Interreg

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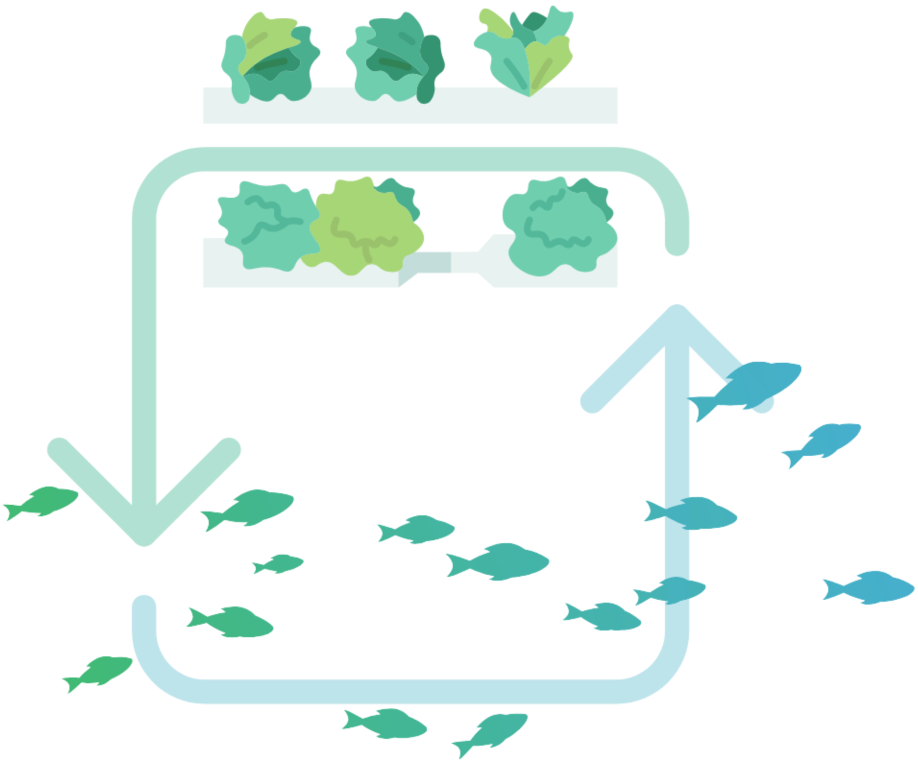
TransFarm

WATER QUALITY IN AQUAPONICS



D.3.2.1. – Training materials on water quality

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Abstract

Aquaponics is a system that combines the principles of aquaculture and hydroponics. The fish through their metabolism of fish feed release waste and through metabolic activity of microorganism this waste is transformed to a form of nitrogen that is readily available to plants. The main element connecting all three of the living organisms within an aquaponics system is water. Water is the living environment of the fish and microorganisms and the feeding environment for plants, all of which are affected by the water quality. While separate technologies of aquaculture and hydroponics have specific requirements of water quality that are suited for the specific fish species or plant species, in aquaponics a compromise must be elaborated that suits fish, plants and microorganisms. The intricate relationship between these three organism groups co-exist in close symbiosis to provide each other with the necessary nutrients. This report summarises the most important water quality parameters in an aquaponics system. Information on water quality parameters such as pH, dissolved oxygen, water hardness, conductivity, temperature and the nitrogenous cycle has been described from the point of each included organism within this system. Water quality monitoring and troubleshooting has also been described based on the most common issues that are seen in such systems. This report includes general information for entrepreneurs and individuals interested in and those starting an aquaponics system.

Keywords: *TransFarm, aquaponics, water, quality, parameters*

The information included in this report is a compilation of various articles and books of which the references can be found in the report section “References”.

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1. Introduction

1.1. TransFarm project

There are several environmental and social challenges that the food sector has to face: Agriculture is a sector particularly affected by climate change, our seas are overfished, and the world population is estimated to continue growing, being about 9.7[1] billion people by 2050. Countries in the Baltic Sea Region are strongly dependent on food import, especially for vegetables, fruit and fish; in recent years the pandemics and the war in Ukraine have exposed the need of more self-sufficient food systems. Moreover, agriculture and aquaculture are among the main contributors to the eutrophication of the Baltic Sea.

To answer these challenges TransFarm project wants to bring food production closer to consumers by promoting soil-less farming methods that can be implemented even indoors and allow to grow all year round. Examples of these methods are hydroponics, where plants are grown in water, and aquaponics, that combines hydroponics with aquaculture.

