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Review

Biocontrol of Phytopathogens under Aquaponics Systems

Tomás Rivas-García [1], Ramsés Ramón González-Estrada [2], Roberto Gregorio Chiquito-Contreras [3], Juan José Reyes-Pérez [4], Uriel González-Salas [5], Luis Guillermo Hernández-Montiel [1] and Bernardo Murillo-Amador [1,*]

1 Programa de Agricultura en Zonas Áridas, Centro de Investigaciones Biológicas del Noroeste S.C. La Paz, Baja California Sur 23096, Mexico; eltom_r@hotmail.com (T.R.-G.); lhernandez@cibnor.mx (L.G.H.-M.)
2 Tecnológico Nacional de México, I. T. Tepic, Tepic, Nayarit 63175, Mexico; ramgonzalez@ittepic.edu.mx
3 Facultad de Ciencias Agrícolas, Universidad Veracruzana, Xalapa, Veracruz 91090, Mexico; contrerasch@yahoo.com
4 Facultad de Ciencias Pecuarias, Universidad Técnica Estatal de Quevedo, Quevedo, Los Ríos 120501, Ecuador; jjreyesp1981@gmail.com
5 Facultad de Agricultura y Zootecnia, Universidad Juárez del Estado de Durango, Gómez Palacio, Durango 35000, Mexico; urgosa87@hotmail.com
* Correspondence: bmurillo04@cibnor.mx

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Abstract: Aquaponics is an alternative method of food production that confers advantages of biological and economic resource preservations. Nonetheless, one of the main difficulties related to aquaponics systems could be the outbreak and dissemination of pathogens. Conventional treatments need to be administrated carefully because they could be harmful to human, fish, plants and beneficial microorganisms. Aquaponics practitioners are relatively helpless against plant diseases when they occur, especially in the case of root pathogens. Biological control agents (BCAs) may be an effective alternative to chemical inputs for dealing with pathogens of plants under aquaponics systems. Research of BCAs on aquaponics systems is limited, but there are numerous publications on the use of BCAs to control plant pathogens under soilless systems which confirm its potential use on aquaponics systems. The present review summarized the principal plant pathogens, the conventional and alternative BCA treatments on aquaponics systems, while considering related research on aquaculture and soilless systems (i.e., hydroponic) for its applicability to aquaponics and future perspectives related to biological control. Finally, we emphasized the case that aquaponics systems provide relatively untapped potential for research on plant biological control agents. Biological control has the potential to reduce the perturbation effects of conventional treatments on microbial communities, fish and plant physiology, and the whole function of the aquaponics system.

Keywords: aquaponics; soilless systems; plant protection; phytopathogens; biocontrol

1. Introduction

The growing population projected in 2050 will be of 10 billion people [1]. To supply global food demand, production will need to increase by 50% [1]. Unfortunately, this demand will be affected by factors such as climate change, pollution, and the available resources i.e., arable land, available water and mineral nutrients which are finite [2,3]. Trying to prevent these scenarios, the General Assembly of the United Nations (UN) presented "The 2030 Agenda for Sustainable Development", concluding that there is a need to change from intensive food production systems towards sustainable ones [4]. Aquaponics is an alternative method of food production that combines fish and plant growing technologies by conferring advantages of resources, and biological and economic preservation [5]. It is a healthy and environmental option for food production which has encouraged research into many different aspects [6]. Aquaponics has been compared with aquaculture [2,7,8] and hydroponic [9–12] technologies in terms of production and profitability. Up to now, the research on aquaponics has been focused on sustainability [13–15], economic optimization [16–18], functional setup [19,20], stocking density [21,22], cultivation media [23,24], water recirculation [25,26], food safety [9,27], fish-plant pathogens [6,28] and beneficial microorganisms [29,30].

