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Review

Horticultural Irrigation Systems and Aquacultural Water Usage: A Perspective for the Use of Aquaponics to Generate a Sustainable Water Footprint

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Abstract: The expansion of food production is becoming more important due to a rising world population, which is relying on food security on regional and local scales. Intensive food production systems exert a negative impact on the regional ecosystem because of agrochemical pollution and nutrient-rich water discharging into nearby rivers. Furthermore, these systems highly depend on regional water resources, causing water scarcity and soil erosion due to the overexploitation of natural resources in general. The objective of this article is to review the water usage in the two most water-intensive food production systems, agriculture and aquaculture, showing lacking areas like system management and climate change, which must be considered in the implementation of a sustainable water footprint. In addition, the review includes an analysis of the combination of both production systems in aquaponic food production and the possibilities of water saving. There are a variety of analyses related to water usage for crop and aquatic animal production, but in these analyses, there is a lack of information about system management in general, which includes cleaning processes, water substitution, pond removal, water evaporation, and, especially in aquaculture, the water usage required for industrially elaborated fish feed.

Keywords: food production; food security; sustainability; water resources

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Citation: Schoor, M.; Arenas-Salazar, A.P.; Parra-Pacheco, B.; García-Trejo, J.F.; Torres-Pacheco, I.; Guevara-González, R.G.; Rico-García, E. Horticultural Irrigation Systems and Aquacultural Water Usage: A Perspective for the Use of Aquaponics to Generate a Sustainable Water Footprint. *Agriculture* **2024**, *14*, 925. https://doi.org/10.3390/agriculture14060925

Academic Editor: Ronald Kennedy Luz

Received: 7 May 2024
Revised: 7 June 2024
Accepted: 10 June 2024
Published: 12 June 2024

1. Introduction

The last few years have shown the importance of increasing agricultural production output and food security to support the rising world population [1], which is expected to increment by up to 30% in the next 40 years [2]. Therefore, the food industry has adopted profitable grain varieties [3] and genetically modified grains and introduced new plant technologies [4] to create better food security and productivity [5]. These methods have formed a high dependency on agrochemical products [6], causing an impact on agricultural soil due to certain contamination, erosion, pollution, and plague resistance [7], which can lead to high social [5] and biodiversity-based effects in the long term [7]. Moreover, it is projected that the enhancement of the remaining farmland using the intensification of plants still requires new agricultural cultivation areas, which could accelerate the environmental impacts [2].

One of the biggest consequences of the enhancement of the current agricultural food production systems is the rise in nitrogen fertilization, which can aggravate water pollution because fertilizers cannot completely be absorbed via the different types of crops [8]. Therefore, the overuse of different agrochemical products (fertilizers, pesticides, and herbicides) is causing not only soil deterioration but also retention due to their chemical nature [9].

In addition, substantial groundwater contamination is leading to the destruction of natural habitats and, in the long term, can lead to a variety of human health problems [10] due to the presence of nitrogen, phosphorous, and persistent chemical pesticide residues' concentration in drinking water [11].

The intake of water resources into the food production chain highly relies on the irrigation system used and its characteristics; the most common systems for monoculture plant production are surface irrigation, drip irrigation, sprinkler irrigation, and sub-surface drip irrigation [12]. Depending on the system design, every irrigation method has its own advantages and disadvantages in water employment for plant production processes and ecological impact due to the use of the different materials [13]. Irrigation system designs have different water footprints and freshwater consumption rates to support plant production in the elaboration of a final food product [14]. Thus, the agricultural industry is searching for and examining the optimization of many possibilities with higher crop yield numbers and a more positive ecological impact [15]. In general, agricultural food production is a water-intensive industry [14,16] with an estimated freshwater use of 70% of the worldwide natural water resources, which is employed in different irrigation systems to irrigate 25% of the world's cropland [17].

Aquaculture is another water-intensive sector of food production that is contributing to food security [18], requiring great freshwater inputs for the production process of aquatic animals [19]. Terrestrial aquaculture is considered part of the blue revolution due to the domestication of the aquatic landscape to generate more food inside a functional ecosystem, but today's aquacultural production is exercised in intensive monoculture, causing pollution attributable to the emission of waste materials, aquatic feed contamination, and nutrient discharges [20]. Moreover, aquacultural food production is an increasing industrial sector that requires even more access to and use of groundwater resources [21].

The understanding of the freshwater consumption rate of the agricultural industrial sector and aquacultural food production has put a focal point on the analysis of the global groundwater depletion rate [22] by putting the water consumed in contrast to the natural renewal rate of freshwater [23]. Moreover, the natural renewal rate of freshwater is important to quantify the hydric resources needed to sustain the world's ecosystem [24]. It has been demonstrated that there has been a lack of quantification of the global water footprint [25], which could help avoid the depletion of water resources [26]. Therefore, the hydric footprint definition for agricultural food production needs to consider the three major water resources, which are the use of surface and groundwater resources (blue water footprint), the consumption of rainwater resources for plant production (green water footprint), and the wastewater residuals coming from agricultural production processes (gray water footprint) [27].

In the past, there have been a variety of studies on different crops and plants to determine the water footprint of their production processes, including tomato, maize, strawberry, and wheat [14]. There are similar studies about water usage in the production of aquatic animals like tilapia, carp [28], and catfish [29].

Furthermore, there is an elevated potential to optimize the use of water in agriculture and aquaculture by boosting the development of new technologies or the enhancement of conventional irrigation and achieving a better exploitation rate for water [30]. In addition, sustainable technologies can minimize water contamination [31]. Therefore, it is necessary to establish a complex soil–water–food–energy nexus to create an equilibrium involving the productivity rate and the stability of the ecosystem inside the different sustainable food production processes [32]. One recent example of this improvement in production systems is the creation of vertical farming systems in combination with IoT-based water optimization, which is contributing to the enhancement of metabolite profiles of plants and is an example of introducing a more sustainable production method [33].

