



Integration of probiotics in aquaponic systems: an emerging alternative approach

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Received: 21 March 2023 / Accepted: 16 August 2023

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Abstract

The increasing demand on water resources, reduced land for agriculture, and concerns over food and nutrition security have prompted the evolution of innovative and complex food production systems. In this context, efficient and sustainable food production systems such as aquaponics are viewed as an important and environmentally friendly technology for adaptation under resource-limited environments. Producing food in soilless systems is a promising strategy, as this method utilizes significantly less water than traditional agriculture. However, optimizing growing conditions to enhance crop and fish yields in aquaponics is frequently ambiguous and is often not economically feasible. One of the strategies to improve plant yields and supply of nutrients in aquaponics is the application of probiotics. With this strategy, the crop yields in aquaponics are improved via a variety of mechanisms, including nitrogen fixation, solubilization of mineral nutrients, organic matter mineralization, plant hormone modulation, and biocontrol. As a result, incorporating probiotics in aquaponic systems is a strategy for mitigating environmental effects and advancing sustainable agriculture. This review paper provides the current knowledge of the use of probiotics in aquaponics. Suggestions for further studies on the effects of probiotics in aquaponic systems are proposed. Through literature review, integrating probiotics into aquaponic systems has the potential to improve nutrient supply, modulation of water quality parameters, and microbial communities, which are key processes in enhancing the productivity of aquaponic systems.

Keywords Aquaponics · Probiotics · Sustainable · Soilless systems

Handling Editor: Gavin Burnell

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Introduction

As the human population grows and the demand for high-quality food rises, food production needs to increase by 50% by 2050 (FAO 2017). Due to recent trends in urban agriculture and climate change, there is an emerging need for alternative sustainable food production systems with minimal dependence on land and soil such as aquaponics (Folorunso et al. 2020). Aquaponics is a technology of growing fish and plants symbiotically, in which the nutrient-rich effluent excreted by fish undergoes microbial transformations to be used as a source of nutrients for plant biomass (Yep and Zheng 2019). Due to recycling, aquaponic systems utilize 50 to 70% less water compared to traditional agricultural systems (Dhal et al. 2022a). The concept of aquaponics was initiated in the 1970s as an environmentally sustainable agricultural method (Naegel 1977; Okomoda et al. 2022). As a result, this emerging food production technology is now perceived to be a potential sustainable solution to the inadequate production of fish and crops as well as unemployment in many developing countries (Bosma et al. 2017).

Although aquaponics is seen as an important food production technology, several aspects such as optimizing nutrient and water quality requirements for plants remain a major challenge to realizing its profitability and full potential (Krastanova et al. 2022). The relatively low concentrations of macro- and micronutrients in the recirculating water are one of the major challenges affecting production output from aquaponic systems. These low levels of nutrients cause nutrient deficiencies in the plants and suboptimal plant growth rates. Ultimately, nutrient and energy re-use must be optimized for aquaponics to be successfully applied at a large scale (Goddek et al. 2019a; Dhal et al. 2022b). Balancing appropriate growth conditions including water quality parameters and nutrients with little systemic volatility is necessary for the healthy growth of plants and aquatic organisms (Okomoda et al. 2022; Krastanova et al. 2022). Aquaponic systems are increasingly relying on technology to optimize system performance and save time and resources. Recent studies have investigated ways to monitor and stabilize water quality parameters like pH, temperature, humidity, mineral concentrations, and heavy metals through intelligent control (Wei et al. 2019; Dhal et al. 2023). However, using technology to optimize nutrient requirements for plants remains a major challenge as advancements in developing machine learning techniques to regulate nutrient concentrations in aquaponics are limited by lack of sufficient data (Dhal et al. 2022a, b) and inefficiency in extreme climatic conditions (Dhal et al. 2022b).

The use of probiotics provides a promising emerging alternative to enhance nutrient availability in aquaponics. Research on probiotics in aquaponic systems may alleviate costly nutrient supplementation through integrating beneficial microorganisms (Bartelme et al. 2018). Comprehensive reviews on the use of probiotics have been published in the context of fish culture and with emphasis on fish growth, survival, and health (Verschuere et al. 2000; Balcázar et al. 2006; Hai 2015). However, those reviews only considered recirculating aquaculture systems (RAS) without plants. Aquaponic systems are generally more complex than traditional hydroponic systems and RAS because of the need to balance system parameters to meet both the requirements of fish and plants. Aquaponics is a niche agricultural technique that requires more biological and technical knowledge than hydroponics or aquaculture; therefore, incorporation and testing of probiotic products are critical to integrating simultaneous fish and plant production. Currently, the biological approaches for improving crop and fish production are gaining popularity among aquaponic practitioners following integrated plant nutrient management system. Previous reports show that the

use of probiotic products in aquaponics improved the water quality and growth of Mozambique tilapia and plants (Kasozzi et al. 2021a) and improved the composition of mineral content of plants (Gullian-Klanian et al. 2021). To further our understanding of this emerging technology, we focused on reviewing literature that explicitly addresses the use of probiotics in aquaponic systems.

Collection of literature information

This review was developed using a systematic and comprehensive literature review on peer-reviewed publications. Available published data were collated from online databases including Google Scholar, ScienceDirect, PubMed, Scopus, and Web of Science. Some of the keywords used were “probiotics in aquaponics,” “aquaponics,” “probiotics in aquaculture,” “coupled,” and “decoupled” used singly or in combination to generate matches. Only peer-reviewed and published articles in the English language were chosen. In addition to the primary articles that met the search criteria parameters, other articles were obtained by scanning through the relevant cross-references contained therein.