Aquaponics is a circular, closed-loop system, where water from the fish culture is used to grow plants. The fish waste within the water is microbiologically transformed by a biofilter, absorbed by plants and then cleaner water returned to the fish. The system has a completely circular water flow allowing nutrient reuse without emissions of nutrients in the environment. Since the fish, plants and microorganisms in an aquaponics system function in close symbiotic relationship, antibiotics or pesticides are not used, which in turn provides cleaner, healthier produce.

TransFarm will demonstrate aquaponics in Sweden, Estonia and Latvia as well as test alternative water sources such as rainwater and reclaimed greywater: Partners from these countries will build demonstration facilities with different characteristics and aims. The experiences exchange from the different demos will contribute to knowledge co-creation and the facilities will be the opportunity to inspire and educate future aquaponics farmers. The knowledge gathered from the construction and monitoring of the demos will result in education material available for all the actors intrested in aquaponics.

The project will also investigate business models, run activities to inform consumers about the quality of the aquaponics produce, educate entrepreneurs who want to start an aquaponics system as well as inform civil servants and policy makers about the reduced environmental impact of circular soil-less farming methods.

TransFarm project duration is three years (2023-2026) and it is coordinated by **Turku School of Economics** at the University of Turku (Turku, Finland). Project partners are the **Estonian Univervisity of Life Sciences** (Tartu, Estonia), **University of Latvia** (Riga, Latvia), **Campus Roslagen** and **Coompanion Roslagen & Norrort** (Norrtälje, Sweden).

TransFarm project is funded by EU's Interreg Central Baltic program, the total budget of the project is 1.87 million euro, EU financing covers 1.5 million euro.

[1] UN DESA publications – World population prospects 2022

1.2. Water quality in aquaponics

Aquaponics is a sustainable and creative approach to food production that blends aquaculture and hydroponics to establish a mutually beneficial ecosystem. The essential component of water is at the core of this complex system. Water quality plays a crucial role in the dynamic world of aquaponics, where fish and plants interact in a closed-loop system. The importance of this may be seen in the intricate equilibrium needed to maintain ideal circumstances for the cycling of nutrients, the growth of plants, and the health of fish. Therefore, a thorough comprehension of water quality metrics is crucial for aquaponics enthusiasts, researchers, and practitioners alike.

The **pH level**, which denotes the degree of acidity or alkalinity of the water, is essential. Ensuring a precise equilibrium between a pH level of 6.5 and 7.5 is essential for preserving the accessibility of nutrients and promoting microbial activity, which are vital elements for the health and vitality of fish and plants. **Temperature** is a crucial factor that affects metabolic rates, nutritional absorption, and the overall well-being of the environment. Consistent surveillance is crucial to avert any potential extremes that could cause distress or damage to the aquatic and plant elements. **Ammonia** and **nitrite** levels are crucial markers of the nitrogen cycle. It is important to monitor and sustain low levels of these compounds in order to prevent injury to fish and preserve a well-balanced system. **Nitrates**, which are the last result of the nitrogen cycle, function as a fundamental source of nutrients for plants. Maintaining an optimal equilibrium is crucial to guarantee a flourishing aquaponics ecosystem without jeopardizing the welfare of either element. Adequate levels of **dissolved oxygen** are needed for the overall health and vitality of both aquatic organisms, such as fish, and plant life. Inadequate oxygen levels can result in stress, stunted growth, and even death in fish, underscoring the importance of employing appropriate aeration and oxygenation methods. Conductivity and total dissolved solids are used to quantify the amount of dissolved ions and minerals present in water. Consistent surveillance aids in maintaining an optimal nutrient equilibrium, thereby averting any imbalances or harmful levels in the aquaponics system.

The **bacteria** present in aquaponics systems have a vital function in the nitrogen cycle, since they transform fish waste into critical nutrients (nitrates) that are necessary for the growth of plants. These advantageous bacteria function as biological filters, enhancing water quality by decomposing noxious compounds and averting sickness. In addition, bacteria have a role in maintaining pH levels, stabilizing the system against changes in the environment, and removing ammonia, therefore promoting the overall well-being and adaptability of both fish and plants. The existence of a strong bacterial population is essential for the process of nutrient cycling, avoidance of diseases, and maintenance of stability in aquaponics. This emphasizes their crucial function in supporting a well-balanced and effective environment.

The achievement of aquaponics relies on the careful control of water quality parameters. By ensuring the health and productivity of the system, we also contribute to the broader aims of sustainability and responsible food production. To fully harness the resilient and effective capabilities of aquaponics as a technique of food production, it is crucial to possess a thorough comprehension of water quality factors.