Moreover, there is an effective use of water employment in the production of two different food products using only one hydric income in the production system [34] based on an ancient food production system [35]. One of the most famous food production systems, which uses only one water income and produces products by incorporating fish and plant production into one system, is aquaponics [36]. Furthermore, aquaponics takes advantage of concentrated fish residuals in aquacultural wastewater as a fertilizer to stimulate plant growth [37]. To be employed in a proper way, aquacultural wastewater can be used in a soil-based open aquaponic system [38], in a closed recycling aquaponic system [39], or in a decoupled aquaponic system [40]. The reuse of water resources can support more sustainable food production and contribute to food security by producing two different kinds of proteins in one system [41].

Therefore, the objective of this article is to review the water usage in agricultural irrigation systems and aquacultural fish production systems in comparison to the combination of both production systems in aquaponic food production, which optimizes the water usage in different system designs and compares the water footprint characteristics of these systems.

2. Literature Research Methodology

This systematic review was performed with the objective of establishing comparative information about the water footprint in agricultural, aquacultural, and aquaponic food production in different areas that have to be considered in the future. Therefore, this study was achieved through intensive research, mainly in the Elsevier, Wiley, Taylor & Francis, MDPI, and Google Scholar databases, reviewing 203 articles from different countries using traditional agricultural irrigation, aquaculture, and aquaponic production systems and underpinned by articles from countries using high technology for food production. The differentiation into distinct food production systems guided the methodology into four main sections and a specified subsection regarding irrigation system characteristics by analyzing the reflection of the water footprint, and it excluded sections on food production systems.

Therefore, we posed the following specific questions to analyze the water footprint concepts and considerations in agricultural, aquacultural, and aquaponic food production systems and the systems' water supply:

1. What is the impact of water-intensive food production systems (agriculture, aquaculture, and aquaponics)?
2. What water supply or irrigation systems are used?
3. Are there wastewater or water surpluses considered in the water footprint?
4. What could be a possible ecological impact of using this kind of system?

We sought to answer the mentioned questions by (1) analyzing the water usage in agricultural, aquacultural, and aquaponic food production, (2) linking natural water resources to their employment in the production system, (3) analyzing wastewater reuse, and (4) assessing environmental contamination due to wastewater discharged into the environment.

The analysis of agricultural, aquacultural, and aquaponic food production systems was performed by reviewing the water employment of the system according to the water footprint definition of the Water Footprint Network and the natural resources used. Furthermore, in agricultural and aquaponic food production systems, we analyzed the irrigation systems used for plant production. In addition, we analyzed whether the systems' water input could be reused in other production processes, like whether aquacultural wastewater could be employed again in a different type of food production (plant irrigation).

It was also considered whether a wasteful usage of water or wastewater discharge could cause environmental affectations that could be avoided via the use of new technologies or innovative production system solutions. Therefore, we intended to compare the water usage of traditional agricultural and aquacultural food production with a more innovative production solution in aquaponics, taking into account system management, which may not be considered in the water footprint definition.

This investigation was performed via research in three different languages, English, Spanish, and German, to obtain information from different scientific investigations, research, and experiments that helped explain in a better way the diverse water footprints and water employment in different food production systems. In general, the information collected in this manuscript was gained from 2021 to 2024, and in very specific cases, basic concepts described in research published before 2021 were considered.

3. Groundwater Employment for Agricultural Irrigation

The expanding world population and the impacts of climate change require an appropriate use of hydric resources in food production [42] because water resources are fundamental to gaining food security due to their high usage in different food production processes [43,44]. In general, the agricultural food production industry is one of the leading water-consuming sectors with the lowest return per unit of water used in product development [45]. Nowadays, regional rainy seasons are shorter, and temperatures are higher, which leads to the evaluated evaporation rates of water and insufficient storage systems creating a deficit of hydric resources [46]. The considerations of more efficient use of water resources are important due to the low possibilities of cropland expansions and to guarantee food production productivity [47].

Therefore, plant farmers are in need of advancing in new irrigation methods and are forced to implement more water-efficient strategies, which compromise fewer water units by maintaining the same or obtaining a higher production rate [17,48]. The effective usage of water also has an economic impact because the under- and overuse of water in complex irrigation systems are incrementing operational costs, especially for smaller farmers due to lower economic benefits at the end of the production cycle [49].

Even if agricultural irrigation technology had undergone further developments and improvements to give answers to challenges presented via nature and obstacles to food production in past decades [50], there are a variety of irrigation systems used, such as surface irrigation, drip irrigation, sprinkler irrigation, and sub-surface drip irrigation, around the world (Figure 1) [12].