General description of aquaponic systems

Aquaponic systems are broadly categorized according to (1) the growing technology used for fish and plants and (2) the coupling or uncoupling subsystem. With the hydroponic component taken into consideration, aquaponic systems are classified as media-based culture (MBC), nutrient film technique (NFT), and deep water culture (DWC) (Somerville et al. 2014). The MBC utilizes various media, such as pumice, stones, sand, gravel, or expanded clay pebbles, which provide additional surface for biofiltration and mineralization (Kasozzi et al. 2019). For the NFT, plant roots are exposed to a thin layer of nutrient-rich water that runs through pipes. NFT type provides high oxygen to the plant roots that facilitates plant growth. DWC method allows the plant roots to absorb nutrients in the water without clogging the water channel, although aeration for DWC units is important (Somerville et al. 2014). All the three systems require effective mechanical filtering to avoid fish waste accumulation on the plant roots. Even though limited published research is available to compare production between single-loop and decoupled systems, small-scale experiments have shown that decoupled systems improved plant growth. In the following section, a description of coupled and decoupled aquaponics is outlined.

Coupled aquaponic system

The main components of a coupled aquaponic system are a fish tank, a sedimentation unit (clarifier), substrates for the growth of bacteria or suitable biofilters, and a hydroponic unit for plant growth (Palm et al. 2019). Coupled aquaponic systems use a series of filtration tanks where water from the fish tanks passes before it enters the hydroponic unit of the system (Sallenave and Shultz 2019). Thereafter, the filtered clean water is then pumped back to the fish tank. Coupled aquaponic systems can easily be configured to operate at a scale that is appropriate for the local environment (Palm et al. 2019). Depending on the size of operation, a variety of hydroponic subsystems can be employed, and is suitable for small, semi-commercial to large-scale systems (Palm et al. 2018).

Decoupled aquaponics

A decoupled aquaponic system was published in 2015 by the Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany (Kloas et al. 2015). Using this kind of design, the authors aimed at improving sustainability, increasing productivity, and reducing environmental emissions. Decoupled systems differ from coupled aquaponics due to the separation of the water and nutrient loops for the fish and hydroponic subsystems. In decoupled aquaponics, water from the hydroponic unit is not redirected to the fish tanks, and conditions within the hydroponic unit can be managed separately (Sallenave and Shultz 2019). This feature is important in maintaining specific nutrient and environmental requirements of plants and fish. Decoupling aquaponics enables the collection and remineralization of fish waste solids discharged from the fish rearing component, increasing the amount of nutrients such as iron (Fe), phosphorus (P), potassium (K), and calcium (Ca) that would otherwise bound in the solids and unavailable to the plants. Decoupling the fish and plant systems offers several benefits like providing optimal water quality conditions for the fish and plants without adverse effects to either part resulting in increased productivity and yields. In addition, both systems can be shut down for maintenance or disease management.

Given the differing specific nutrient and environmental requirements of plants and fish, pilot studies involving decoupled systems have been initiated (Monsees et al. 2017; Goddek et al. 2019b). In a pilot study comparing plant and fish yields in both decoupled and coupled aquaponics, Monsees et al. (2017) reported that fruit yield was 36% higher in decoupled aquaponics than in coupled aquaponics, although fish growth was the same in both systems. The independent regulation of the pH and dynamic adaptation of nutrient concentrations were cited as the primary causes of the improved performance. Although decoupled aquaponic systems provide solutions to some challenges inherent to single-loop systems, they are more complex to manage and require greater capital investment, space, and technical expertise (Goddek et al. 2019a).

Probiotics and aquaponics

The term “probiotic” is derived from Greek words “pro” and “bios,” which literally means “for life” (Hoseinifar et al. 2018). Parker (1974) was the first who defined probiotics as “organisms and substances which contribute to intestinal microbial balance.” In 1989, Fuller revised the definition as “live microbial feed supplement which beneficially affects the host animal by improving its intestinal microbial balance” (Fuller 1989). The FAO/WHO joint panel defined probiotics as “live microorganisms, which when administered in adequate amounts, confer a health benefit on the host” (FAO/WHO 2002). A modified definition by Merrifield et al. (2010) refers to probiotics as “a live, dead or component of a microbial cell that when administered via the feed or to the rearing water benefits the host by improving either disease resistance, health status, growth performance, feed utilisation, stress response or general vigour, which is achieved at least in part via improving the hosts microbial balance or the microbial balance of the ambient environment.” Considering the three living components (fish, plants, and microbes) that make up an aquaponic system (Kasozi et al. 2021a), the proposed definition by Merrifield et al. (2010) considers the complexity of aquaponics microbiome and the rearing environment. In fact, terms

such as “friendly bacteria,” “environmentally friendly,” or “healthy” are commonly used to describe probiotics (Cruz et al. 2012; James et al. 2021).

Although application of probiotics in aquaponics seems to be relatively recent, the interest in such environmentally friendly treatments is increasing rapidly. It is regarded as a promising strategy for improving plant and fish production in aquaponics (Bartelme et al. 2018). Currently, commercial products are available in liquid or powder presentations (Cruz et al. 2012). Several plant growth-promoting bacteria (PGPB) have also been used in hydroponic systems such as strains of *Agrobacterium*, *Pseudomonas*, *Azospirillum*, and *Bacillus* (Stegelmeyer et al. 2022). In aquaponics, many studies have focused on the use of *Bacillus* species, which have been reported to have benefits for both fish and plants cultured (Kasozi et al. 2021a). The most frequent *Bacillus* species used as probiotic strains in aquaponics are *B. subtilis*, *B. licheniformis*, *B. pumilus*, and *B. amyloliquefaciens* (Cerozi and Fitzsimmons 2016; Kasozi et al. 2021a). *Bacillus* species have also been reported to have antagonistic attributes towards several plant pathogens by the production of lipopeptides, antibiotics, and enzymes in addition to stimulating plant growth (Shafi et al. 2017). *Bacillus* species such as *B. coagulans*, *B. licheniformis*, and *B. subtilis* have also been reported to efficiently bioremediation of wastewater (Xie et al. 2013; Divya et al. 2015). There is limited data on how probiotics interact with other beneficial organisms in aquaponic system. Table 1 shows the findings of published literature on various dynamics of aquaponics related to probiotic application. It is clear from the table that researchers’ main interests were on improving the water quality (nitrification and organic matter decomposition) and increasing plant biomass. However, research is needed to understand other aspects of aquaponics, such as disease control strategies using probiotics.

