.A.; Oster, M.; Wasenitz, B.; Palm, H.W. Effects of Ortho-Phosphate on Growth Performance, Welfare and Product Quality of Juvenile African Catfish (*Clarias gariepinus*). *Fishes* **2019**, *4*, 3. [CrossRef]
159. Gao, Y.; Zhu, G.; Tian, Y.; Li, K.; Zhao, Y.; Liang, J.; Gu, Q.; Li, X. Blood Biochemistry Profile of Qihe Crucian Carp *Carassius auratus* in Different Aquaponic Systems. *Environ. Sci. Pollut. Res.* **2020**, *27*, 42898–42907. [CrossRef] [PubMed]
160. Liu, M.; Yuan, J.; Ni, M.; Gu, Z. Effect of Water Spinach Floating Bed and *Chlorella pyrenoidosa* on Water Quality and Shrimp Growth in an Aquaponics System. *Pol. J. Environ. Stud.* **2022**, *31*, 189–198. [CrossRef]
161. Villarroel, M.; la Lama, G.C.M.D.; Escobar-álvarez, R.; Moratiel, R. Fish Welfare in Urban Aquaponics: Effects of Fertilizer for Lettuce (*Lactuca sativa* L.) on Some Physiological Stress Indicators in Nile Tilapia (*Oreochromis niloticus* L.). *Water* **2022**, *14*, 935. [CrossRef]
162. Mao, H.; Wang, B.; Zhao, J.; Wang, Y.; Du, X.; Shi, Q. Influences of Aquaponics System on Growth Performance, Antioxidant Parameters, Stress Parameters and Gene Expression of Carassius Auratus. *Fishes* **2023**, *8*, 360. [CrossRef]
163. Ng, J.J.Y.; Yusoff, N.A.H.; Elias, N.A.; Norhan, N.A.S.; Harun, N.A.; Abdullah, F.; Ishak, A.N.; Hassan, M. Phytotherapy Use for Disease Control in Aquaculture: A Review of the Last 5 Years. *Aquac. Int.* **2023**, *32*, 2687–2712. [CrossRef]
164. Mariappan, B.; Kaliyamurthi, V.; Binesh, A. Medicinal Plants or Plant Derived Compounds Used in Aquaculture. In *Recent Advances in Aquaculture Microbial Technology*; Academic Press: Cambridge, MA, USA, 2023; pp. 153–207. [CrossRef]
165. Reverter, M.; Bontemps, N.; Lecchini, D.; Banaigs, B.; Sasal, P. Use of Plant Extracts in Fish Aquaculture as an Alternative to Chemotherapy: Current Status and Future Perspectives. *Aquaculture* **2014**, *433*, 50–61. [CrossRef]
166. Chakroborty, K.; Lima, R.A.; Hossain, M.F.; Rafiquzzaman, S.M. Biobased Functional Feed Additives in Asian Aquaculture: Trends, Impacts, and Future Directions. *Anim. Feed Sci. Technol.* **2025**, *320*, 116222. [CrossRef]

167. Sumana, S.L.; Xue, T.; Hu, H.; Abdullateef, M.M.; Shui, Y.; Ayana, G.U.; Kayiira, J.C.; Zhang, C.; Samwel, B.J.; Zhu, J.; et al. Medicinal Plants as Ecological Solutions for Fish Growth and Immunostimulatory Effects in Aquaculture. *Aquac. Res.* **2025**, *2025*, 9778623. [CrossRef]
168. Stoyanova, S.; Sirakov, I.; Velichkova, K. Sustainable Production: Integrating Medicinal Plants with Fish Farming in Aquaponics—A Mini Review. *Sustainability* **2024**, *16*, 6337. [CrossRef]
169. Albadwawi, M.A.O.K.; Ahmed, Z.F.R.; Kurup, S.S.; Alyafei, M.A.; Jaleel, A. A Comparative Evaluation of Aquaponic and Soil Systems on Yield and Antioxidant Levels in Basil, an Important Food Plant in Lamiaceae. *Agronomy* **2022**, *12*, 3007. [CrossRef]
170. Braglia, R.; Costa, P.; Di Marco, G.; D'Agostino, A.; Redi, E.L.; Scuderi, F.; Gismondi, A.; Canini, A. Phytochemicals and Quality Level of Food Plants Grown in an Aquaponics System. *J. Sci. Food Agric.* **2022**, *102*, 844–850. [CrossRef] [PubMed]
171. Flores-Aguilar, P.S.; Rico-Chávez, A.K.; Rodriguez-deLeón, E.; Aguirre-Becerra, H.; Zamora-Castro, S.A.; Soto-Zarazúa, G.M. Bioactive Compounds of Endemic Medicinal Plants (*Cuphea* spp.) Cultured in Aquaponic Systems: A Short Study. *Agriculture* **2023**, *13*, 2018. [CrossRef]