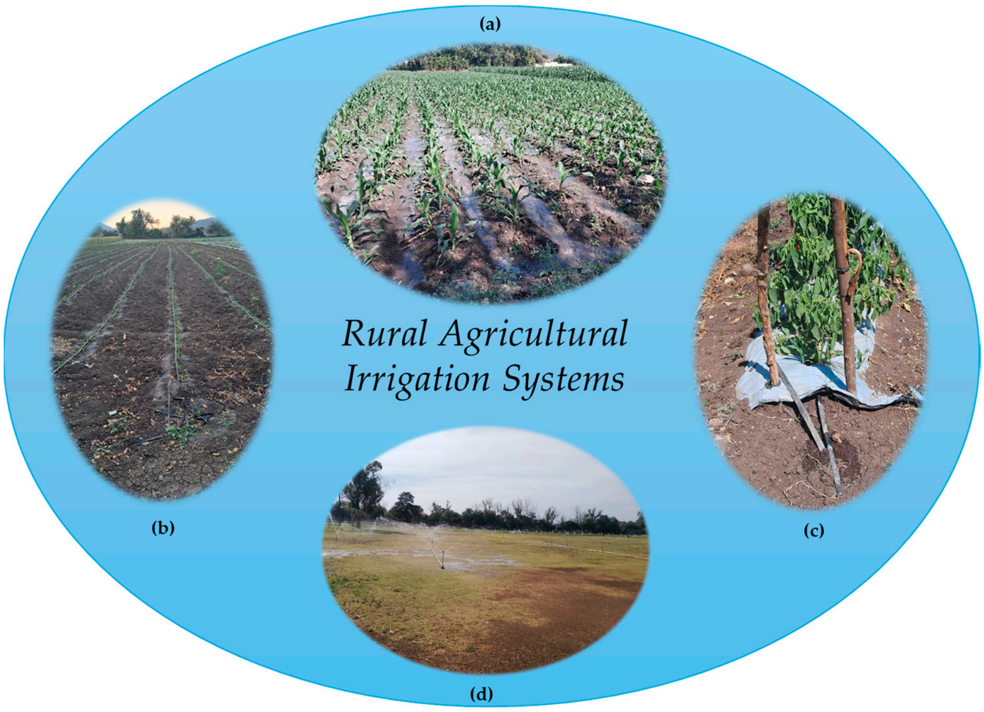

Figure 1. Images of rural agricultural irrigation systems: (**a**) surface irrigation; (**b**) drip irrigation; (**c**) sub-surface drip irrigation; (**d**) sprinkler irrigation.

3.1. Surface Irrigation

Surface irrigation is a very common irrigation system around the world and even if it shows a lack of efficiency, it is still utilized in more than nine percent of the world's cropland which are based on implemented irrigation systems [51,52]. The implementation of surface irrigation requires soil preparation, commonly raised beds and furrows [53] to canalize water movement across plant fields adding hydric resources to the plant roots. Therefore, surface irrigation uses flooding or semi-flooding of the planted cropland using the field gravity to contribute water to the soil in three different categories: furrow irrigation, border irrigation, and basin irrigation [54].

Often, surface irrigation strategies are supported through the large-scale use of agrochemicals with excessive usage of nitrogen fertilizers, causing high rates of absorbable residues in deep soil layers [55]. Moreover, the high usage of nitrogen fertilizers constantly contaminates groundwater layers, which is affecting the safety of potable water [56] and changing the physicochemical and structural properties of soil permeabilities' microbial activities [57]. In rural areas with uncomplicated access to surface water (rivers and lakes), this irrigation method is a very common system for watering plants by redirecting surface water into small channels supplying the cropland, but one of the biggest disadvantages is the irregularity of the plant water supply [58], which can do more harm than good to the cultivated area [59].

The function of an agroecosystem and cropland soil fertility is reflected in the water drainage rate and water retention rate, the nutrient capacity, erosion risks, and the existent microbial soil communities [53]. Studies have shown that surface irrigation causes less soil salinity and maintains a low salinity scale, but the soil pH increases in comparison to different drip irrigation systems. Moreover, it has been shown that, in surface irrigation systems, Na, Ca^{2+}, Mg^{2+}, and K soil concentrations are lower than in drip irrigation systems [60]. Moreover, the surface irrigation of furrow or raised-bed systems needs constant crop management for the verification of soil pH, electrical conductivity, and nutrient disposability to foment plant growth [61].

In countries with the absence of rainfall seasons due to the effects of climate change [62], water management is increasingly important [63]. Therefore, surface irrigation or furrow irrigation systems need to be constantly evaluated and monitored to determine whether low infrastructural investments, the cost of the energy supply, and general cost efficiency still align with the availability of natural resources to maintain these kinds of systems [51]. Poor irrigation management has affected the efficiency of surface irrigation, but there is still a high potential for new technological developments due to the affinity of mechanized agriculture [64]. The future of surface irrigation lies in innovative modifications and improvements regarding on proper design and land leveling to enhance the efficiency of whole systems [65].

3.2. Irrigation Systems Based on Drip Lines

In many agricultural regions, farmers implement crop or plant irrigation systems based on drip lines, the most common of which are surface drip irrigation or sub-surface irrigation.

3.2.1. Drip Irrigation

Drip irrigation systems are based on a micro-irrigation method using plastic irrigation tape or hoses [66], which contributes water directly to the plant roots in an efficient way and, at the same time, reduces the evaporation rate and drainage losses of water [67,68]. By applying drip irrigation, it is possible to control the soil temperature, saving water via precision irrigation and, in this way, creating a positive usage rate for hydric resources [48]. Furthermore, this kind of system facilitates the application of fertilizers and decreases their quantity because fertilizers can be applied directly in plastic hose lines from the irrigation system to plants [60]. Moreover, drip irrigation has improved agricultural food production because there are no restrictions to the yield size, and it optimizes the cropping depth for cultivated plant species [69]. In addition, drip irrigation increments land suitability by 38% in comparison to surface irrigation and increments water and land usage by supporting efficient nutrient plant distribution, causing less plant stress, which provides a superior yield and crop quality, minimizing the plant waste products by the end of a harvest [60].