Probiotics can be used individually or in a combination of different strains (Cerozi and Fitzsimmons 2016; Sirakov et al. 2020; Gullian-Klanian et al. 2021). It might be more advantageous to use various bacterial strains than single strain to enhance the performances of aquatic animals and plants in aquaponic system due to the higher likelihood that a consortium of microorganisms will survive in a changing environment.

Putative probiotics are probiotics that have been isolated from different natural sources including the gastrointestinal tract (GIT), stomach, gill, kidney, gonads, and other internal organs (Chauhan and Singh 2019). Commercial probiotics (non-putative) on the other hand comprise of those which are already synthesized and commercially available in the market. Within aquaponic systems, genus *Bacillus* is the most utilized probiotic (Cerozi and Fitzsimmons 2016; Kasozi et al. 2021a, 2022). When compared to other probiotics, *Bacillus* species are more viable choices because they have characteristics such as sporulation capacity, which allows them to survive under harsh environmental conditions, produce antimicrobial substances, and are non-pathogenic and non-toxic when administered to fish (Balcázar et al. 2006; Kuebutornye et al. 2019; James et al. 2021).

The aquaponic compartments where the probiotics are added are vital in influencing fish and plant growth (Joyce et al. 2019). Previous research by Kasozi et al. (2021a) demonstrated that addition of probiotic product in the sump component of an aquaponic system significantly increased the concentration of nitrate and phosphate in deep water culture solution. However, further research is needed to test how the introduction of probiotics into different compartments (fish tank, deep water tank, sump, or biofilters) influences the growth of fish and plants. Probiotics also provide benefits for plants in aquaponic systems as they have been reported to enhance the decomposition of organic matter, thus making more nutrients available to the plants (Joyce et al. 2019). In doing so, probiotics provide an additional benefit to the fish as a result of improving water quality in the culture environment.

Table 1 Probiotic species used in aquaponics, source, and beneficial effects to aquaponic systems

Probiotic species	Trade name/source of probiotics	Dosage and mode of application	Beneficial effects	References
<i>Lactobacillus bulgaricus</i> GIB44	Commercial (ProViotic®)	460 mg/kg ProViotic® in fish feed	Increased growth of common carp	Sirakov et al. (2020)
<i>Nitrobacter</i> and <i>Nitrosomonas</i>	N/A	1.5 mg/L in aquaponic water	Improved water quality leading to decreased levels of ammonia and total suspended solids	Dwiardani and Prayogo (2021)
<i>Bacillus subtilis</i> and <i>Bacillus licheniformis</i>	Commercial Sanolife® PRO-W; 5.0×10^{10} CFU/g	0.02 g product/L of water	Highest concentrations of phosphorus, potassium, and zinc in the lettuce leaves were found in aquaponic systems that received the <i>Bacillus</i> product	Kasozi et al. (2021a)
			Probiotic <i>Bacillus</i> significantly increased the concentration of nitrate and phosphate in deep water culture solution	
<i>Bacillus subtilis</i> and <i>Bacillus licheniformis</i>	Commercial Sanolife® PRO-W; 5.0×10^{10} CFU/g	0.02 g product/L of water	<i>Bacillus</i> spp., when introduced in aquaponic system enhanced plant growth and chlorophyll content of the lettuce leaves, and increased the accumulation of phosphorus in plant tissues	Cerozi and Fitzsimmons (2016)

Table 1 (continued)

Probiotic species	Trade name/source of probiotics	Dosage and mode of application	Beneficial effects	References
<i>Bacillus subtilis</i> , <i>Bacillus pumilus</i> , and <i>Bacillus licheniformis</i>	N/A	5.30×10^5 CFU/mL added to aquaponic water	Improved mineralization, and hence the availability of free nutrients such as total phosphorus, potassium, and nitrogen, and controlled the total ammonia nitrogen Stevia leaves from <i>Bacillus</i> supplemented systems produced 38.6% more reducing sugars, 28.6% more flavonoids, and 35.9% more glycosylated flavonoids The fish in the <i>Bacillus</i> -treated system reached a higher final weight than the control	Gullian-Klanian et al. (2021)
<i>Bacillus subtilis</i>	Obtained from intestinal tract of <i>Ambystoma mexicanum</i>	1×10^{-7} CFU/mL directly added to water	Improved yield of <i>Ocinum basilicum</i>	Huitzil-López et al. (2018)
<i>Nitrosomonas europaea</i> and <i>Nitrobacter winogradskyi</i>	Food and Nutrition Culture Collection (FNCC), Gadjah Mada University	10^7 cells/mL added to aquaponic water	Increased the daily growth rate, relative growth rate of lettuce, and the orthophosphate concentration	Ajjiah et al. (2021)
<i>Azospirillum brasilense</i>	Strains of <i>A. brasilense</i> were provided by Dr. Rosalind Deaker, University of Sydney	Basil seedlings were inoculated at concentration of 8.65 CFU/mL	Increase in basil leaf area, fresh herbage yield, and root weight	Mangmang et al. (2016)
<i>Lactobacillus casei</i> and <i>Saccharomyces cerevisiae</i>	N/A	N/A	Water spinach (<i>Ipomoea aquatica</i> Forsk) showed higher growth and yields than that of the uninoculated control	Khastini et al. (2019)

