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Horticulture Irrigation Systems and Aquaculture 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 getting more important due to a rising world population, which is relying on food security on a regional and local scale. Intensive food production systems create a negative impact on the regional ecosystem because of agrochemical pollution and nutrient rich water discharges into nearby rivers. Furthermore, these systems are highly depending 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 sustainable water footprint. In addition, the review includes an analysis if the combination of both production system into aquaponic food production and the possibilities of water saving. There are a variety of water footprint analyses for crop and aquatic animal production, but there is also a lack of information about the system management including irrigation systems, system cleaning processes, water substitution, pond removal, evaporation due to climate change and especially in aquaculture, the water footprint of industrial elaborated fish feed.

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

1. Introduction

The last years have shown the importance of an increasing agricultural production output and food security to support the rising world population [1], which is expected to increment up to 30% in the next 40 years [2]. Therefore, the food industry has adopted profitable grain varieties [3], genetic modified grains and introduced new plant technologies [4] to create a 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 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 raise of nitrogen fertilization which can aggravate water pollution, because fertilizers cannot completely be absorbed by the different types of crops [8]. Therefore, the over usage of different agrochemical products (fertilizers, pesticides, herbicides) is not only causing soil deterioration and retention due to their chemical nature [9]. In addition, a substantial groundwater contamination is leading to the destruction of natural habitats and in the long term can posture a

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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 is highly relying on the used irrigation system and its characteristics; being the most common systems for monoculture plant production; surface irrigation, drip irrigation, sprinkler irrigation and sub-surface drip irrigation [12]. Depending on the system design, every irrigation method has its own advantage and disadvantage of water employment in 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]. Therefore, the agricultural industry is searching 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 being employed in different irrigation systems to irrigate 25% of the worlds cropland [17].

Aquaculture is another water intensive sector of food production which 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 todays aquacultural production is exercised in intensive monoculture causing pollution due to the emission of waste materials, aquatic feed contamination and nutrient discharges [20]. Moreover, aquaculture food production is an increasing industrial sector, which requires even more access and use of groundwater resources [21].

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

In the past, there have been a variety of studies of different crops and plants to determine the water footprint of their production processes, including tomatoes, maize, strawberry or wheat [14]. There are similar studies about the water usage in the production of aquatic animals like tilapia, carp [28] or 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 with the enhancement of conventional irrigation and getting a better exploitation rate of water [30]. In addition, sustainable technologies can minimize water contamination [31]. Therefore, it is necessary to establish a complex soil–water–food and 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 of production systems is the creation of vertical farming systems in combination with a IoT based water optimization is contributing to the enhancement of metabolite profiles of plants and which is an create example to introduce a more sustainable production method [33].

Moreover, there is an effective use of water employment in the production of two different food products by using only one hydric income into 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 by incorporating fish and plant production in one system is aquaponics [36]. Furthermore, aquaponics is taking advantage of concentrated fish residuals in aquaculture wastewater as fertilizer to stimulate plant growth [37]. To employe in a proper way aquacultural

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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 to proteins in one system [41].

Therefore, the objective of this article is to review the water usage in agricultural irrigation systems and aquaculture 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 compare the water footprint characteristics of these systems.

2. Literature Research Methodology

This systematic review was performed with the objective to establish comparative information about the water footprint in agriculture, aquaculture and aquaponic food production with different areas which have to be considered in the future. Therefore, this research was achieved through by an intensive research mainly in Elsevier, Wiley, Taylor & Francis, MDPI and Google Scholar databases. The differentiation into the distinct food production systems guidance the methodology into four main section and specific subsection regarding irrigation system characteristics by analyzing the reflection of water footprint and excluded sections on the food production systems.

Therefore, we implemented the following sub 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, aquaponics)?
2. What water supply or irrigation systems are used?
3. Are there wastewater or water surpluses considered into the water footprint?
4. What could be a possible ecological impact by using this kind of system?

We pursuit to answer the mentioned sub questions by: (1) analyzing the water usage in agriculture, aquaculture and aquaponic food production; (2) linking natural water resources to its employment in the production system; (3) analyzing wastewater reuse and (4) the environmental contamination due to wastewater discharges into the environment.