172. Zantanta, N.; Kambizi, L.; Etsassala, N.G.E.R.; Nchu, F. Comparing Crop Yield, Secondary Metabolite Contents, and Antifungal Activity of Extracts of *Helichrysum odoratissimum* Cultivated in Aquaponic, Hydroponic, and Field Systems. *Plants* **2022**, *11*, 2696. [CrossRef] [PubMed]
173. Delgadillo-Díaz, M.; Gullian-Klanian, M.; Sosa-Moguel, O.; Sauri-Duch, E.; Cuevas-Glory, L.F. Evaluation of Physico-Chemical Characteristics, Antioxidant Compounds and Antioxidant Capacity in Creole Tomatoes (*Solanum lycopersicum* L. and *S. pimpinellifolium* L.) in an Aquaponic System or Organic Soil. *Int. J. Veg. Sci.* **2019**, *25*, 124–137. [CrossRef]
174. Ashry, A.M.; Habiba, M.M.; El-Zayat, A.M.; Badreldeen, A.H.; Younis, N.A.; Ahmed, H.A.; El-Dakroury, M.F.; Ali, M.A.M.; Dawood, M.A.O. Effects of Ginger (*Zingiber officinale*) on the Growth Performance, Digestive Enzyme Activity, Antioxidative Response, and Antibacterial Capacity of Striped Catfish (*Pangasianodon hypophthalmus*) Reared in Outdoor Conditions. *Aquac. Rep.* **2023**, *33*, 101760. [CrossRef]
175. Bhadra, S.; Krishnani, K.K.; Sharma, A.; Sahoo, U.; Majeedkutty, B.R.A. *Curcuma longa* and Allium Sativum as Health Promoters in Genetically Improved Farmed Tilapia (GIFT)—A Green Drug Approach in Hi-Tech Aquaculture Using Biofloc. *Aquaculture* **2024**, *582*, 740516. [CrossRef]
176. Reverter, M.; Tapissier-Bontemps, N.; Sarter, S.; Sasal, P.; Caruso, D. Moving towards More Sustainable Aquaculture Practices: A Meta-Analysis on the Potential of Plant-Enriched Diets to Improve Fish Growth, Immunity and Disease Resistance. *Rev. Aquac.* **2021**, *13*, 537–555. [CrossRef]
177. Freeman, K.K.; Valencia, V.; Baraldo, J.; Schulte, R.P.O.; van Zanten, H.H.E. On-Farm Circular Technologies for Enhanced Sustainability: The Case of Uruguay. *J. Clean. Prod.* **2022**, *372*, 133470. [CrossRef]
178. Wang, Q.; Rossignoli, C.M.; Dompreh, E.B.; Su, J.; Griffiths, D.; Htoo, K.K.; Nway, H.M.; Akester, M.; Gasparatos, A. Diversification Strategies Have a Stabilizing Effect for Income and Food Availability during Livelihood Shocks: Evidence from Small-Scale Aquaculture-Agriculture Systems in Myanmar during the COVID-19 Pandemic. *Agric. Syst.* **2024**, *217*, 103935. [CrossRef]
179. Baganz, G.; Schrenk, M.; Körner, O.; Baganz, D.; Keesman, K.J.; Goddek, S.; Siscan, Z.; Baganz, E.; Doernberg, A.; Monsees, H.; et al. Causal Relations of Upscaled Urban Aquaponics and the Food-Water-Energy Nexus—A Berlin Case Study. *Water* **2021**, *13*, 2029. [CrossRef]
180. Roy, K.; Kajgrova, L.; Mraz, J. TILAFeed: A Bio-Based Inventory for Circular Nutrients Management and Achieving Bioeconomy in Future Aquaponics. *New Biotechnol.* **2022**, *70*, 9–18. [CrossRef] [PubMed]
181. Langergraber, G.; Castellar, J.A.C.; Pucher, B.; Baganz, G.F.M.; Milosevic, D.; Andreucci, M.B.; Kearney, K.; Pineda-Martos, R.; Atanasova, N. A Framework for Addressing Circularity Challenges in Cities with Nature-Based Solutions. *Water* **2021**, *13*, 2355. [CrossRef]
182. Yang, B.; Young, R.F. (Eds.) *Ecological Wisdom: Theory and Practice*; EcoWISE; Springer: Singapore, 2019; ISBN 978-981-13-0570-2.
183. Chary, K.; Jaeger, C.; Jansen, H.M.; Harchaoui, S.; Aubin, J. Evaluating Nutrient Circularity in Integrated Aquaculture Systems: Criteria and Indicators. *J. Clean. Prod.* **2025**, *504*, 145414. [CrossRef]