Recently, it has been demonstrated that a complete understanding of the hydroponic subsystem is essential to improving the whole aquaponics system [31]. One of the main difficulties related to aquaponics system is the potential dissemination of pathogens [6], because water recirculation and controlled parameters such as temperature provides the perfect environment for pathogen proliferation [28]. Evidence of previous outbreaks in aquaculture and hydroponics shows the consequences of such events. *Streptococcus iniae* caused 40% mortality on Barramundi fish [32] and, *Pythium aphanidermatum* after three days of inoculation in a hydroponic cucumber, infected 100% of the plantation [33]. Such outbreaks could ruin an entire crop, or even provoke the end of all the production system because of the high initial investment cost [34]. Diseases control is mainly based on disinfecting water methods at various points of the aquaponics systems, depending on the method [6]. Chemical and non-chemical disinfection methods have been applied in aquaponics and hydroponics systems to kill pathogens on the recirculating water [6,28]. However, these methods need to be administrated carefully because they could be harmful to humans, fish, plants and beneficial microorganisms [35]. At the moment, there is no pesticide nor bio-pesticide specifically developed for aquaponics systems [6,28,35,36]. Somerville et al. [36] mentioned inorganic compounds which could be used against fungi in aquaponics. Nonetheless, as Stouvenakers et al. [28] state, "At the moment aquaponics practitioners operating a coupled system are relatively helpless against plant diseases when they occur, especially in the case of root pathogens".

As previously mentioned, one of the research topics on aquaponics system relies on beneficial microorganisms, but, most of them have been focused on nitrifying bacteria [24,30,37] or plant growth promoters rhizobacteria (PGPR) [35,38,39]. Biological control agents (BCAs) may be an effective alternative to chemical inputs for dealing with pathogens of plants under aquaponics systems [40]. Therefore, there is an opportunity to work with BCAs to manage: (i) plant disease under aquaponics systems because of the limited use of chemical treatments, (ii) the initial investment cost production, and (iii) the increase of whole aquaponics food production system [28]. There is limited research of BCAs on aquaponics systems, but publications have increased in the last few years [28,40]. Additionally, there are numerous publications on BCAs to control plant pathogens under soilless systems which confirm its potential use on aquaponics systems [41–43]. Biological control is defined as the use of BCAs (microorganisms or their derivatives) as antagonists to manage plant disease [44]. The aim of present review was to summarize the principal plant pathogens, the conventional and alternative BCA treatments on aquaponics systems, while considering related research to aquaculture and soilless systems (e.g., hydroponic) for its applicability to aquaponics and future perspectives related to biological control. Finally, we emphasized the case that aquaponics systems provide relatively untapped potential for research on plant biological control agents.

2. General Description of Aquaponics Systems

Since modern aquaponics started in 1970s, they have been focused on sustainable practices by sharing water and nutrient resources between fish and plants subsystems [2,45,46]. Aquaponics is a complex system which combine aquaculture (raising fish in tanks) and hydroponics (growing plants in soilless media) subsystems [2]. Simplifying the aquaponics system, it is composed of a fish tank connected to a hydroponics unit connected back to fish tank creating a recirculating system [7]. Additionally, depending of the type and functionality of the system, other components such as biofilters, water clarifiers and pumps are included [36]. The fish metabolize their feeding, then the faeces and waste are transformed by microbial communities which make available the nutrients for plants, simultaneously cleaning the water and recycling nutrients [31]. Aquaponics demand more technical knowledge than hydroponics and aquaculture to maintain a balance between all the elements of the system and, specifically, to prevent plant pathogen diseases [2], and for that reason the whole system is described briefly in this review.

Aquaponics systems are classified according to: (1) the growing technology used for fish and plants; and (2) the coupling or uncoupling subsystems [36]. In general, the aquaponics systems work as follows, fish grow in tanks of different materials (plastic, fiberglass, concrete, among others) [47]. Mechanical filters retain most of the solids dissolved in water to avoid the formation of biofilm that could reduce the oxygen available to the roots of plants; and bio-filters increase the area for the growth of beneficial bacteria that transform ammonia (NH_3^-) and nitrite (NH_2^-) into nitrates (NO_3^-) in order to detoxify water for fish and to assimilate available nitrogen for plants [36]. Plants absorb the nutrients from water, thereby reducing dissolved solids and ion concentrations; and finally the water returns to the aquaculture subsystem (coupled subsystem) or is discarded and/or used as irrigation water in conventional crops (uncoupling subsystem) [35].