There is no question about the importance of irrigation technologies in relation to the economic management of natural resources due to climate change; drip irrigation is especially increasing resource efficiency significantly [67]. One big problem of this system is the high use of different types of plastic, the short life of the material, and difficulties in retreating all materials and parts of the system from cropland after the end of the production cycle [70]. Furthermore, plastic products require accurate storage to avoid different types of contamination and degradation in rivers, lakes, and oceans caused by microplastics [71]. Therefore, materials for drip irrigation systems also require accurate storage to avoid soil contamination due to damaged and degraded system parts, which could be blown away in the wind and mixed with soil during cropland preparations [72]. In addition, it must be possible for the stored waste materials of the drip irrigation system to enter a recycling process [73]. Due to these high standards, drip irrigation systems are not commonly used in developed or underdeveloped countries because of costly technology equipment and infrastructure requirements [59]. Climate change makes it necessary to put more emphasis on irrigation systems and technologies that permit water-saving strategies, including drip irrigation and enabling the accurate management of valuable natural resources [74,75]. Studies have shown that the persistence of water needs in plant production requires special designs of drip irrigation systems, taking into consideration the availability of natural water sources and a water-saving strategy to limit water employment in drip irrigation systems [67].

3.2.2. Sub-Surface Drip Irrigation

Sub-surface drip irrigation systems are defined as low-pressure, highly efficient irrigation systems based on an underground or hidden soil dripper system in which water is deliberately supplied into soil-covered dripper tubes or drip tape with micro-irrigation emitters [76]. Micro-irrigation permits partial soil wetting at a high application frequency and the transportation of soil properties, which place less importance on the water storage capacity [77].

The effect of sub-surface drip irrigation generates significant hydric resource savings by lowering water evaporation and extending the life cycle of the materials used in the entire system [78]. The advantage of subsurface drip irrigation is less employment of hydric resources, providing more consistency in soil water and the nutrient environment, which leads to crop growth optimization [76]. Moreover, subsurface drip irrigation has a better yield performance than overground drip irrigation due to efficient water usage [79]. The disadvantages are related to some external impacts affecting the irrigation system, of which the most important are climate effects, soil type, and crop cultivation [76]. Also, soil salinity, soil water redistribution, and the application of agrochemical products can affect the interaction between plant roots and soil, affecting the growth of cultivated crops in the long term [80]. Moreover, a big problem for sub-surface drip irrigation is the possibility of soil degradation and the loss of fertile cropland caused by deep leakage and concentrated soil salinity [81]. Subsurface drip irrigation implies, for farmers, high investments in infrastructure installations and difficult handling processes for the system [13] because of the effects on soil nutrients due to a reduction in soil moisture [82].

A viable alternative to subsurface drip irrigation is subsurface irrigation using ceramic water emitters [83]. This irrigation technology also distributes water directly to the plant roots using an interconnected microspore of a ceramic emitter [84]. Also, using ceramic emitters for subsurface irrigation is water-saving, and the product is developed from natural materials using the molded sintering method [85]. Ceramic emitters in subsurface irrigation systems are energy-efficient and water-saving, which allows for the implementation of this technology in arid and semi-arid regions [86], and it has been utilized in the small-capacity farming industry [84].

3.3. Sprinkler Irrigation

Sprinkler Irrigation technology is based on water distribution via high-overhead-pressure sprinklers, which permits the support of plants with water by piping water to a central location on cropland to contribute hydric resources via sprinklers to plants [87]. This enables uniform water transportation into plant fields [88]. Therefore, rotor sprinklers are a solid irrigation method that radiates a constant spray above the plants, which is the most common method of providing sufficient water for plant growth [12]. Like drip irrigation, sprinkler irrigation is capable of supporting plant growth with nutrient solutions and pesticides for plant protection against plagues [89,90]. Furthermore, labor and applications of agrochemicals are more efficient and less intensive in sprinkler irrigation systems compared to surface irrigation using irrigation canals due to the constant water flow and its consequent nutrient loss [88].

One of the biggest problems with sprinkler irrigation is the high usage of water and the effects on plants due to high-water applications, which can cause fungal effects on plant leaves [91]. In addition, sprinkler irrigation systems could cause water surface runoff and overflows, consequently increasing the water–soil erosion of the cropland through a decline in drainage and nutrient soil properties. In addition, the decline in soil humus content, porosity, moisture capacity, water permeability, and biogenicity leads to a general soil density increase [92]. The technological concept permits a higher evaporation rate and external effects due to wind and air humidity [93]. Furthermore, this system requires a high infrastructure investment and has high energy costs for plant production [94]; also, the efficiency of sprinkler irrigation depends on the demographic characteristics of the farm [88].

In winter time, financial and yield losses due to frost damage affect farmers [95]; various studies have shown that sprinkler irrigation systems are feasible for frost protection. Sprinkler technology gives farmers the opportunity to employ water during frosty nights, spraying water on their plant fields to generate a crop-protecting ice shield to prevent frost damage [93], which gives the technology a future in food production. Also, the latest technological advancements, especially the introduction of the Internet of Things (IoT), make it possible to implement smart sprinkler irrigation, which simplifies farming and plant production in general by monitoring the irrigation status, sprinkler flow strength, and water usage [96]. Moreover, it is possible to use a smart irrigation control with different electronic devices [97], which improves the production quality and yield [96].

In general, extensive agricultural production activities, especially in rural areas, put regional water resources in danger, causing the degradation of water quality and a decline in underground freshwater levels [98]. In addition, climate change and the scarcity of water in many countries induce farmers to improve the water efficiency of their irrigation systems [78] in order to generate a positive hydric footprint, depending on the efficiency in comparison to the yield of every production systems, but every mentioned system faces the same problem: the single employment of water income for food production to produce only one food product outcome, which is equal to a traditional aquacultural food production system.