Table 1 (continued)

Probiotic species	Trade name/source of probiotics	Dosage and mode of application	Beneficial effects	References
<i>Nitrosomonas</i> and <i>Nitrobacter</i>	10^7 CFU/g	Different dosages were applied but 1.5 mg/L was the most effective	Decrease in nitrite concentration and increase in nitrate levels	Setiawan and Prayogo (2021)
<i>Nitrosomonas</i> , <i>Nitrobacter</i> , and <i>Nitrospira</i>	Microbe-lift (Cape Coral, FL, USA)	30 mL added to aquaponic biofilter	Improved lettuce growth, enriched lettuce roots with nitrogen-fixing <i>Rahnella</i>	Day et al. (2021)
One multi-nitrification probiotics capsule (Nitrobacteria, denitrifying bacteria, <i>Bacillus</i> , <i>Lactobacillus</i> , and actinomycetes)	B103; BIOZYM, USA	Added to aquaponic water	Addition of nitrifiers in aquaponics improved nitrogen utilization by 8.8%. TAN and NO_2^- concentrations were maintained at relatively low levels compared to the control	Zou et al. (2016)
<i>Bacillus</i> spp.	Sanolife® Pro-W; 5×10^{10} CFU/g	100 mg/L added to aquaponic water	Fresh weight of mint (<i>Mentha spicata</i>) at harvest was significantly higher than the control. Improved growth of Nile tilapia	Said et al. (2022)
<i>Saccharomyces cerevisiae</i> , <i>Lactobacillus acidophilus</i> , <i>Bacillus subtilis</i> , <i>Aspergillus oryzae</i> , <i>Rhodopseudomonas</i> , <i>Actinomyces</i> , and <i>Nitrobacter</i>	N/A	Different doses of 2–6 mL/kg added to fish feed	Adding probiotics in the fish feed had a significant effect on feed conversion ratio and improved growth of <i>Clarias gariepinus</i>	Santoso and Sunadji (2020)
<i>B. lactis</i> , <i>L. acidophilus</i> DDS-1, <i>S. thermophilus</i> , <i>B. bifidum</i> , <i>B. longum</i>	Commercial Bio balance® Bio care, Copenhagen, Denmark	10^8 CFU/mL added to fish feed	Improved leaf gas exchange parameters and nitrate reductase activity in lettuce from systems supplemented with commercial symbiotic product Higher phagocytosis activity of <i>Cyprinus carpio</i> than the control group	Sirakov et al. (2018).

Table 1 (continued)

Probiotic species	Trade name/source of probionts	Dosage and mode of application	Beneficial effects	References
<i>Bacillus</i> spp.	Commercial Pondplus®	1 g of the product/1000 L of water	Increased the body weight of <i>Oreochromis niloticus</i>	Saufie et al. (2022)
<i>Bacillus megaterium</i>	N/A	5.09×10^8 CFU/mL added to aquaponic water	Increased potassium availability in cum holy basil leaf. Increased the mean body weight of Nile tilapia	Angkha et al. (2020)
<i>Bacillus subtilis</i> and <i>Bacillus licheniformis</i>	Sanolife® PRO-W; 5.0×10^{10} CFU/g	0.02 g product/L of water	Increased weight gain of Mozambique tilapia. <i>Bacillus</i> treatment increased the activities of amylase, protease, and alkaline phosphatase	Kasozi et al. (2021b)
<i>Bacillus subtilis</i> and <i>Bacillus licheniformis</i>	Commercial Sanolife® PRO-W; 5.0×10^{10} CFU/g	0.02 g product/L of water	Food-borne pathogens belonging to the <i>Shigella</i> and <i>Aeromonas</i> were less abundant on fresh lettuce leaf surfaces in the probiotic-treated system than in the control	Kasozi et al. (2022)
<i>Lactobacillus</i> , <i>Bacillus</i> , <i>Nitrosomonas</i> , <i>Nitrobacter</i>	N/A	Different concentrations (0.12 mg/L, 0.25 mg/L, and 0.37 mg/L)	Addition of probiotic at 0.25 mg/L decreased the concentration of ammonia. Improved specific growth rate of Sangkuriang Catfish, <i>Clarias gariepinus</i>	Hasan et al. (2019)
<i>Pseudomonas aeruginosa</i> and <i>Achromobacter insuavis</i>	Commercial (RIFA)	10 ml/m ³	Improved the growth and survival of Asian reftail catfish, <i>Hemibagrus nemurus</i>	Yosmaniar et al. (2022)

NA not available

Methods of administration of probiotics

Although there are several techniques described in aquaculture studies, the two common probiotic administration techniques in aquaponic systems are described in this review. In aquaponics, probiotics have been used either as a food additive added directly to water or mixed with feed (Cruz et al. 2012; Santoso and Sunadji 2020; Kasozi et al. 2021a). The mode of administration of a probiotic is vital to ensure its maximum efficacy. The method of supplementation, dosage, design of aquaponic system, and period of application are key determinants of probiotic delivery and functionality (James et al. 2021). Chauhan and Singh (2019) reviewed various studies about the use of probiotics in aquaculture, and the authors reported that the time period for application of a probiotic product can be as short as 6 days or as long as 5 months or even 8 months.