The analysis of agriculture, aquaculture and aquaponic food production system were 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 agriculture and aquaponic food production system, we analyzed the used irrigation systems for plant production. In addition, we analyzed if the systems water input could be reused in other production processes, like aquaculture wastewater could be employed again in a different type of food production (plant irrigation).

It was also considered if a wasteful usage of water or wastewater discharges could cause environmental affectations which can be avoided by the use of new technologies or innovative production system solutions. Therefore, we intend to compare the water usage of traditional agriculture and aquaculture food production with a more innovative production solution in aquaponics taking into account the system management which my not be considered in the water footprint definition.

This investigation was performed by research in three different languages, English, Spanish and German to obtain information from different scientific investigations, researches and experiments which helped to understand in a better way the different water footprints and water employment in different food production systems. In general, the information was gained from 2021 to 2024, and in special cases basic concepts published before 2021.

3. Groundwater Employment for Agriculture Irrigation

The expanding world population and the impacts of climate change requires an appropriate use of hydric resources in food production [42], because water resources are fundamental to gain food security due to the 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 raining seasons are shorter, temperatures higher which leads to 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 low possibilities of cropland expansions and to guarantee food production productivity [47].

Therefore, plant farmers are in need to advance in new irrigation methods and are forced to implement more water efficient strategies which compromises less water units by maintaining the same or obtaining a higher production rate [17,48]. The effective usage of water has also an economic impact because 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 gone over further developments and improvements to give answers to challenges presents by nature and obstacles of food production in the 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].

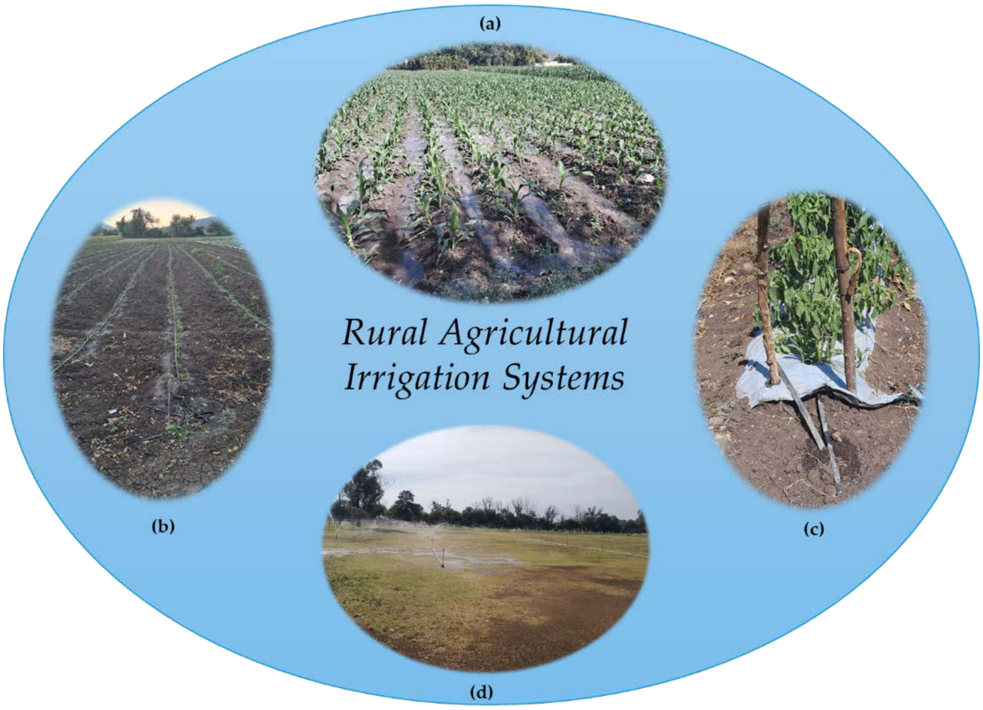

Figure 1. Images of Rural Agricultural Irrigation Systems: (**a**) Surface Irrigation; (**b**) Drip Irrigation; (**c**) Sub-Surface Drip Irrigation; (**d**) Sprinkler Irrigation.