4. Groundwater Usage and the Environmental Impact in Aquacultural Food Production

As much as agricultural food production, aquacultural fish farming also has a key role in food security because this type of food production is capable of reducing food shortages and avoiding the exploitation of international fish markets [99]. Recent years have shown that the consumption of food elaborated in aquaculture has incremented [20], but this increased demand for elaborated products based on aquatic animal production and the advanced use of production spaces has created a critical ecological impact [100].

These ecological impacts are the overuse of natural resources due to aquacultural production, in which two of the biggest problems are the high use of freshwater [101] and water pollution because of untreated wastewater discharge into the environment [102], which causes a high impact on the ecosystem [103]. Inland aquacultural food production has a high freshwater consumption rate and a high dependency on nearby natural water resources [104], and it requires nearby water streams, lakes, or groundwater deposits [105]. Aquacultural food production is still an expanding economic sector, which is leading to an increase in the water footprint rate of 4.6% [106]. Furthermore, the last 15 years have shown a growth rate in aquaculture production between 2007 and 2018; this could come to an end because of freshwater limitations and water scarcity [107]. Although there is still a high demand for piscary products, which gives aquacultural food production the mentioned major role in food security [99,108], especially in developing countries with low and middle incomes [109], the consequence of water limitations could cause a decrease in terrestrial aquaculture production systems, triggering ecological and social impacts [108].

Freshwater dependency and water scarcity could be some of the main reasons for the possible downturn in aquacultural fish production [110], even if future human food production depends on aquaculture products as an important contributing part of food security [111]. In addition, the lack of biodiversity protection regulations and the absence of a push for the implementation of new technological solutions could also have negative environmental impacts [112], even if there is a socioeconomic advantage in favor of aquacultural food production [108].

A second problem in aquacultural food production is the return of wastewater residuals with high aquatic effluent concentrations back into the environment [21], causing surface water pollution in the local ecosystem [55]. Moreover, aquaculture wastewater nutrient emissions have high concentrations of fish aliments based on fishmeal and fish oil, contributing high water pollution in nearby aquifers [108]. Local ecosystems can bio-process aquaculture residues [113,114], but the high quantity of introduced aquacultural wastewater causes the eutrophication of rivers and lakes [115]. Furthermore, aquacultural wastewater residuals emitted into a local ecosystem without proper treatment can cause algal blooms [116,117]. For this reason, aquacultural production requires the implementation of new technologies [118] or an optimization of existing technologies to avoid negative impacts on local environments [119,120]. Normally, algae are a nutritious source of aquatic animal feed due to their beneficial properties and capacity to convert atmospheric carbon into this nutritious aquatic animal feed, but untreated waste emission can create a toxic environment due to excessive algae production [118].

Nevertheless, life cycle assessment strategies are essential for sustainable fish production and to generate a positive ecological footprint [108,121]. There has been variability in investigations about life cycle assessments and the quantification of sustainability in aquacultural food production [118], especially in comparison to the production of other animals (cows, chicken, and pigs) [106], but the life cycle assessment methods are presently not capable of measuring the interactions between the natural aquatic environment and aquacultural food production [121].

Even if aquacultural food production is considered part of the Blue Revolution due to the high demand for food [122] and is important in achieving sustainable development goals [103], the lack of wastewater treatment puts the achievement of this goal at risk [123].

Nowadays, climate change and wastewater scarcity require the reuse of water resources in an essential way to respond to the increase in global food demand [124]. FAO projects show the need to increment global food production by 50% to satisfy this global food demand [123]. New concepts focused on water reuse are necessary because, in some countries in Asia, aquaculture production has an important role in food security and represents 90% of today's aquacultural production worldwide [125]. Furthermore, insufficient knowledge of wastewater treatment and good sanitary practices requires farmers' capacity to avoid contamination [126], as well as the misusage of pharmaceuticals, which can be concentrated in fish tank sediments [127]. The discharge of fish tank sediments into the environment and the contamination of surrounding aquifers [128,129] can also pose human health risks due to ground and drinking water contamination [130].

The future of aquacultural food production needs to face a lot of challenges, including the preservation of water quality, cost effectiveness, food quality, and space utility [99], but one of the most important is waste compound usage, which is important to transform the system into a sustainable production method [129]. Nowadays, different and new technologies are helping transform aquacultural food production with the use of sensors, artificial intelligent models [131], or the introduction of the Internet of Things to make production management easier [132]. Wastewater treatment is one of the most important aspects, and the future lies in the capacity to remove a high quantity of residues using different biofilter and recirculation systems [133,134] with different plants and aquatic animals to avoid damaging nutrient discharged into the environment [117].

Therefore, the optimization of water usage to create a positive, sustainable impact is fundamental for food production. The combination of agricultural plant production and aquacultural fish production in one system, aquaponics, could help reduce the water consumed due to one hydric resource income in one system that is capable of producing two different proteins for human consumption [135].

5. Optimization of Groundwater Employment in Aquaponic Food Production

The interrelationship between traditional agriculture and aquacultural food production systems is due to the codependency of groundwater resources [104,136]. This water dependency makes it viable to increment the water usage of agricultural irrigation systems [137], water recirculation, and the use of different filters in aquaculture [138]. Moreover, the combination of these two production methods achieves general water footprint optimization [139]. Therefore, the incorporation of both production methods into one system, called aquaponics [140], benefits the use of two central resources for human activities, food production, and water usage optimization [141], by using only one water income to produce foods that contain proteins of plant and animal origin, among other nutrients [142].