The modules of plants in aquaponics are classified, as mentioned, by the growing technology used. The type of growing technology will be closed in relationship with the general objective of production [48]. The technologies applied in plant cultivation are, (1) nutrient film technique (NFT), (2) deep water culture (DWC), and (3) media bed units [49]. NFT and DWC are the most common production technologies [50].

3. Plant Disease in Aquaponics Systems

3.1. Source of Inoculum

Aquaponics is based on recirculation of water through the entire system which makes perfect conditions for pathogen dissemination [6]. Water is an important element on the entire aquaponics system, because it circulates in all the subsystems, transport the nutrients and influence the growing environment of fish, plant or microorganisms [2]. Water sources may contain microbial pathogens affecting fish, plants and even human health, i.e., rainwater used not to contain microbes but the way it is stored may allow microbial proliferation, and ground and river water could contain microbial pathogens depending on its source area like animal farming and human waste treatment [31]. Waterborne dissemination occurs when the plant pathogen is transferred by an inoculum source i.e., infected plants release the pathogens which then are absorbed by healthy plant roots [51]. Moreover, the rate of dissemination is related to pathogen shedding and survival ability in the circulating water [6]. Other source of inoculum could be the reuse of growth media, particles i.e., dust, vectors i.e., insects and rodents, and human i.e., cloths, tools and handling [52,53].

3.2. Factors Related to Phytopathogen Proliferation

Several factors have been associated to phytopathogens proliferation in aquaponics; some are related to environmental conditions, and others to phytopathogens infective capacity and plant mechanism of resistance. In aquaponics systems, plants are breeding under controlled conditions to optimize their yield [53]. Nonetheless, these controlled conditions could be exploited by phytopathogens [28].

In the environmental factors, plant cultivation density, high nutrient availability and humid warm environments facilitate growth of microorganisms, in particular fungal phytopathogens which quickly spread by zoospore release in recirculating water causing considerable die-offs such as *Phytophthora* spp. and *Pythium* spp. [54]. Other fungi, bacteria and viruses are disseminated by infected material, mechanical wounds, infected tools, vectors and particles [55]. The temperature of recirculating water is an important parameter for maintaining the physiological development of fishes and plants, but also has been demonstrated that promote phytopathogens proliferation, i.e., *Phytium* spp. which caused 100% and 69% to 0% of mortality on Spinach under a hydroponic system at 30 and 20 °C, respectively [56]. The difference in disease severity is related to temperatures that are optimal to phytopathogens development [6]. In conventional agriculture, injury is a factor that facilitates the phytopathogen colonization causing worse disease outcomes, but is not an important parameter in soilless systems [57].

Factors related directly to phytopathogens are inoculum density, time of exposure and viability time of the phytopathogen [6]. Longer exposure time and concentration of the phytopathogens give them more opportunity for root colonization [58]. The rate of surviving on soilless systems varies between phytopathogens i.e., tobacco mosaic virus (TMV), potato virus and pepino mosaic virus can survive for more than 5 to 21 days [51,59]. There is a positive dose-response relationship between pathogen concentration and the mortality rate of plants [58].

After the phytopathogens come into contact with the plant, several cases related to plant resistance are possible: (1) incompatible is when disease not develop; (2) tolerance is when there exists a host relation but the plant does not show symptoms; (3) resistance occurs when pathogen and plant are compatible but defense mechanism inhibit the disease progression; (4) plant-sensitive is when the pathogen infects the plant, but does not cause severe symptoms; and (5) severe disease is when symptoms could cause its death [60].

3.3. Most Common Phytopathogens

There are a variety of phytopathogens such as fungi, bacteria, viruses and parasite that could damage plants under soilless systems like aquaponics. Plant diseases in aquaponics systems might be similar to those in hydroponics because of the continuous presence of water [28]. Oomycetes and virus were the most common pathogens investigated on plants such as tomato and cucumber [31]. *Pythium* spp. and *Phytophthora* spp. are oomycetes well adapted to the humid/aquatic conditions and are the most common plant root pathogens [28]. These oomycetes have a motile structure called zoospore which allow them dissemination by moving independently in aqueous media [61]. *Fusarium, Colletotrichum, Rhizoctonia* and *Thielaviopsis* genera could be opportunistic phytopathogens [52,62]. Tobacco mosaic virus survive for more than 5 days in recirculating water on a hydroponic system [59]. Potato virus, mosaic virus and potato spindle tuber viroid remain infectious for 1, 3 and 7 weeks [51].