3.1. Surface Irrigation

Surface irrigation is very common irrigation system around the world and even if it shows lack of efficiency, it is still utilized in further 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 by large use of agrochemicals with excessive usage of nitrogen fertilizers causing high absorbable rates of residues in deep soil layers [55]. Moreover, high usage of nitrogen fertilizers constantly contaminating groundwater layers, which is affecting the safety of portable water [56] and change physicochemical and structural properties of

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soil permeabilities microbial activities [57]. In rural areas with uncomplicated access to surface water (rivers, lakes), this irrigation method is a very common system for plant watering by redirecting surface water into small channels supplying the cropland, but one of the biggest disadvantages is irregular of plant water supply [58], which can do more harm than good to the cultivated area [59].

The function of agroecosystem and the cropland soil fertility is reflected in the water drainage rate and water retention rate, 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, Ca2+, Mg2+ and K soil concentration is lower than in drip irrigation systems [60]. Moreover, surface irrigation of furrow or raised bed systems need constant crop management to verification of soil pH, electrical conductivity and nutrient disposability to foment plant growth [61].

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

3.2. Irrigation Systems based on Drip Lines

In many agricultural regions, farmers implement crop or plant irrigation systems based on drip lines being the most common normal surface drip irrigation o sub-surface irrigation.

3.2.1. Drip Irrigation

Drip irrigation systems are based on a micro-irrigation method using plastic irrigation tape o hoses [66] which contributes in an efficient way water directly to the plant roots and at the same time reducing the evaporation rate and drainage loses of water [67,68]. By applying drip irrigation, it is possible to control the soil temperature, saving water by precision irrigation and in this way create a positive usage rate of hydric resources [48]. Furthermore, this kind of system facilitate the application of fertilizers and decreases their quantity because fertilizers can be applicated directly in plastic hose lines from the irrigation system to the plants [60]. Moreover, drip irrigation has improved agricultural food production because there are no restrictions of yield size and it optimizes the cropping depth from cultivated plant species [69]. In addition, drip irrigation increments the land suitability by 38% in comparison to surface irrigation and increments water and land usage by supporting an 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 the harvest [60].

There is no question about the importance of irrigation technologies in relation to economic management of natural resources due to climate change, especially drip irrigation is 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 to retreat all materials and parts of the system from the cropland after the end of the production cycle [70]. Furthermore, plastic products require an accurate storage to avoid different tips of contamination and degradation in rivers, lakes and the ocean to microplastics [71]. Therefore, materials for drip irrigation systems require also accurate storage to avoid soil contamination by damaged and degraded system parts, which could be blown away by wind and be 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

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which permit water saving strategies including drip irrigation and granting an 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 defined as a low pressure and high efficient irrigation system is based on an underground o soil hidden dripper system, in which water is deliberately supplied into soil covered dripper tubes or drip tape with microirrigation emitters [76]. Microirrigation permits partial soil wetting at a high application frequency and the transportation of soil properties which puts less importance on the water storage capacity [77].

The effect of sub-surface drip irrigation generates significant hydric resource savings by lowering the water evaporation extending the life cycle of the used materials of the entire system [78]. The advantage of subsurface drip irrigation is less employment of hydric resources, provides more consistence of 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 being the most important climate affectations, soil type and crop cultivation [76]. Also, soil salinity, the soil water redistribution and the application of agrochemical products can affect the interaction between plant roots and soil affecting the growth of the cultivated crops in the long term [80]. Moreover, a big problem of sub-surface drip irrigation is the possibility of soil degradation and loss of fertile cropland caused by deep leakage and the concentrated soil salinity [81]. Subsurface drip irrigation implies for farmers high investments of infrastructure installations and difficult handling processes of the system [13] due to effects on the soil nutrient cycle because of reduced 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 the 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 permits the implementation of this technology in arid and semi-arid regions [86] and has been utilized in small capacity farming industry [84].

3.3. Sprinkler Irrigation

Sprinkler Irrigation technology is based on water distribution by high overhead pressure sprinklers, which permits to support plants with water by piping water to a central location inside the cropland to contribute hydric resources via sprinklers to the plants [87]. This permits a uniform water transportation into the plant fields [88]. Therefore, rotor sprinklers are a solid irrigation method that radiate a constant spray above the plants being the most common method to provide sufficient water to plant growth [12]. Like drip irrigation, sprinkler irrigation is capable to support 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 in its consequence nutrient loss [88].