Aquaponic food production systems are based on water usage optimization, employing one income of freshwater for fish production and reutilizing this nutrient-enriched water income, fish wastewater residues [143], as hydration and fertilizer to promote plant growth [144,145]. The combination of fish and plant production in one aquaponic system can have different designs for food production, which have been modified and adapted in the last decades [140]. The most common aquaponic system design is based on water recirculation in a single loop between the fish tank and the hydroponic plant production system [146], also called coupled aquaponic systems using fish residues directly as plant nutrition [147]. Coupled aquaponic systems are characterized by their simple handling and production management, but it has been observed that one of the biggest challenges is the optimization of environmental and water quality conditions for fish and plant production due to the single-loop recirculation system [148].

In the last few years, a decoupling aquaponic system came into the focus of investigators due to the separation between fish and plant production in a multi-loop water circulation system instead of a recirculation system [149]. Decoupled aquaponic systems use aquaculture residues in a separated, decoupled recirculating system, one for oxygenation and water recirculation in fish production and one for water and nutrient circulation in the hydroponic system [150]. Decoupled aquaponic systems permit the supply of additional plant nutrients based on aquaculture wastewater and an additional mineral fertilizer supply without affecting fish production, promoting the most efficient plant growth and yield [151].

The differences between these distinct aquaponic system designs are the different contribution rates of the water nutrient concentration from each system contributing to the plant growth in the plant production area. Both recirculating aquaponics and decoupled aquaponics are capable of granting a substantial reduction in water use [34] due to the maximized exploitation of aquacultural wastewater and the controlled use of these water resources [135].

The plant production area of these systems varies between different hydroponic system designs, which benefits the wastewater income usage in the different recirculation configurations:

(i) The floating raft technology—based on a floating Styrofoam raft above the water line of the fish tank, implementing a system where the roots of the plants move under the waterline and absorb the nutrients of fish effluents concentrated in the tank [152].
(ii) The gravel bed technology—based on a substrate (organic or inorganic)-filled growing bed to support plant development with recirculating aquaculture wastewater residues watering the plants using nutritious fish effluents [153,154].
(iii) The nutrient film technique—based on grow-bed channels or grow beds in pipes by recirculating fish wastewater residues through plant roots and providing nutrients to plants [155].

A less-known aquaponic system is open aquaponics, which consists of an aquaponic food production system based on soil plant production using aquaculture effluents as water and fertilizer supply in an implemented agricultural irrigation system [38]. Open aquaponics is also known as a wastewater irrigation system, utilizing nutrient-rich aquacultural wastewater as organic fertilizer and hydric support in plant production, which is also implemented in plant-based wastewater treatments [135].

Therefore, open aquaponic systems combine aquacultural fish and soil plant production by integrating wastewater effluents from the aquaculture production into a land crop irrigation system to provide water and organic nutrients to the plant-cultivated area [156]. In this special system design, there is no water recirculation; moreover, the water income for plant irrigation is used only once and requires a higher water usage rate [38] but still reutilizes wastewater.

In general, the purpose of aquaponic food production is the employment of wastewater resources from aquacultural production in plant production to optimize water usage via the use of only one water income and avoiding or minimizing the use of agrochemicals due to the biofertilization of nutrient concentrations in fish effluents [141].

Recirculating or decoupled aquaponic systems have an advantage over open aquaponics because of the lower consumption of water resources, even if all three systems reuse wastewater and prevent surface or groundwater pollution by evading nitrogen nutrient contamination [157,158]. Moreover, these aquaponic system designs can be used in a denitrification process for water due to water filtration in hydroponic systems [145]. In contrast, open aquaponics are capable too of optimizing water usage in food production [38], but this system design can still cause soil pollution if there is an uncontrolled application of concentrated nutrients in aquaculture wastewater [38,159].

There are a variety of investigations related to aquaponic food production and system sustainability, which support the reduction in different environmental impacts; nevertheless, subjects related to the actual impact of aquaponic food production, water usage, including the welfare management of aquatic animal production, and the emission of wastewater effluents require more investigation.

6. The Importance of the Water Footprint in Food Production Systems

Water efficiency is very important in the achievement of the Sustainable Development Goals for 2030 implemented by the United Nations, which include five important key goals for food production: water security, food security, environmental health, energy security, and economic stability [160]. The use of fresh water for food production is the biggest industrial sector using worldwide groundwater resources, which account for around 92% of the world's total water usage [161]. Nowadays, water scarcity is causing major concerns about the availability of water due to the worldwide employment of fresh water, which requires the implementation of water footprint analysis in different food production systems [162]. Therefore, measuring a water footprint is important, according to Hoekstra and Mekonnen, who presented the differentiation between its types (Table 1) [163]:

Table 1. Water footprint types.

Water Footprint	Characteristics
Green	Rainwater resources Seasonal water supply Suitable for crop production
Blue	Surface and groundwater resources Evaporation effects Used in different production areas
Gray	Polluted water resources Outputs from production processes High ecological impact

In agricultural food production, the water footprint takes into account all water resources required for the different production processes, which in agriculture have the highest water usage around the world and create the need for the implementation of more efficient irrigation methods and water management [164]. Therefore, the water footprint is fundamental to agricultural food production to evaluate water efficiency in order to implement and make improvements to water usage concepts [165]. The water categories of the water footprint definition used to specify the water employment in agriculture are the green and blue water footprints. They refer to water employment for crop consumption from rainwater, the surface, and groundwater [109]. In general, the agricultural water footprint depends on the type of crop produced and takes into account the volume of water consumed during the whole production process from the plant-sowing and -growth process and ends with the harvest [166]. Moreover, the water footprint in agricultural food production can be defined as the amount of water resources employed by humans to generate different kinds of food products, taking into consideration the production perspective, the inter-regional agricultural product trade, and the virtual water flow [167]. Therefore, regional and local water shortages have to be put into focus to guarantee ecological sustainability and, consequently, the importance of reducing the water footprint for crop production [168].