It is important to mention that in some plant disease under soilless systems, the causal agent remains unknown because of lack of technical knowledge on phytopathology [31,63]. There is also cross contamination between phytopathogens to aquaponics, i.e., *Gilbertella persicaria* is a phytopathogen which could cause severe damage and mortality to black tiger shrimp (*Penaeus monodon*) [64]. Interspecies transmission was also recorded like *Colletotrichum coccodes* which spread from a co-culture with eggplant to tomatoes [65]. Plant pathogens could infect also shrimp [66]. Stouvenakers et al. [28] summarized the results of the first international survey on plant disease in aquaponics systems affecting practitioner members of the COST FA1305, the American Aquaponics Association and the European Union (EU) Aquaponics Hub (Tables 1 and 2).

Table 1. Common phytopathogens summarized from 2018 international survey analysis in aquaponics systems and existing literature.

Plant Species	Phytopathogens Identified *
Allium schoenoprasum	*Pythium* sp. (b)
Beta vulgaris (Swiss chard)	*Erysiphe betae* (a)
Cucumis sativus	*Podosphaera xanthii* (a)
Fragaria spp.	*Botrytis cinerea* (a)
Lactuca sativa	*Bremia lactucae* (a) *Fusarium* sp. (b) *Pythium dissotocum* (b) *Pythium myriotylum* (b) *Sclerotinia* sp. (a)
Mentha spp.	*Pythium* sp. (b)
Nasturtium officinale	*Aspergillus* sp. (a)
Ocimum basilicum	*Alternaria* sp. (a) *Botrytis cinereal* (a) *Pythium* sp. (b) *Sclerotinia* sp. (a)
Pisum sativum	*Erysiphe pisi* (a)
Solanum lycopersicum	*Pseudomonas solanacearum* (a) *Phytophthora infestans* (a)

Source: Stouvenakers et al. [28] (http://creativecommons.org/licenses/by/4.0/). Phytopathogens identified by foliar symptoms (a) and by root symptoms (b) reports. * It summarized results from specific symptoms that could be linked to specific phytopathogens.

Table 2. Common symptoms summarized from 2018 international survey analysis in aquaponics systems.

Symptoms	Plant Species
Foliar chlorosis	*Allium schoenoprasum* [1], *Amaranthus viridis* [1], *Coriandrum sativum* [1], *Cucumis sativus* [1], *Ocimum basilicum* [6], *Lactuca sativa* [4], *Mentha* spp.[2], *Petroselinum crispum* [1], *Spinacia oleracea* [2], *Solanum lycopersicum* [1], *Fragaria* spp. [1]
Foliar necrosis	*Mentha* spp.[2], *Ocimum basilicum* [1].
Stem necrosis	*Solanum lycopersicum* [1].
Collar necrosis	*Ocimum basilicum* [1]
Foliar mosaic	*Cucumis sativus* [1], *Mentha* spp.[1], *Ocimum basilicum* [1].
Foliar wilting	*Brassica oleracea* [1], *Lactuca sativa* [1], *Mentha* spp.[1], *Cucumis sativus* [1], *Ocimum basilicum* [1], *Solanum lycopersicum* [1].
Foliar, stem and collar mould	*Allium schoenoprasum* [1], *Capsicum annum* [1], *Cucumis sativus* [1], *Lactuca sativa* [2], *Mentha* spp.[1], *Ocimum basilicum* [4], *Solanum lycopersicum* [1].
Foliar spots	*Capsicum annum* [1], *Cucumis sativus* [1], *Lactuca sativa* [2], *Mentha* spp.[1], *Ocimum basilicum* [5].
Damping off	*Spinacia oleracea* [1], *Ocimum basilicum* [1], *Solanum lycopersicum* [1].
Crinkle	*Beta vulgaris* [1], *Capsicum annum* [1], *Lactuca sativa* [1], *Ocimum basilicum* [1].
Browning or decaying root	*Allium schoenoprasum* [1], *Amaranthus viridis* [1], *Beta vulgaris* [1], *Coriandrum sativum* [1], *Lactuca sativa* [1], *Mentha* spp.[2], *Ocimum basilicum* [2], *Petroselinum crispum* [2], *Solanum lycopersicum* [1], *Spinacia oleracea* [1].