One of the biggest problems of sprinkler irrigation is the high usage of water and the effects on the plants due to high water applications which can cause fungal affectations on the plant leaves [91]. In addition, sprinkler irrigation systems could cause a water surface runoff, overflows and in its consequences increasing water soil erosion of the cropland by the decline of drainage and nutrient soil properties. In addition, the decline of soil humus content, porosity, moisture capacity, water permeability and biogenicity leads to a general soil density increase [92]. The technology concept permits a higher evaporation rate and external affectations due to wind and air humidity [93].

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Furthermore, this system requires a high infrastructure investment and has high energy costs for plant production [94], also, the efficiency of sprinkler irrigation depend on the demographic characteristics of the farm [88].

In winter times financial and yield loses due to frost damages affecting farmers [95], 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 from frost damage [93], which gives the technology a future in food production. Also, the last technological advancements, especially the introduction of the Internet of Things (IoT) makes it possible to implement smart sprinkler irrigation which simplifies farming and plant production in general by monitoring irrigation status, sprinkler flow strength and water usage [96]. Moreover, it is possible to use a smart irrigation control on different electronical devices [97], which improves production quality and yield [96].

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

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

Equally as agricultural food production, aquaculture fish farming is also having a key role in food security, because this type of food production is capable to reduce food shortages and avoid the exploitation of the international fish markets [99]. The last 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 have created a critical ecological impact [100].

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

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

A second problem of aquaculture 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 [113]. Moreover, aquaculture wastewater nutrient emissions have high concentrations of fish aliments based on fishmeal and fish oil contributing a high-water pollution in nearby aquifers [108]. Local ecosystems can bioprocess aquaculture residues [114,115], but the high

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quantity of introduced aquaculture wastewater creates eutrophication of rivers and lakes [116]. Furthermore, aquaculture wastewater residuals emitted into the local ecosystem without proper treatment can cause algal blooms [117,118]. For this reason, aquaculture production requires the implementation of new technologies [119] or an optimization of existent technologies to avoid negative impacts on local environments [120,121]. Normally, algae are a nutritious source for aquatic animal feed due to the beneficial properties and capacity to convert atmospheric carbon into these nutritious aquatic animal feed, but the untreated waste emission can create a toxic environment due to excessive algae production [117].

Nevertheless, life cycle assessment strategies are essential for sustainable fish production and to generate positive ecological footprint [122108]. There has been a variability of investigations about life cycle assessment and the quantification of sustainability in aquaculture food production [119], especially in comparison to the production of other animals (beef, chicken, pork) [106], but the life cycle assessment methods are presently not capable to measure the interactions between the natural aquatic environment and aquaculture food production [122].

Even if aquaculture food production is considered to be part of the Blue Revolution due to the high demand of food [123] and being important to achieve the sustainable development goals [103], the lack of wastewater treatment puts the achievement of this goal in risk [124].

Nowadays, climate change and wastewater scarcity requires the reuse of water resources in an essential way to give an answer to the increase of global food demands [125]. The FAO projects a need to increment global food production by 50% to satisfy this global food demand [124]. New concepts focused on water reuse are necessary because in some countries in Asia, aquaculture production has an important role for food security and represents 90% of today’s aquaculture production worldwide [126]. Furthermore, the insufficient knowledge of wastewater treatment and good sanitary practices requires farmers capacitation to avoid contamination [127], also the misusage of pharmaceuticals, which can be concentrated in fish tank sediments [128]. The discharge of fish tank sediments into the environment and the contamination of surrounding aquifers [129,130], can also have human health risks due to ground and drinking water contaminations [131].

The future of aquaculture food production needs to face a lot of challenges among them 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 [130]. Nowadays, different and new technologies are helping to transform aquaculture food production with the use of sensors, artificial intelligent models [132] or the introduction of the Internet of Thinks to make production management easier [133]. Wastewater treatment is one of the most important aspects and the future lies in the capacity to remove a high quantity of residues by using different biofilter and recirculation systems [134,135] with different plants and aquatic animals to evade damaging nutrients discharges into the environment [118].

Therefore, optimization of water usage to create a positive sustainable impact is fundamental for food production. The combination of agricultural plant production and aquaculture fish production in one system, aquaponics could help to reduce water consume due to one hydric resource income into one system which is capable to produce two proteins for human consumption [136].