Regional and local water shortages require an extended review of water sustainability for crop production, of which the blue water footprint is less impactful in the global water performance assessment than the green water footprint, which presents more water scarcity on a global scale and pollution due to excessive nitrogen introduction [166]. In general, the blue water footprint is more impactful in crop production in arid regions than the green water footprint, but it all depends on local water resource management [169]. Different studies have shown that the water footprint of crop production could be reduced by changing crop varieties and agricultural management [170]. Therefore, the number of varieties of investigations to define the use of the different water footprints (green, blue, and gray) has included whole countries and regions, agricultural irrigation systems, and aquatic animal production [166].

The water footprint for aquacultural food production is essential because it shows the direct (water for animal production) and indirect (animal feed) usage of fresh water in aquatic animal production [171]. Moreover, aquacultural food production does not use water that is suitable for human consumption [172]. Furthermore, water losses expected from aquacultural food production include ponds via seepage or infiltration, evaporation [173], water for fish production [174], and systems' cleaning processes using a siphon [175] or water replacements. Also, the aquacultural water footprint for food production depends on the aquatic species produced in this type of terrestrial farming system [171]. The production of aquatic animals in regions suffering from freshwater scarcity limits terrestrial aquacultural food production and requires new freshwater usage concepts [106] and taking into account the reduction in grain-based animal feed for aquacultural production, maximizing the aquaculture water footprint by utilizing fewer water-consuming aliments [176].

In general, aquacultural food production systems can impact the surrounding ecosystem negatively due to residues emitted into the environment, also known as polluted water, expressed in the gray water footprint [109]. In addition, there is a big difference between the human consumption of marine fish and terrestrial aquaculture because marine-captured fish or marine aquacultural fish production has a water footprint close to zero [177]. Moreover, the future prospection is a water footprint increase of 4.6% in water usage if marine food production is reinstalled in terrestrial aquacultural production [106]. The availability of blue and green water for aquacultural production highly depends on rainfall, subject to the risk of flooding events and the possibility of longer drought seasons, which could limit regional aquacultural food production due to climate change [171].

As mentioned, in traditional agriculture, the demand for water is high, the same as the costs for fertilizers and irrigation systems' construction; in addition, the possibilities for yield expansion are limited due to land scarcity and cropland losses [161]. Aquacultural production has also been considered a food production sector with a high demand for natural water resources and, at the same time, creating certain ecological and environmental impacts due to gray water discharged into the environment [173], which makes the incorporation of both systems into aquaponics suitable for accomplishing more water efficiency [178].

In aquaponic systems, there are two types of water employment: blue water resource inputs for aquacultural production [179] and the use of the residues of this production as gray water to fertilize and irrigate plants in different types of aquaponic cultivation beds [180]. Furthermore, aquaponic systems use a lower water input and, therefore, have a better water use efficiency with a range between 95% and 99% [161], but the water quality of aquacultural discharge and residue use for food production is critical due to possible food and groundwater contaminations, which can also lead to possible human health risks [98].

In general, water usage in aquaponic systems is altered via fishpond discharge and fish feeding, evaporation, and evapotranspiration [181], but there can be water usage optimization processes attributable to mechanical water movement via water pumping, rainfall, and runoff, which can reduce water losses to only certain discharge, minimizing water evaporation and seepage losses [182]. The type of plant cultivation in different hydroponic system designs used in aquaponics does not represent a significant impact on the possible water loss [183]. Therefore, the water footprint of aquaponic systems is remarkably better than that in conventional agricultural production systems with the side effect of a fertilizer cost reduction. In the future, the importance will lie in the incorporation of new technologies, the optimization of aquacultural residue water employment, and water management [161]. Furthermore, the minimization of the water footprint in aquaponics can only be guaranteed through a suitable system design and the optimization of the ratios of fish water to plants in order to ensure water efficiency and nutrient circulation [178].

In addition, the quantification of water consumed has the objective of implementing more efficient water use practices by analyzing four different stages of water footprint implementations: (1) goals and scope setting, (2) water footprint accounting, and (3) the sustainable analysis of the water footprint and, in the case of sustainability deficits, the concept of achieving sustainable water usage [162].

7. Discussion

The rising demand for fresh water on a worldwide scale for food production using traditional agricultural or terrestrial aquacultural production systems in an industrialized measure [104] and, at the same time, expanding regional droughts due to climate change are affecting global food security [184]. These environmental impacts, with effects on food production through the use of intensive farming practices, dramatically affect local water quality due to the pollution of rivers, lakes, and groundwater, consequently limiting regional water availability [185]. Therefore, every day, it is becoming more important to implement water footprints for specific crops and aquatic animals in food production [165], taking into account the advantages and disadvantages of the production system mentioned (Table 2).

Table 2. Important aspects of agricultural irrigation, aquaculture, and aquaponics.