Source: Stouvenakers et al. [28] (http://creativecommons.org/licenses/by/4.0/). Exponents represent the occurrence of reported symptoms for a specific plant on a total of 32 aquaponics systems.

4. Conventional Protection Against Phytopathogens

Nowadays, practitioners are limited in how to protect plants because no pesticide nor biopesticide is specifically developed for aquaponics use [36,40,67]. Disinfecting the water is an option to control disease by decreasing the inoculum, the phytopathogens concentration and their proliferation [6]. Disinfecting can be applied in many parts of the system, depending of the method. The conventional methods available are divided into physical treatments such as ultraviolet (UV) irradiation, media filtration, heat, sonication; and chemical methods such as chlorination, and ozonation. Nonetheless, disinfecting methods could have negative effects on fish, plants and beneficial microorganisms which cohabit in the system, or even human health, so their use must be limited [35].

4.1. Physical Disinfection Methods

Physical disinfection methods are defined as agents that not rely on chemical nor biological control agents [6]. These methods reduce phytopathogens concentration but they are not effective when there already exist the plant disease [28]. According to Mori et al. [6], UV disinfection is the most studied method for soilless production systems. In the UV method, recirculating water is exposed to a wavelength light between 225 to 312 nm [68]. These treatment acts by causing damage on DNA replication [69]. Inactivation with UV is determined by the energy per unit area on a period of time exposure and it is commonly expressed in mJ/cm^2 [70]. UV treatment at doses of 250 to 300 mJ/cm^2 has demonstrated the ability to eliminate >95% of *Pythium* spp. in hydroponics [71]. Dose and results are too variable and are dependent of many factors like device used, light reflection, refraction, intensity, length of exposure time and presence or particulate matter [6,72]. Moreover, phytopathogen sensibility to UV fluctuate among species and inclusively between different strains [72].

Media filters could be located before or after production tanks to prevent recirculation of phytopathogens [6]. Slow filtration occurs as mechanical and biological process where particles are retained from the recirculating water and microorganisms from water interacts with microorganisms growing in the filter [73]. The two principal limitations of slow filtration techniques are the formation of a layer by suspended solids accumulation and a limited flow rates which are insufficient for large production systems [6]. Media filtration has removed pathogens like *Fusarium* spp., *Phytophthora* spp. and *Pythium* spp. with more than 95% of efficiency [74–76]. There are gaps in the research regarding to filter bed depth, flow rate, grain size or material density which difficult to replicate the results reported [6]. Sand, anthracite, pumice and rockwool were tested from its efficiency to remove the phytopathogen *Xanthomonas campestri*, finding that rockwool was more efficient [77]. Sand located at a depth of 40 cm were more effective than a depth of 20 cm on removing 100% and >98% of oomycetes respectively [78]. Also, the depth depends upon particulate size; for example, it was found that a sand filter of 0.8 m large and ≤0.8 mm pore size caused no infection of the inoculated *Phytophthora cinnamomi* [79]. Maturation time of microorganisms in the filter is an important parameter. Sand filter after 10 weeks was more efficient to remove *Phytophthora nicotianae* than a new sand filter with 99.75% and 95.3% respectively [78].

Heat acts on denaturing proteins of the phytopathogens, deactivating them. This treatment is applied when the recirculating water is pumped to a separate tank and heated for a period of time at a certain temperature [80]. *Pythium* spp., *Fusarium oxysporum*, tomato mosaic virus, and *Radopholus similis* were inactivated after 48 to 95 °C during 0.5 to 5 min of heat exposure or recirculating water [80–82]. But, some studies showed that lower temperatures are sufficient without increasing the time of exposure. In a hydroponics system heating the water to 60 °C for 1 min reduced root damage by *Pythium aphanidermatum* by >95% [83]. Heat treatment should be researched further to demonstrate the ability to kill both fish and plant pathogens in soilless systems.