5. Optimization of Groundwater Employment in Aquaponic Food Production

The interrelationship between traditional agriculture and aquaculture food production systems are due to the codependency of groundwater resources [104,137]. This water dependency makes it viable to not only increment the water usage of agricultural irrigation systems [138], water recirculation and the use of different filters in aquaculture [139]. Moreover, the combination of these two production methods for a general water footprint optimization [140] Therefore, the incorporation of both production methods into one system, called aquaponics [141], benefits the use of two central resources for human activities, food production and water usage optimization [142]. by using only one water income to produce two proteins, fish and plant [143].

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 [144], as hydration and fertilizer to promote plant growth [145,146]. 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 [141]. 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 [147], also called coupled aquaponic systems using fish residues directly as plant nutrition [148]. 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 [149].

In the last years, 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 [150]. Decoupled aquaponic systems are using aquaculture resides in a separated decoupled recirculating system, one for oxygenation and water recirculation in the fish production and one for water and nutrient circulation in the hydroponic system [151]. Decoupled aquaponic system permit the supply of additional plant nutrients based on aquaculture wastewater and additional mineral fertilizer supply, without affecting the fish production promoting the most efficient plant growth and yield [152].

The differences between these distinct aquaponic system designs are the different contribution rates of water nutrient concentration from each system contributing to the plant growth in the plant production area. Both, recirculating aquaponics and decoupled aquaponics are capable to grant a substantial reduction of water use [34] due to the maximized exploitation of aquaculture wastewater and the controlled use of these water resources [136].

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 water line of the fish tank, implementing a system where the roots of the plants moving under the waterline and absorbing the nutrients of fish effluents concentrated in the tank [153].
ii. The gravel bed technology – based on a substrate (organic or inorganic) filled growing bed to support the plant development with recirculating aquaculture wastewater residues watering the plants with nutritious fish effluents [154,155].
iii. The Nutrient Film Technic – based on grow bed channels or grow beds in pipes by recirculating fish wastewater residues through the plant roots and providing nutrients to the plants [156].

A less known aquaponic system is open aquaponics, which consists in 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 wastewater irrigation system by utilizing the nutrient rich aquaculture wastewater as organic fertilizer and hydric support in plant production, which is also implement in plant-based wastewater treatments [136].

Therefore, open aquaponic systems combine aquaculture 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 [157]. 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 reutilizing wastewater.

In general, the propose of aquaponic food production is the employment of wastewater resources from aquaculture production in plant production to optimize the water usage by the use of only one water income and avoiding or minimizing the use of agrochemicals due to the biofertilization of nutrient concentrations in the fish effluents [142].

Recirculating or decoupled aquaponic systems have an advantage over open aquaponics, because of a lower consumption of water resources, even if all three systems reuse wastewater and

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the prevention of surface or groundwater pollution by evading nitrogen nutrient contamination [158,159]. Moreover, these aquaponic system designs can be used in a denitrification process of water due to water filtration in the hydroponic systems [146]. In difference, open aquaponics are capable too to optimize the water usage of food production [38], but this system design can still cause soil pollution if there is an uncontrolled application of concentrates nutrients of aquaculture wastewater [38,160].

There are a variety of investigations related to aquaponic food production and the system sustainability which supports the reduction of different environmental impact, but the actual impact of aquaponic food production, water usage including wealth fare management of aquatic animal production and the emission of wastewater effluents are requiring 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 includes five important key goals for food production; water security, food security, environmental health, energy security and economic stability [161]. The use of freshwater for food production is the biggest industrial sector using the worldwide groundwater resources, which is around 92% of the world´s total water usage [162]. Nowadays, water scarcity is causing major concerns about the availability of water due to the worldwide employment of freshwater, which requires the implementation of water footprint analysis in different food production systems [163]. Therefore, measuring a water footprint is important and includes according to Hoekstra and Mekonnen the differentiation between (Table 1) [164]:

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
Grey	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 has the highest water usage around the world and creates the need of the implementation of more efficient irrigation methods and water management [165]. Therefore, the water footprint is fundamental in agricultural food production to evaluate the water efficiency to implement and to make improvements of water usage concepts [166]. The water categories of the water footprint definition used to specify the water employment in agriculture are the green and blue water footprint. This refers to water employment for crop consumption coming from rainwater, surface and groundwater [109]. In general, the agricultural water footprint is depending on the type of crop produced and takes on account the volume of water consumed during the whole production process from the plant sowing, growth process and ends with the harvest [167]. 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 in consideration production perspective, the inter-regional agricultural product trade and the virtual water flow [168]. Therefore, regional and local water shortages have to be put into a focus to guarantee ecological sustainability and in its consequences the importance to reduce the water footprint for crop production [169].