2. Water quality parameters

2.1. Temperature

Aquaponic system components and characteristics are all impacted by the temperature of the water. A usual compromise range is between 18 and 30°C. Both the toxicity (ionization) and dissolved oxygen (DO) levels of ammonia are influenced by temperature; a rise in temperature results in an increase in unionized (toxic) ammonia and a drop in DO levels.

More so than air temperature, the temperature of the water influences the plants in aquaponics. For most vegetables, the temperature range of 18 to 30°C is appropriate. Some veggies, nevertheless, are far better suited to growing in particular environments. Cucumbers, lettuce, and Swiss chard are just a few of the cool-season veggies that thrive in temperatures between 8 and 20°C. On the other hand, warm-weather herbs and vegetables like basil, cabbages, and okra require a temperature between 17 and 30°C. Warmer than 26°C causes leafy greens to bolt, producing seeds and blossoms that turn the greens bitter and unmarketable. Plants will experience heat stress due to the rising water temperatures. When exposed to hot water, the plant eventually shuts its roots and goes into survival mode. Wilting, low dissolved oxygen levels, plants dropping blooms and ceasing to fruit, soft, brown, slimy roots, lettuce plants bolting (elongating and going to seed), and restrictions on the plants' ability to absorb calcium are some signs of heat stress. The humidity and air temperature also have an impact on how severe the heat stress is that plants are experiencing.

Because they are cold-blooded, fish are less able to adapt to a wide variety of water temperatures. Fish can also be divided into three categories: cold to cool water, and warm water fish. Tropical fish, such as tilapia, common carp, often do well in water that is between 22 and 32°C. Still, cold-water species like trout prefer temperatures between 10 and 18°C. Common carp, for instance, have a greater temperature tolerance range of 5 to 30°C than other temperate water species (Table 1). Optimal temperature for each species is needed to ensure faster growth rates, ensure efficient feed conversion and minimise risks of diseases. Higher water temperatures might increase the respiration rates and metabolism. Higher temperature in water means that less dissolved oxygen (DO) will be available, however, in elevated temperature fish demand for DO increases. An essential component of aquaponics is matching the water temperature to the fish and keeping it within 2 degrees Celsius (i.e., a high degree of temperature control). This is because fish that have optimal metabolism and feed conversion when the water temperature is accurate and stays close to the ideal average have better fish growth rates and stable, predictable waste load releases, which support plant culture.

Table 1. Organisms and their optimal temperature ranges in aquaponics systems.

Type of organism	Optimal T range, °C	Example
Warm water fish	22-32	Tilapia, carp, perch, eels, crayfish, sturgeons
Cold water fish	10-18	Salmonids
Warm weather plants	23-28	Cabbages, basil
Cool weather plants	17-25	Lettuce
***Nitrobacter* spp.**	25-29	
***Nitrosomonas* spp.**	21-29	
Overlapping temperature, **°C**	18-30	Majority of plants and fish

For bacteria and aquaponics in general, the water's temperature is essential. 17–34°C is the ideal temperature range for bacterial growth and productivity. The temperature range provided indicates optimal conditions for the action of nitrifying bacteria, however, if the temperature drops lower, the nitrification efficiency will be reduced, but not stopped – the bacteria become inactive at 4°C. Temperatures below 0°C and over 49°C are known to destroy nitrifying bacteria. Wintertime system management is significantly impacted by the low temperatures if the systems are a subject to the outside weather conditions.

Considering the optimal growth and survival temperatures of each group of organisms – fish, plants, bacteria – species that have matching conditions should be chosen. If a system that is more prone to changes of the outside weather conditions is used, the plant and fish species should be carefully considered, therefore it is more advisable to use aquaponics systems within indoors, where the climate can be set to constant values throughout the year.

Case study!

Growth performance, nutrients and microbial dynamic in aquaponics systems as affected by water temperature

In an aquaponics system that produces brown trout and sweet basil, this study looked at the effects of a low water temperature of 11°C compared to 21°C on nutrient flow, plant and fish growth, and microbial dynamics. The findings demonstrated that in aquaponics systems, fish and plant growth is significantly influenced by water temperature. The aquaponics system under study found that using surplus heat from water at 21°C was more appropriate for culture because fish and plants grew more quickly at that temperature. The system's microbiological characteristics, biofilter effectiveness, and nutrient uptake were all negatively impacted by water that was 11°C. It was demonstrated that basil was a horticulture crop that could be grown in an aquaponics system. The findings also showed that at low water temperatures, plant requirements must be met while selecting fish feed and optimizing nutrient levels. In this case, the plant-to-fish ratio was 15:8, but further research is needed to determine other ratios related to nutrients. Another crucial factor is the caliber of the fish and plants that are generated.