In sonication, a probe transmitting high-frequency probes (2040 KHz) into the nutrient solution to induce the formation of low-pressure pockets inside cells causes their collapse in a process called cavitation [84]. Sonication deactivates effectively plant pathogens like *P. aphanidermatum* at in vitro and in vivo small solution tests [81,83]. In combined treatment, sonication at 25 KHz and UV at 40 mJ/cm^2 was not more effective than UV treatment against *P. aphanidermatum* and *Anguillicoloides crassus* [84]. It is yet to be determined if sonication is effective at a large scale production systems with thousands of effluent solution liters, and determines its frequencies and exposure times too.

4.2. Chemical Treatments

Ozone (O_3) is injected to stored water for a period of time before continue the recirculating process and reacts with iron chelate which damage cell viability [85]. It was demonstrated that 1 h to 10 h per m^3 of ozone treatment can eliminate all phytopathogens [86]. Also, the microbial population was reduced by ozone treatment in a soilless system of vegetables production [87]. Nonetheless, human exposure should be avoided because ozone may cause damage to mucous membranes [85].

Hydrogen peroxide (H_2O_2) is an oxidizing agent that reacts forming water and oxygen radicals. Formic acid and acetic acid are commercially called activators which decrease pH in the nutrient solution to promote the reaction [85]. It is an inexpensive but not efficient method helpful for cleaning rather than disinfection. Dosages of 0.01 to 0.005% are efficient against *Pythium* spp., *Fusarium* spp., and other fungi but it is also reported that higher concentrations are harmful to plant roots [88].

Sodium hypochlorite (NaOCl) is a chemical product with many commercial names. It is inexpensive and widely used as water treatment, especially in swimming pools [85]. When added to water it reacts to form Cl^- and O^+ for strong oxidation of any organic material. The chemical reaction of sodium hypochlorite depends on climatic conditions, for example high temperatures and contact with air cause rapid decomposition, thus forming $NaClO_3$ [89]. Sodium hypochlorite is an effective treatment against a number of pathogens, i.e., 15-mg Cl L^{-1} during 2 h reduced 90–99% of *Fusarium oxysporum*, but it is not effective against viruses, and increasing Na^+ and Cl^- concentrations decrease productivity of growing systems [85].

4.3. Preventive Treatments

Nonetheless, according to a survey on EU Aquaponic Hub members, specific plant pest management in aquaponics systems is an area that needs further investigation [63]. The better option will depend on the type of system (coupled or decoupled) [28]. If the water does not recirculate to the fish part after plant root circulation, some chemical products (pesticides and chemical disinfection agents) could be allowed but not promoted because of the presence of microbial communities [28]. As mentioned, there are no specific chemical products like pesticides or biopesticides developed for aquaponics [40,67,90]. As a consequence, preventive rather than curative treatments are mainly promoted in aquaponics systems.

There are good agricultural practices (GAPs) that prevents and minimize the proliferation or dissemination of phytopathogens within aquaponics systems [91]. GAPs try to limit the entry of the inoculum, to limit and/or to avoid the phytopathogens dissemination [28]. In order to limit the entry of the inoculum actions like a room sanitization (i.e., removal of plant debris), specific clothes, certified seeds, germination room and physical barriers are needed [36]. To limit and/or avoid phytopathogen dissemination, actions like selecting resistant plant varieties, disinfection to avoid plant stress, good plant densities, and environmental management should be promoted [28].

5. Biological Control as Alternative Treatment in Aquaponics

Research on introducing microorganisms in aquaponics systems have been focused on nitrifying bacteria [29] or plant growth promoters [35]. Research on biological control agents is needed because conventional treatments are not specific against phytopathogens cultivated in aquaponics conditions [36,40]. Moreover, information about biological control agents against aquaponics phytopathogens is scarce [28]. Biological control agents are antagonistic microorganisms which limit or stop the development of fungal phytopathogens [92].