Regional and local water shortages require an extend review of water sustainability for crop production being the blue water footprint less impactful in the global water performance assessment

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than the green water footprint, which presents more water scarcity on a global scale and pollution due to excessive nitrogen introduction [167]. In general, the blue water footprint is more impactful in crop production in arid regions than the green water footprint, but all is depending on local water resource management [170]. Different studies have shown that the water footprint in crop production could be reduced by changing the crop varieties and agricultural management [171]. Therefore, the number of varieties of investigations to define the use of the different water footprints (green, blue, grey) has included whole countries and regiones, agricultural irrigation systems and aquatic animal production [167].

The water footprint for aquaculture food production is essential because it shows the direct (water for animal production) and indirect (animal feed) usage of freshwater in aquatic animal production [172]. Moreover, aquaculture food production does not use water which is suitable for human consumption [173]. Furthermore, water losses expected from aquaculture food production includes ponds by seepage or infiltration, evaporation [174], water for fish production [175] and systems cleaning processes by siphon [176] or water replacements. Also, the aquacultural water footprint for food production depends on the aquatic species produced in this type of terrestrial farming systems [172]. The production of aquatic animals in regions suffering freshwater scarcity is limiting terrestrial aquaculture food production and requiring new freshwater usage concepts [177] and taking in account the reduction of grain-based animal feed for aquaculture production maximizing the aquaculture water footprint by utilizing less water consuming aliments [178].

In general, aquaculture food production systems can impact the surrounding ecosystem negatively due to residues emitted into the environment, also known as polluted water, expressed in the grey water footprint [109]. In addition, there is a big difference between human consumption of marine fish and terrestrial aquacultural, because marine captured fish o marine aquacultural fish production has a water footprint close to cero [179]. Moreover, the future prospection is a water footprint increase by 4.6% of water usage if marine food production would be reinstalled in terrestrial aquacultural production [177]. The availability of blue and green water for aquacultural production is highly depending on rainfall up to the risk of flooding events and the possibility of longer drought seasons which could limit regional aquacultural food production due to climate change [172].

As mentioned, in traditional agriculture, the demand for water is high as same as the costs for fertilizers and irrigation systems construction, in addition the possibilities for yield expansion are limited due to land scarcity and crop land loses [162]. Aquaculture production has also been considered as a food production sector with a high demand for natural water resources and at the same time creating certain ecological and environmental impact due to grey water discharges into the environment [174], which makes the incorporation of both systems into aquaponics suitable to accomplish more water efficiency [180].

In aquaponic systems, there are two types of water employment; blue water resource inputs for aquaculture production [181] and the use of the residues of this production as grey water to fertilize and irrigate plants in different types of aquaponic cultivation beds [182]. Furthermore, aquaponic systems use a lower water input and therefore have a better water use efficiency with a range between 95% and 99% [162], but the water quality of aquaculture discharges and the 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 by fishpond discharges and fish feeding, evaporation, and evapotranspiration [183], but there can be water usage optimization processes due to mechanical water movement by water pumping, rainfall and runoff, which can reduce the water loses to only certain discharges, minimized water evaporation and seepage loses [184]. The type of plant cultivation in different hydroponic system designs used in aquaponics does not represent a significantly impact in possible water loss [185]. Therefore, the water footprint of aquaponic systems is remarkably better than in conventional agricultural production systems with the side effect of fertilizer cost reduction. In the future the importance lies in the incorporation of new technologies, optimization of aquaculture residue water employment and the water management [162]. Furthermore, the minimization of the water footprint in aquaponics can only be guaranteed by a

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suitable system design and the optimization of the ratios of fish water to plants to assure water efficiency and nutrient circulation [180].

In addition, quantification of water consume has the objective to implement more efficient water use practices by analyzing four different stages of water footprint implementations; 1. goals and scope setting; 2. water footprint accounting; 3. Sustainable analysis of water footprint and in case of sustainability deficits, the concept to achieve sustainable water usage [163].