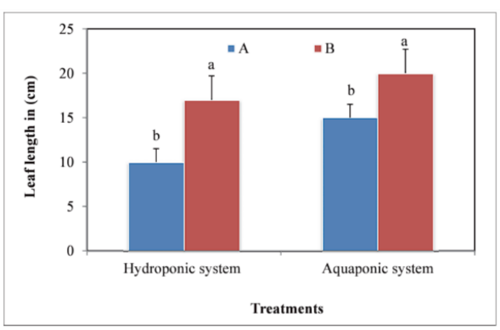

FIGURE 1. Effect of water temperature A = 11°C or B = 21°C in the hydroponics (control) system and the aquaponics system on leaf length (in cm) of sweet basil. Treatment means were separated using Tukey's HSD, with $P<0.05$ considered significant. Each bar represents mean ± standard error. $n=13$.

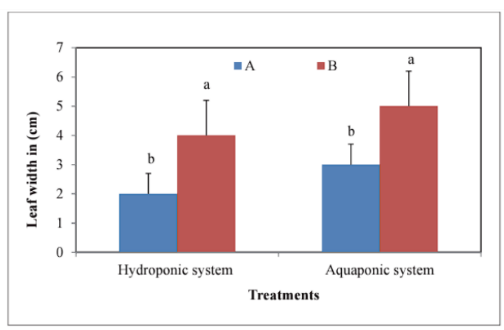

FIGURE 2. Effect of water temperature A = 11°C or B = 21°C in the hydroponics (control) system and the aquaponics system on leaf width (in cm) of sweet basil. Treatment means were separated using Tukey's HSD, with $P<0.05$ considered significant. Each bar represents mean ± standard error. $n=13$.

Khalil, S. (2018). Growth performance, nutrients and microbial dynamic in aquaponics systems as affected by water temperature. Eur. J. Hortic. Sci, 83, 388-394.

2.2. Oxygen

Definition

Dissolved oxygen in water refers to the amount of oxygen that is present in water, typically at ambient temperatures. It is a crucial factor for the survival of aquatic organisms, as most aquatic organisms, such as fish, bacteria, and some invertebrates, require oxygen to respire and carry out their metabolic processes.

The level of dissolved oxygen in water is usually measured in milligrams per liter (mg/L), as a percentage of the saturation level or parts per million (ppm). The saturation level is the maximum amount of oxygen that water can hold at a specific temperature and pressure. It varies with temperature and salinity, as colder water can hold more dissolved oxygen than warmer water.

One of the most crucial factors for fish growth is dissolved oxygen (DO), which is also essential to the good nitrifying bacteria that transform fish waste into nutrients plants can absorb. To maintain health and growth, warm-water fish need above 5 parts per million (ppm) DO, which can be used interchangeably with milligrams per liter (mg/L). Cold-water fish, on the other hand, need above 6.5 ppm of DO. Although tilapia, some carp species may tolerate decreased DO levels, growth rates will be impacted (Figure 1). A fish's consumption of oxygen is determined by its size, kind, activity level (feeding and reproduction), and water temperature. Larger fish, for instance, typically take in more oxygen than smaller fish. Smaller fish, however, use more oxygen per weight unit.