Direct application to aquaponic water

Several studies have investigated the benefits of probiotic application in aquaponics through direct application to the rearing water. Most of the probiotic treatments particularly those in powder form are first dissolved in water before being added to the sump tank or biofilter compartments of aquaponic systems. Direct application of probiotic into aquaponic water has a positive effect on improving water quality, modulating the natural microbial composition of water (Kasozi et al. 2021a, b). Hasan et al. (2019) demonstrated that a probiotic mixture of *Lactobacillus*, *Bacillus*, *Nitrosomonas*, and *Nitrobacter* bacteria applied at a concentration of 0.25 mg/L every 10 days showed a significantly lower concentration of ammonia and phosphorus levels in the culture water. Gullian-Klanian et al. (2021) reported that the addition of a probiotic product in the last section of the sedimentation tank of an aquaponic system facilitated mineralization, resulting in the availability of free nutrients such as P, K, and N, in addition to controlling the level of total ammonia nitrogen for 56 days without the need for water replacement. Similarly, Kasozi et al. (2021a) reported that the mean shoot dry weight and the mean fresh weight of lettuce from the *Bacillus* treatment were significantly higher than those observed for the control plants when a commercial probiotic product was being introduced into the sump of a coupled aquaponic system. Overall, administration via rearing water has been the most beneficial administration mode of probiotics in aquaponics.

Addition to the diet

Probiotics can also be mixed with feed supplement before being applied in aquaponic systems. Santoso and Sunadji (2020) applied a probiotic mixture of *Saccharomyces cerevisiae*, *Bacillus subtilis*, *Actinomyces*, *Aspergillus oryzae*, *Lactobacillus acidophilus*, *Rhodopseudomonas*, and *Nitrobacter* in fish feed. These were administered at three different concentrations ranging from 2 to 6 mL/kg in addition to using clams as a biofilter at densities ranging from 50 to 200 clams⁻² in an aquaponic system, comprising of African catfish (*Clarias gariepinus*) and aquatic spinach (*Ipomoea aquatica*). The authors reported that delivery of probiotics via fish feed had a significant effect on the growth of catfish but not on aquatic spinach biomass production. In another study by Sirakov et al. (2020), commercial probiotic ProViotic was added to common carp (*Cyprinus carpio*) feed at a concentration of 460 mg/kg. However, the probiotic treatment did not have any significant effect on the weight of head and length of roots in lettuce. Probiotics can also be applied as

synbiotics, i.e., feed additives combining probiotics and prebiotics. In a study by Sirakov et al. (2018), commercial synbiotic Bio balance[®] was mixed in oil up to a concentration of 10^8 CFU/mL and sprayed like aerosol on commercial common carp (*Cyprinus carpio*) feed. The authors reported an improved leaf gas exchange and nitrate reductase activity in lettuce from systems supplemented with commercial synbiotic product. However, the fish growth was not significantly improved.

Applications of probiotics in aquaponics

Biological nitrogen fixation

Nitrogen is an essential macronutrient for plant growth. The primary supply of nitrogen in aquaponic systems is feed, which is excreted by the fish in the form of ammonia nitrogen (Wongkiew et al. 2017). Depending on the concentration and physiological makeup of the plant, nitrogen can be absorbed by the plants either in the nitrate (NO_3^-) or ammonium (NH_4^+) (Graber and Junge 2009; Wongkiew et al. 2017). Because the concentration of NO_3^- in aquaponic systems is higher than NH_4^+ , plants growing in these systems uptake NO_3^- as their primary nitrogen source (Graber and Junge 2009). A fully functioning aquaponic system should maintain NO_3^- concentrations in the range of 5 to 150 mg/L (Somerville et al. 2014; Reyes-Yanes et al. 2020). According to Kasozi et al. (2021a), supplementing *Bacillus* in aquaponics enhanced nitrate availability in deep water solution, which contributed to improved lettuce growth in a tilapia-lettuce system.

Phosphate solubilization

Phosphorus (P) is an essential nutrient required in adequate amounts for plant growth and development (Joyce et al. 2019). At cellular level, phosphorus plays an important role in energy transfer, growth of new tissues, respiration, and cell division, as well as photosynthesis. Fish feed provides the main source of P in an aquaponic system (Cerozi and Fitzsimmons 2017; Ajijah et al. 2021). However, 95 to 99% of phosphorus in solution exists as insoluble inorganic phosphorus and cannot be utilized by plants (Kalayu 2019). Under P-deficient conditions, plant growth is impeded, while in excess conditions, P may lead to antagonistic interactions with micronutrients, particularly zinc (Barben et al. 2010; Cerozi and Fitzsimmons 2017). The solubility of P depends on the pH, and a higher pH than 7.0 will contribute to the precipitation of P, thus making it unavailable for the plants (Barben et al. 2010; Wongkiew et al. 2017). As pH increases above 7.0 in aqueous solutions, most of the dissolved phosphorus reacts with calcium forming calcium phosphates (Cerozi and Fitzsimmons 2017).

Phosphate-solubilizing microorganisms are capable of hydrolyzing organic and inorganic insoluble phosphorus compounds to soluble forms that can easily be assimilated by plants. *Bacillus* spp. transform the complex form of phosphorus into simple bioavailable forms such as dihydrogen phosphate (H_2PO_4^-), hydrogen phosphate (HPO_4^{2-}), and phosphate (PO_4^{3-}), which can be absorbed by the plant roots (Gouda et al. 2018). Research conducted by Ajijah et al. (2021) demonstrated that the addition of nitrifying bacteria (*Nitrobacter* and *Nitrosomonas*) in an aquaponic system significantly increased the orthophosphate concentration.