Sirakov et al. [40] screened bacterial isolates from diverse compartments of an aquaponics system to exert their inhibitory effect against *Pythium ultimum.* From the 964 bacterial isolates tested, 86 were effective as an in vitro antagonist of *P. ultimum*. Further research to evaluate in vivo potential and to identify at species level of the isolates belonging to *Pseudomonas* and *Bacillus* genera is needed. *Pseudomonas* species are the most common biological control agents studied in hydroponics systems [28]. Schmautz et al. [29] found that *Pseudomonas* spp. associated to plant roots of growing lettuce may had been selected for its inherent activity as possible biological control agents. *Pseudomonas* spp. and *Bacillus* spp. could control phytopathogens in soilless systems by mechanisms of action like resistance induction, space and nutrient competition (i.e., siderophores), and secondary metabolites (i.e., antibiotics and biosurfactants) [93–95].

There are many research works on biological control agents against plant pathogens in hydroponics and soilless systems that could be useful and applicable to aquaponics systems [28]. Microbial antagonists are selected by their ability to grow in aqueous conditions or by their biological cycle [54]. The most common in literature are *Pythium* spp., *Fusarium* spp., *Pseudomonas* spp., *Bacillus* spp., and *Lysobacter* spp. [35,54,96]. However, research continues into finding better antagonists and ways to improve their efficiency [44]. Secondary metabolites like bio-surfactants have been studied as alternatives to plant disease control [97,98]. The mixture of compatible microbial antagonists could increase the spectrum of activity and effectiveness of individual treatments [92,99].

6. The Role of Microbial Communities in Phytopathogen Suppression in Aquaponics

Microbial communities are essentials in the aquaponics systems due to its role in nutrient recycling, degradation of organic matter, treatment and controlling disease [100]. Microbial diversity relies on nutrients availability and prevailing environmental conditions, but in general microbial diversity in aquaponics systems belongs mainly to the bacterial group actinobacteria, alpha-proteobacteria, beta-proteobacteria, gamma-proteobacteria, firmicutes, bacteriodetes and archaea (Table 3) [101–103]. Aquaponics systems can have many components, as mentioned before, which makes an interesting topic of research to study the microbial communities and their differences between compartments [36].

Schmautz et al. [29] concluded that microbial communities of fish faeces from the genus *Cetobacterium* in the biofilter were principally conformed of nitrification bacteria but in low proportion in the periphyton or plant roots. Microorganisms in the medium interacts with plant roots by promoting uptake of nutrients, stimulating plant growth and acting as antagonist against phytopathogens [104,105].

Table 3. Common microbial diversity and bacteria examples in aquaponics systems.

Phyla Group	Bacteria	Description
Actinobacteria	*Frankia* spp. *Leifsonia* spp. *Mycobacterium* spp. *Streptomyces* spp.	Gram − N_2 Fixing Plant commensals
Alpha-proteobacteria	*Methylobacterium* spp. *Rhizobium* spp. *Wolbachia* spp. *Rickettsia* spp.	Gram +/− Degrade organics Plant symbionts
Beta-proteobacteria	*Nitrosomonas* spp. *Burkholderia* spp.	Gram − ammonia oxidizing Pathogenic, organic degrading and metal degrading
Gamma-proteobacteria	*Enterobacter* spp. *Vibrio* spp. *Pseudomonas* spp.	Gram − Pathogenic
Firmicutes	*Clostridia* spp. *Bacillus* spp.	Gram + Pathogenic
Bacteriodetes	*Flavobacterium* spp. *Sphingobacterium* spp. *Cytophaga* spp.	Gram − Opportunistic pathogen

Source: Srivastava et al. [105] (http://creativecommons.org/licenses/by/4.0/).