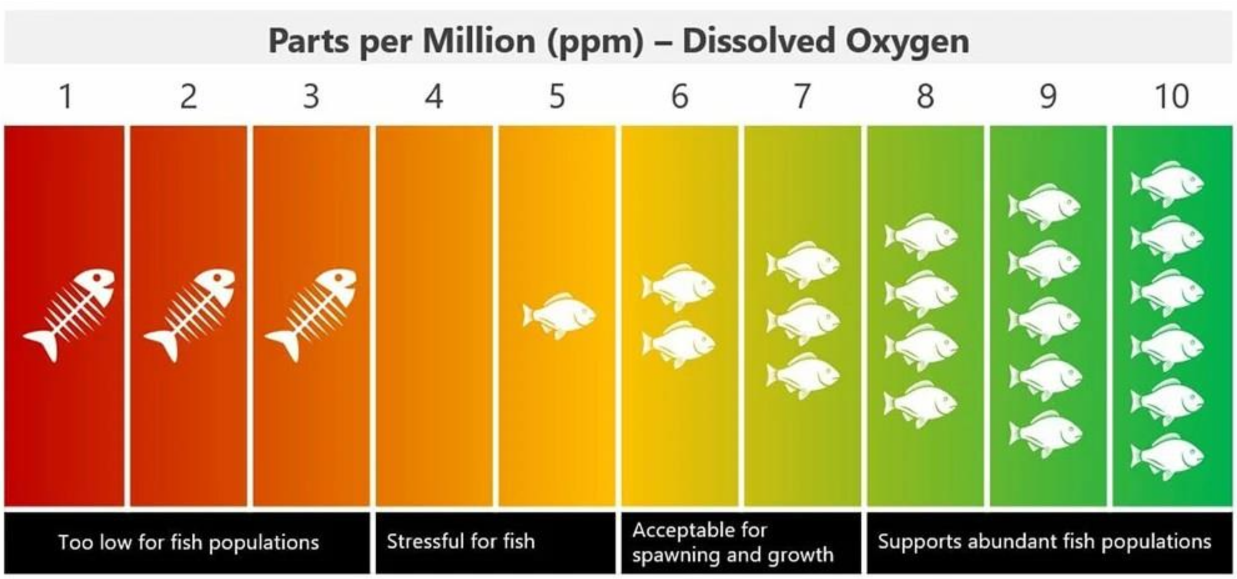

Figure 1. Dissolved oxygen (DO) levels needed to sustain fish healthy fish population in aquaponics systems. Values represented in ppm (mg DO/L water)[2].

[2] https://atlas-scientific.com/blog/dissolved-oxygen-in-water-ppm-for-fish/

In aquaponics systems, it is advised that DO levels be kept at 5-6 ppm or above. In a new system, oxygen levels should be monitored often, but after protocols are established (e.g., appropriate fish stocking and feeding rates are established, adequate aeration is provided) the DO measurements are not necessary as often. Low fish stocking rates in amateur aquaponics growers typically do not have an issue with low DO levels. High stocking rate commercial enterprises are more likely to have this issue. Increase aeration in your system by adding more air stones or using a larger pump if the DO levels are too low. There's no chance of adding too much oxygen because it will all just evaporate into the atmosphere once the water gets saturated. Oxygen solubility in water decreases with increasing temperature, which indicates the necessity for constant water temperature within the system.

One exception in respect to DO levels and its influence to water chemistry can occur in DWC (deep water culture) beds covered with floating materials therefore limiting CO_2 solubility in water, which in combination with abundance of O_2 may result in slight increase of water pH.

The processes of diffusion, aeration, photosynthesis, respiration, and decomposition all impact the quantities of dissolved oxygen. Thus, variations in salinity, temperature, and pressure typically result in variations in the water's dissolved oxygen content.