Potassium solubilization

After nitrogen and phosphorous, potassium (K) is one of the essential plant macronutrients influencing plant growth, development, and fruit quality (Angkha et al. 2020). It not only performs physiological functions like synthesis of cells, enzymes, proteins, starch, cellulose, and vitamins but also increases the effectiveness of how nitrogen is used (Somerville et al. 2014; Angkha et al. 2020). Aquaponic systems are often deficient in K due to low amounts in commercial fish feeds (Seawright et al. 1998; Somerville et al. 2014). Ideally, when K is supplemented in fish feed for aquaponics, the goal is to provide benefits to both fish and plants. Finding the optimum level and source of K is crucial as this could affect its availability for the fish and plants. Using K-solubilizing microbes is one of the most effective strategies to increase plant of K uptake in aquaponics. Various genera of bacteria, such as *Bacillus*, *Paenibacillus*, *Acidithiobacillus*, *Pseudomonas*, and *Burkholderia* have been reported to exhibit K-solubilizing characteristics (Ahmad et al. 2016). Gullian-Klanian et al. (2021) reported that the addition of multi-strain probiotic containing *Bacillus* spp. into aquaponic system resulted in the availability of K. Furthermore, Angkha et al. (2020) reported that inoculation of *Bacillus megaterium* at dosage of 5×10^8 CFU/mL increased K availability in aquaponics, which were not treated with mica (a K-bearing mineral).

Probiotic as plant growth promoters

Several researchers have reported positive effects of probiotics on plant growth and yield under aquaponic systems (Mangmang et al. 2016; Ajijah et al. 2021; Kasozi et al. 2021a). In general, investigations of probiotics in aquaponic systems have been primarily tested on leafy vegetables particularly basil (*Ocimum basilicum*) and lettuce (*Lactuca sativa*). Leafy vegetables have a short growing period as well as low to medium nutritional requirements (Yep and Zheng 2019; Thaiparambil and Radhakrishnan 2022). This may explain why many researchers have used leafy vegetables in their studies. Application of *Azospirillum brasilense* improved the growth and yield of basil crop under aquaponics system (Mangmang et al. 2016). Ajijah et al. (2021) reported that the addition of nitrifying bacteria had a significant effect on daily growth rate and relative growth rate of lettuce in an aquaponic system integrated with common carp and lettuce. Similarly, Kasozi et al. (2021a) found that the fresh weight of the harvested shoots and the shoot dry weight of lettuce were significantly higher in the *Bacillus*-treated systems than in the control systems. A study by Said et al. (2022) that investigated the effects of the addition of probiotic (*Bacillus* spp.) on mint (*Mentha spicata*) found that the plant fresh weight and length at harvest were better in probiotic-treated systems than in the control systems.

In reference to fruiting plants, García et al. (2004) investigated the effects of *B. licheniformis* on the growth of pepper and tomato in hydroponics. The authors reported that the total weight of pepper harvested and the number of tomato fruits produced were increased significantly by the inoculation. The growth-promoting activities of probiotics on plants can be explained in various ways, including biocontrol and induction of disease resistance in the inoculated plant, biological nitrogen fixation, solubilization of mineral nutrients, mineralization of organic compounds, and production of phytohormones (Mangmang et al. 2016; Shafi et al. 2017; Radhakrishnan et al. 2017).

Effect of probiotic on leaf mineral composition, antioxidant, and metabolic activities of plants

The benefits of vegetable consumption depend on its composition, particularly antioxidants, which can function as nutrients. Kasozi et al. (2021a) reported that *Bacillus* spp., when introduced in aquaponic system, enhanced concentrations of phosphorus, potassium, and zinc in lettuce leaves. Similarly, Cerozi and Fitzsimmons (2016) reported enhanced chlorophyll content of the leaves, and increased the accumulation of phosphorus in plant tissues when probiotic was supplemented in aquaponic system. Plant leaves from probiotic-supplemented aquaponic systems produced 38.6% more reducing sugars, 28.6% more flavonoids, and 35.9% more glycosylated flavonoids than the control (Gullian-Klanian et al. 2021). According to Mangmang et al. (2016), inoculation of basil seedlings with *Azospirillum brasilense* enhanced peroxidase activity and endogenous plant indole-3-acetic acid (IAA) in an aquaponic system integrated with *Lates calcarifer*.

Effect of probiotics on diversity and composition of the resident plant root-associated microbiome

Root health is essential for plant health and to the composition of microbial populations close to the root surface (Kasozi et al. 2021a; Lobanov and Joyce 2022). Application of probiotics in aquaponic systems has been shown to modify some changes in root-associated microbiota. The introduction of beneficial bacteria such as *Bacillus* into aquaponics can increase microbiome-associated multifunctionality (Kasozi et al. 2021a). Many strains of *B. subtilis* boost plant iron uptake, produce antibiotics, multiply quickly and can occupy a variety of niches, and contribute to plant health (Radhakrishnan et al. 2017). According to Kasozi et al. (2021a), the composition of bacterial communities around the lettuce root significantly changed as a result of the addition of *Bacillus* to the aquaponic system. The authors reported that members of the bacterial phyla Acidobacteria, Verrucomicrobia, Firmicutes, and Planctomycetes, which play a role in physiological processes like carbon usage, nitrogen assimilation, antimicrobials, metabolism of iron, and abundance of transporter, were more abundant in *Bacillus*-treated systems compared to the control systems. Furthermore, *A. brasilense* inoculation established a beneficial association with the existing bacterial populations in the root rhizosphere of basil grown under aquaponics (Mangmang et al. 2016). Probiotics have been reported to alter root morphology, which could change the amount and pattern of root exudation, thereby influencing the type of specific bacterial community that can colonize the rhizosphere (Mangmang et al. 2016). On the contrary, Lobanov and Joyce (2022) reported that under soilless conditions, plants are able to exert a stronger discriminatory influence on their rhizosphere composition than the presence of exogenous colonizing bacteria. The authors speculated that the selection pressure exerted by the plant to consolidate the rhizobiome near a particular profile is an important aspect of plant physiology despite the influence of the exogenous microbial environment. Regardless, we recommend that the effect of probiotic administration on plant roots, including the effect of root exudates in aquaponic systems, needs further investigation.