System	Advantages	Disadvantages
Agricultural irrigation	- Direct plant water application - Provision of nutrition and minerals - Increase in crop yield - Intensified production cycles - Possibility of producing different plant species	- Single water usage - Emission of agrochemicals - Soil erosion and scarcity - Soil contamination via plastic materials
Aquaculture	- Reduced production spaces - Low-cost production of seafood - Avoids maritime overfishing - Plague and disease control	- Single water usage - Constant wastewater discharges - Environmental nutrient emission and eutrophication - Unsustainable fish feed production
Aquaponics	- Water usage optimization - Single water input for two products - Wastewater reuse and water plant treatment - Use of wastewater nutrient concentration	- Possibility of plant contamination - Environmental contamination due to cleaning processes - Unsustainable fish feed production - Lack of water footprint information

In agricultural food production, there is a variety of investigations about the water footprint of different plants exploited in intensive agricultural production systems, including maize [186], wheat, rice [164], potatoes, cabbages, lettuce, spinach, tomatoes, cauliflowers, pumpkins, aubergines, peppers, onion, beans, dates [187], wolfberries, grapes, pomegranates, and strawberries [188]. In addition to the investigated plants, there have to be an extension and incorporation of new agriculturally produced crops, plants, and fruits according to consumers' preferences and new food trends. The investigation of new water-saving irrigation methods, the enhancement of traditional irrigation systems, and sustainable production systems are vital to guarantee high crop yield rates [189] and a positive water footprint. Therefore, new technologies have to be implemented especially in countries with rural areas that have an insufficient economic capacity to invest in new irrigation technologies in order to support the minimization of the agricultural water footprint [190].

The goal has to be the implementation of sustainable food production practices to avoid groundwater contamination from agrochemicals and residue discharges to protect the environmental ecosystem [31]. Therefore, water quality management is fundamental in measuring the geographical and temporal fluctuations in regional water characteristics and parameters [191], in addition to a strategy to promote organic and biologically orientated fertilizers and pesticides [31].

In aquacultural food production, there are some studies about the water footprint of tilapia production in relation to beef production [28] or the water footprint of catfish production [29], but there is still potential to investigate even more water footprints of different aquatic animal species produced in aquacultural food production by also taking different climate zones into account [192]. Furthermore, there has to be more investigations, including aquacultural system management, water substitutions during cleaning processes, pond removals, water losses due to filter use, evaporation due to local climates [193], and water usage to produce fish feed [194]; all of these aspects will provide more information to analyze the sustainability of different systems.

Regional water management is essential to verify the quantity of local water resources and establish regional water footprints in order to control water usage compared to the natural groundwater regeneration and climate change effects [195]. Moreover, the implementation of regional water footprints could help determine whether agricultural or aquacultural food production is suitable for a region and define which are the most profitable crops, plants, fruits, and aquatic animals to produce in order to enhance local food security [196].

Aquaponics could be a food production system that permits a better understanding of water usage and water optimization using different hydroponic system designs for plant production [140,148,197]. The implementation of these system designs depends on the local space and characteristics, the availability of freshwater, and the regional climate because of water evaporation [144]. The different aquaponic system designs are capable of water optimization in different categories, with open aquaponic systems using soil plant production being the system that employs aquaculture wastewater residues only in an agricultural irrigation system that also provides organic fertilizer [38], which still optimizes water usage. More efficient are recirculation and decoupled aquaponic systems due to the constant reuse of aquacultural wastewater and the application in plant nutrition [40,135,198]. These systems need more plastic and metallic materials to construct infrastructure but are more capable of being adapted to any space and even to places without fertile soil [199].

Food production in aquaponic systems could be a feasible solution to save water and create a positive water footprint [178] due to the incorporation of fish and plant production in one system and the reuse of aquacultural wastewater for plant production [140]. A lot of authors only mention in their aquaponic water footprint investigations water reuse in the production of fish and plants [161] and do not consider the water resources needed for water substitutions, evaporation losses, possible water leaks in the system, or the water employed for animal feed. Also, the water footprint must be defined according to the local climate [200] and whether aquaponic food production is accurate for certain climates and the existence of water resources, also taking into account gray water discharged into the environment [201]. More investigations are necessary concerning the water footprint in aquaponic food production, including the different types of production systems and the cleaning and management process to control the different types of water employment and define whether aquaponics is a suitable solution for food production in some rural areas.

8. Conclusions

Nowadays, there is a real threat to food security due to the still-growing world population, which requires a need for higher yields in food production. In many countries, there exists a cropland limitation and water scarcity, which makes it impossible to increase the cropland space for more food production yield. Furthermore, the last few years have shown that global crises can also affect food production, causing food shortages for countries without the capability of implementing more traditional or innovative production methods. In general, agricultural production requires large amounts of fresh water from natural water resources and high-technology developments to optimize water usage and yield productivity while minimizing the environmental impact to protect local biodiversity.

In addition, in many countries, aquaculture has also been considered a help to secure global food security with the production of aquatic animals in small locations. In the same way as agriculture, aquacultural production is also in need of large quantities of fresh water and the regular substitution of water to keep production running, which leads to great environmental problems because of the possible fish effluent contamination in lakes, rivers, groundwater, and local biodiversity.

The high water consumption of agriculture and aquaculture could be counteracted by using aquaponic systems for organic food production. The combination of plant and fish production is viable to reduce water consumption and, at the same time, create a positive environmental impact. However, there is still a need for more investigations of food production in aquaponic systems, like studies on the incorporation of aquaponics into cycle economic systems, the effects of water quality on the plant production system due to water contaminants like antibiotics, or the impact of wastewater discharged into the environment during system cleaning processes. It is true that aquaponic food production is more sustainable than traditional agriculture or aquaculture, so there is potential for many subjects, such as those mentioned before, to be investigated in order to maintain or enhance actual sustainability and optimize system management processes.

Author Contributions: M.S., A.P.A.-S., B.P.-P., J.F.G.-T., I.T.-P., R.G.G.-G. and E.R.-G. worked equally on this manuscript's conceptualization, information search, writing, and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: Schoor, M., and Arenas-Salazar, AP., thank the Faculty of Engineering of the Autonomous University of Querétaro for supporting their postgraduate studies.

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

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