The absence of sterilization in aquaponics systems leads to a natural ecosystem where microflora interact with each other and with other living organisms. This microflora favor a space-nutrient competition in which no single pathogen microorganism could dominate, and therefore not causing a disease to fish or plants in the system [2]. In general, there is a perception that the coexistence of fish, plant and microorganisms in the same aquatic system generates a synergistic effect in the whole system [106]. Most of the research about microbial communities in aquaponics systems has been focused on nitrifying bacteria [29] or plant growth promotion [35]. Postma et al. [42] and Vallance et al. [62] reviewed the capacity of microbial communities in soilless systems to suppress pathogens like *Phytophthora cryptogea*, *Pythium aphanidermatum* and *Fusarium oxysporum*.

7. Future Perspectives

7.1. Biological Control in Soilles Systems

Research on biological control in soilless systems like aquaponics has the potential to allow the understanding of interactions between biological control agent, phytopathogens and plant roots. There are many studies of biological control agents, but the mechanisms involved are difficult to elucidate from soil-based studies [107]. Microbial diversity in soil matrices is heterogeneous and soil is chemically complex [108]. The soil matrix limits the technology to study this interaction, i.e., soil matrix-based studies are based on DNA extraction, subsequently, and sequence-based analysis, thus omitting the exploration of microbial community structure [109], genetic information about nutrients flux [110], and microbial screening of candidate biological control agents [111]. In contrast, aquaponics systems operate under controlled parameters (nutrient concentrations, temperature, pH), and their matrix are not too complex [35]. As a result, soilless systems like aquaponics are scalable, reproducible and adjustable laboratories where results are prone to be technological transferred [35]. The researchers reported that *Pseudomonas* spp. was effective as a biological control agent against the fish pathogen *Saprolegnia parasitica* and the phytopathogen *Pythium ultimum*, and other bacterial isolates from the aquaponics system.

7.2. Mixed Treatment versus Fish-Plant Pathogens

The overlap between fish gut microbiome and rhizosphere microbiome could be an opportunity to manipulate biological control agents to benefit both plant and fish [112]. *Bacillus* species are well studied as probiotics in aquaculture and biological control agents in hydroponics [113]. In aquaponics systems some studies include *Bacillus* species in their experimentation as plant growth promoters and nutrient fixers in a tilapia-lettuce production system [39]. Until now, research is missing on how to prove that microorganisms applied at aquaculture subsystem with benefits for fish also will be beneficial for plant growth and health, and vice versa. It is important to determine the inoculum site too, i.e., whether in tank of fish production, plant roots, nutrient solution or bio-filters [30]. Sirakov et al., [40] performed a screening of bacterial isolates from different compartments of an aquaponics system to exert their inhibitory effect over fish and plant pathogens.

7.3. 'Omic' Technologies

Omics technologies like metagenomics and metatranscriptomics analysis will be the future for the study of microbial communities in aquaponics systems [114]. Recent studies based on 16S rRNA and functional gene-specific probes or libraries rather than culture techniques provide insights into new strategies for evaluating microbial diversity and a better understanding of bacterial community interactions [115]. Other advances in eukaryotes, fungi and yeast relies on 18S, 26S and 16S with 26S fragments of rRNA to study these microbiotas [116]. It was demonstrated that dynamics and flexibility of microbial communities is linked to influent water changes like C/N ratios and bio-filter performance [117]. Microbial community is still difficult to study and control [118–120] and many of the difficulties could be originate by the factors mentioned before [121]. There is still limited information about the role of microbial communities over plant rooting, growth and health in aquaponics systems. The lack of information limits the productivity of the systems and their potential to improve the health of the whole system through a specific understanding of the diverse interactions between living organisms [30].

8. Conclusions

There is a need to investigate in more depth different phytopathogens that affect numerous plants under aquaponics systems in order to improve their management and treatment. There is limited research on microbes, especially on microbiota interactions into each compartments of the system. Microbial communities assist plants growing in aquaculture systems in many ways that could not be the case if the water were sterilized like in standard hydroponic cultures. Conventional treatments in soilless systems could have negative effects on fish, plant and beneficial microorganisms which cohabit in the system, so their use must be limited. "Omics" techniques could elucidate the structure of microbial communities, metabolic functions and interactions for a better identification of strains and their metabolites with specific purposes. Biological control has the potential to reduce the perturbation effects of conventional treatments on microbial communities, fish and plant physiology, and the whole function of the aquaponics system.

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