Improvement of water quality

Aquaponic systems are usually associated with the accumulation of nitrogenous and increased loads of organic matter. Optimization of water quality parameters for the plants,

fish, and microbes is key to a productive aquaponic system (Munguia-Fragozo et al. 2015; Yildiz et al. 2017). Probiotics help to improve water quality due to their ability to participate in the turnover of organic nutrients in aquaponics (Gullian-Klanian et al. 2021). Most of the feed that is not consumed or metabolized by fish ends up as waste in aquaponics, either in dissolved form (e.g., ammonia) or as suspended or settled solids (Munguia-Fragozo et al. 2015). Improvement in water quality in aquaponics has been recorded in studies involving the addition of probiotics. Several studies have also reported the use of *Nitrosomonas* and *Nitrobacter* as probiotics to improve water quality in aquaponic systems. The use of the combination of these probiotic species at a dosage of 1.5 mg/L was reported to significantly reduce ammonia level and total suspended solids (Dwiardani and Prayogo 2021). The use of microbial consortia consisting of *Nitrosomonas* sp. and *Nitrobacter* sp. and *Bacillus* species has been reported to increase yield of aquaponically grown spinach (Khastini et al. 2019). In another study, Zou et al. (2016) applied one multi-nitrification probiotic capsule comprising nitrobacteria, denitrifying bacteria, *Bacillus*, *Lactobacillus*, and actinomycetes in an aquaponic system of common carp (*Cyprinus carpio*) and pakchoi (*Brassica chinensis*). The authors reported that the total ammonia (TAN) and nitrite (NO_2^-) concentrations were maintained at relatively low levels (TAN < 0.5 mg/L, NO_2^- < 0.1 mg/L). Other mechanisms through which *Bacillus* species improve water quality are by ammonification, nitrification, denitrification, and nitrogen fixation (Hlodzi et al. 2020). A study by Yu et al. (2005) reported that *Bacillus amyloliquefaciens* reduced ammonia by up to 93% after 24 h of inoculation with an initial concentration of ammonia of 200 mg/L, at a temperature of 35 °C and a pH of 7.0. Jasmin et al. (2020) reviewed various studies in which *Bacillus* species were used under a wide range of aquaculture conditions to treat wastewater from aquaculture operations, in particular from shrimp culture, and the authors reported that *Bacillus* species lowered ammonia and nitrite concentrations in several studies.

Probiotics as a biological control of plant and fish pathogens

Various phytopathogens such as fungi, bacteria, viruses, and parasites have the potential to harm plants in soilless systems like aquaponics. Plant diseases in aquaponic systems may be comparable to those in hydroponics because of the continuous presence of water (Kasozzi et al. 2021b). Because of their propensity for humid/aquatic environment conditions, soil-borne pathogens, such as *Fusarium* spp., *Phytophthora* spp., and *Pythium* spp., are the most problematic among the variety of plant pathogens that occur in aquaponic systems (Stouvenakers et al. 2019). Information about the possible natural plant protection capacity of aquaponic microbiota is scarce, but the potential of this protective action can be envisaged based on elements currently understood in hydroponics or in recirculated aquaculture. Probiotics are considered non-pathogenic and non-toxic, with health benefits to the host. In a study by Said et al. (2022), addition of commercial *Bacillus* probiotic at 100 mg/L per week promoted the growth of beneficial lactic acid bacteria and prevented the emergence of pathogenic bacteria in an aquaponic system involving Nile tilapia (*Oreochromis niloticus*) integrated with mint (*Mentha spicata*). In another study, Kasozzi et al. (2022) demonstrated a potential risk of pathogen contamination in lettuce grown in an indoor aquaponic system; however, the authors reported a relatively lower abundance of *Shigella* and *Aeromonas* on lettuce leaf surfaces in systems supplemented with a *Bacillus* probiotic than the control. Figure 1 indicates a summary of the benefits of probiotics on the three major life forms (plants, fish, and bacteria) which constitute an aquaponic system.

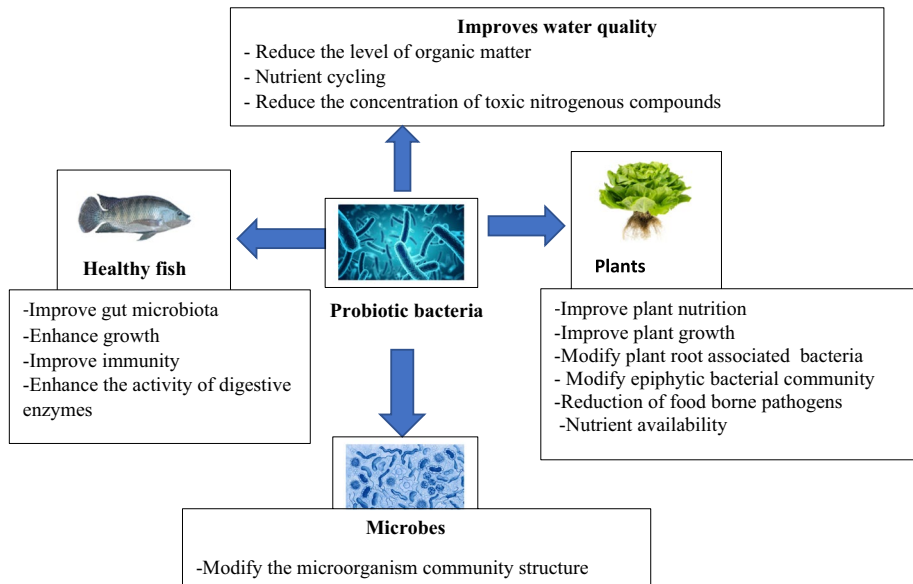


Fig. 1 Benefits of probiotics on the three major life forms which constitute an aquaponic system

Fish growth promoter

Although they are several fish species suitable for aquaponic farming, tilapia species are the most frequently utilized and arguably most successful in aquaponics, followed by common carp and African catfish (Yep and Zheng 2019; Pinho et al. 2021; Palm et al. 2022). Tilapia species thrive in aquaponic systems primarily because they are tolerant to a wide range of environmental conditions and able to feed on low trophic levels (Yep and Zheng 2019). Additionally, tilapia do not require a high quantity of growing space due to their low dissolved oxygen requirements. Tilapia can consume small organisms such as phytoplankton as well as small organic particles (El-Sayed 2019). Nile tilapia (*Oreochromis niloticus*) is becoming established in aquaponic systems (Yep and Zheng 2019).