7. Discussion

The ascending demand for freshwater on a worldwide scale for food production using traditional agricultural or terrestrial aquacultural production systems on an industrialized measure [104] and at the same time expanding regional droughts due to climate change are affecting global food security [186]. These environmental impacts with effects on food production by the use of intensive farming practices affecting dramatically the local water quality due to the pollution of rivers, lakes and groundwater, and in its consequence limiting regional water availability [187]. Therefore, every day it is getting more important to implement water footprints for specific crops and aquatic animals in food production [166].

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 [188], wheat, rice [165], potatoes, cabbages, lettuce, spinach, tomatoes, cauliflowers, pumpkins, auberges, peppers, onion, beans, dates [189], wolfberries, grapes, pomegranates, and strawberries [190]. In addition to investigated plants, there has to be an extension and incorporation of new agricultural produced crops, plants and fruits according to the consumers preferences and new food trends. The investigation of new water saving irrigation methods, enhancement of traditional irrigation systems and sustainable production systems is vital to guarantee high crop yield rates [191] and a positive water footprint. Therefore, new technologies have to be implemented especially in countries or rural areas which have insufficient economic capacity to invest in new irrigation technologies to support the minimization of agricultural water footprint [192].

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 to measure the geographical and temporal fluctuations of the regional water characteristics and parameters [193], 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 [29], but there is still potential to investigate even more water footprints of different aquatic animal species produced in aquacultural food production taking also different climate zones in account [194]. Furthermore, there has to be more investigation including the aquacultural system management, water substitutions during cleaning processes, pond removals, water losses due to filter use, evaporation due to local climate [195] and water usage to produce fish feed [196].

Regional water management is essential to verify the quantity of local water resources and to establish regional water footprints to control the water usage in comparation to the natural groundwater regeneration and climate change affectations [197]. Moreover, the implementation of regional water footprints could help to decide if agricultural o aquacultural food production is suitable for a region and define which are to most profitable crops, plants, fruits or aquatic animals to produce to enhance the local food security [198].

Aquaponics could be a food production systems that permit a better understanding of water usage and water optimization using different hydroponic system designs for plant production [141,149,199]. The implementation of these system designs depend on the local space and characteristics, the availability of freshwater and the regional climate because of water evaporation (145). The different aquaponic system designs are capable of water optimization in different categories being open aquaponic systems with soil plant production the system which employs aquaculture wastewater residues only ones in an agricultural irrigation system providing also

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organic fertilizer [38], which still optimizes the water usage. More efficient are recirculation and decoupled aquaponic systems due to the constant reuse of aquaculture wastewater and application for plant nutrition [40,136,200]. These systems need more plastic and metallic materials to construct the infrastructure but are more capable being adapted to any space and even to places without fertile soil [201].

Food production in aquaponic systems could be a feasible solution to save water and to create a positive water footprint [180], due to the incorporation of fish and plant production in one system and the reuse of aquacultural wastewater for plan production [141]. A lot of authors only mention in their aquaponic water footprint investigation the water reuse in the production of fish and plant [162] and do not consider the needed water resources for water substitutions, evaporation losses, possible water leaks in the system or the water employed for the animal feed. Also, the water footprint must be defined according to the local climate [202]) and if an aquaponic food production is accurate for certain climates and existents of water resources, taking also into account grey water discharges into the environment [203]. More investigation is necessary about the water footprint in aquaponic food production including the different types of production systems, cleaning and management process to control the different types of water employment and to define if aquaponics is a suitable solution for food production in some rural areas

8. Conclusions

Nowadays there is a real threat for food security due to the still growing world population, which requires a need for a higher yield in food production. In many countries there exists a cropland limitation and water scarcity, which makes it not possible to increase the cropland space for more yield food production. Furthermore, the last years have shown that global crisis can also affect food production causing food shortage for countries without the capability to implement more traditional or innovative production methods. In general, agricultural production requires large amounts of freshwater from natural water resources and high technology developments to optimize the water usage, yield productivity and the minimization of the environmental impact to protect the local biodiversity.

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

A solution to the high-water consumption of agriculture and aquaculture could be aquaponics for organic food production. This combination of both production systems is viable to reduce water consumption creating a positive impact. There is a need for more investigation of aquaponic food production management, the incorporation of aquaponics into cycle economic systems and the usage of wastewater discharges into the environment due to system cleaning process, which are causing ecological impacts, even if aquaponic production is more sustainable than traditional agriculture or aquaculture production.

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