Studies on the application of probiotics in aquaponic systems have mainly focused on the growth of plants. However, the limited literature indicates that the addition of exogenous probiotic to aquaponic system has some positive impact on tilapia, catfish, and common carp. For example, the addition of a mixture of *Bacillus subtilis* and *B. licheniformis* (Sanolife® PRO-W; 5.0×10^{10} CFU/g) for 10 weeks in an aquaponic system increased weight gain of Mozambique tilapia, as well as increased the activities of amylase, protease, and alkaline phosphatase (Kasozzi et al. 2021b). The increased intestinal amylase and protease activities facilitate the digestion and utilization of carbohydrates and proteins, respectively. This may have contributed to the higher weight gain of the tilapia in the *Bacillus*-treated aquaponic system. Similarly, Said et al. (2022) demonstrated that the use of *Bacillus* significantly improved the growth performance of Nile tilapia, as well as the feed conversion ratio (FCR) in an integrated aquaponic system.

A study by Santoso and Sunadji (2020) reported an improved FCR and a significantly increased growth of *Clarias gariepinus* when different concentrations (2 mL/kg, 4 mL/kg, and 6 mL/kg) of probiotic were mixed in fish feed. Furthermore, Yosmaniar et al. (2022)

also reported improved growth and survival of Asian redtail catfish, *Hemibagrus nemurus*, when a probiotic mixture of *Pseudomonas aeruginosa* and *Achromobacter insuavis* at an application rate of 10 mL/m³ was administered every 5 days for 70 days in an aquaponic system. According to Sirakov et al. (2020), supplementing a diet with probiotic ProViotic® increased the growth of common carp, *Cyprinus carpio*, raised in aquaponic recirculation system. In addition, the quantity of glucose, triglycerides, and alkaline phosphatase in the blood of *C. carpio* fed with feed supplemented with ProViotic was lower than the control.

Increasing biologically available iron for plant uptake

Iron (Fe) is an essential micronutrient for proper plant development and plays a key role in regulating numerous cellular processes (Radzki et al. 2013; Kasozi et al. 2019). Fe deficiencies can cause disruptions in respiration and photosynthesis, which in turn can result in chlorosis. The levels of Fe in aquaponic systems are usually too low to sustain hydroponic vegetable production (Bartelme et al. 2018; Kasozi et al. 2019). This is common in aquaponic systems that exclusively rely on fish waste for supply of plant nutrients. Due to aerobic conditions in aquaponics, Fe is mainly present as Fe³⁺, which is not readily accessible to plant and microbes because it regularly forms insoluble oxides or hydroxides that limit bioavailability (Kasozi et al. 2019). This deficiency can be solved using bacterial siderophores produced by *Bacillus* or *Pseudomonas* (Bartelme et al. 2018) or by Fe supplementation using synthetic Fe chelates (Kasozi et al. 2019). The iron-chelating properties of *Bacillus* spp. via siderophore production help to solubilize iron from minerals and organic compounds in rhizosphere (Kasozi et al. 2019). Additionally, Radzki et al. (2013) reported an improved Fe nutrition in tomato under hydroponic system when siderophore-producing bacteria, *Chryseobacterium* spp. C138, were delivered to plant roots.

Conclusion and the future of probiotic applications in aquaponics

The above reviewed studies demonstrate that probiotics can play a vital role for sustainable production of fish and plants under aquaponic system. The use of probiotics in aquaponics has the potential to increase the bioavailability of phosphate and nitrates and the modulation of water quality parameters, which are key processes in enhancing the productivity of aquaponic systems. Most of the studies on the effect of probiotics have been tested on leafy vegetables. Further research is required to expand current findings by evaluating the efficacy of probiotic products in aquaponic systems integrated with fruiting plants such as tomatoes, peppers, and strawberries.

Administration of probiotics directly through rearing water has been reported to give the best outcomes regarding water quality improvement, fish, and plant growth. This method is also applicable for all ages of fish. Given the fact that the conditions for aquaponic systems prevent using antimicrobial/antiparasitic agents or disinfectants to eradicate diseases or parasites, integrating probiotics may be an effective strategy to meet the plant and fish growth requirements in aquaponic system. Studies on probiotics in aquaponic systems have focused on *Bacillus* spp. For the future, it is important to test the potential of other probiotics in large-scale commercial systems. Another knowledge gap that has emerged from this review is the mechanism(s) of inter-cell communication and interactions between bacteria and probiotics in the fish rearing and hydroponic subsystems of an aquaponic system. Addressing this knowledge gap will likely contribute to an understanding of the potentials of probiotics in the production of antimicrobial compounds and as potential biocontrol agents of plant pathogens.

Author contributions NK conceptualized the idea; NK and SL participated in the writing of the original draft. NK, SL, GDI, and JK participated in reviewing and editing the manuscript. All authors read and approved the final manuscript.

Data availability All required data are included in this article.

Declarations

Ethical approval Not applicable

Competing interests The authors declare no competing interests.

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