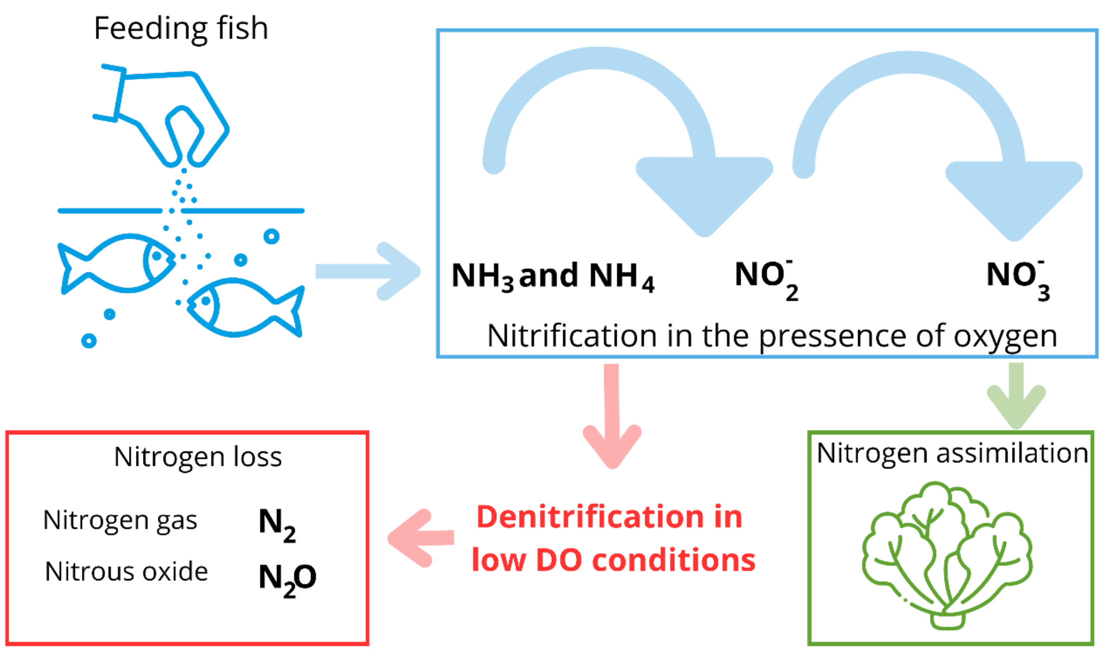

Figure 2. Microbial activity in oxygen rich and anoxic conditions.

DO is also an important factor affecting the nitrification process in an aquaponics system. Biofilter where nitrification is most active intense aeration happens, which introduces oxygen into the water and then the nitrifying bacteria consume the dissolved oxygen to oxidize ammonia. Without constant supply of oxygen the nitrification reaction essentially halts. Optimal DO levels for nitrification are 4-8 mg/L (4-8 ppm). With lower oxygen levels (lower than 2ppm) the nitrification will significantly decrease. The low DO concentration can give favourable conditions for another type of bacteria – denitrification bacteria (Figure 2). This bacterium can convert the valuable plant nutrient nitrogen back into potentially harmful ammonia and further into nitrogen gas or nitrous oxide, which are gases. Denitrification essentially causes losses of nitrogen within the system, thus it can potentially halt the growth of plants (Figure 2).

Plant roots that are in direct contact with the water also require minimal levels of DO. Plants are generally more resilient for low oxygen conditions than fish or the bacteria involved in the functioning of aquaponic system, therefore it is more important to meet the requirements of the microbial community and most importantly fish. In aquaponics systems, the dissolved oxygen requirements for plants are often similar to what they need in traditional hydroponic systems. Both fish and plants in aquaponics rely on dissolved oxygen in the water to thrive. The ideal dissolved oxygen level for plants in aquaponics typically ranges from 5 to 8 milligrams per liter (mg/L), however also lower levels can be tolerated.

Another gas that is dissolved in the aquaponics system is carbon dioxide (CO_2). Fish respiration results in the release of carbon dioxide (CO_2) into the water. Elevated levels of dissolved CO_2 in the water impede the process of CO_2 diffusion from the bloodstream of fish. Elevated levels of carbon dioxide in the bloodstream of fish lead to a decrease in the pH of the blood, which subsequently lowers the ability of haemoglobin to bind with oxygen. In water carbon dioxide reduces pH by undergoing continuous dissociation into carbonic acid (H_2CO_3) upon contact with water. Increasing the density of fish stocked in a unit leads to a greater release of carbon dioxide, thus resulting in a decrease in the overall pH level. This phenomenon is amplified when the fish exhibit higher levels of activity, such as during elevated temperatures. Similarly to oxygen, also CO_2 solubility decreases as the temperature of the water raises. Any gas transfer or aeration device that is exposed to the atmosphere will inevitably result in the removal of CO_2. In high-throughput systems and large scale aquaponics systems a degassing unit could be added as an optional module – this helps in releasing the dissolved CO_2, however, normally sufficient degassing is achieved by the biofilter or trickling of water in between the different parts of the system. This again shows that proper aeration of fish tank, the biofilter and generally throughout the system is necessary not only to ensure adequate DO levels, but also to ensure the release of CO_2.

2.3. pH

Definition

pH is a measure of the acidity or basicity of an aqueous solution. The term "pH" was first introduced by Danish biochemist Søren Peter Lauritz Sørensen in 1909. The pH scale is a logarithmic scale that ranges from 0 to 14, with 7 being considered neutral. A solution with a pH below 7 is considered acidic, while a solution with a pH above 7 is considered basic or alkaline. The pH value of a solution depends on the concentration of hydrogen ions (H+) present in the solution. A low pH means that there is a high concentration of H+ ions, while a high pH means that there is a low concentration of H+ ions. The pH of a solution can be measured using a pH meter or pH paper. pH plays an important role in many biological and chemical processes, and maintaining the correct pH balance in aquaponics systems is critical for propper plant and fish growth.

The pH of the water in hydroponics is essential for the plants' ability to receive ionic nutrients (Figure 3). Based on the pH of the system water, research suggests that certain nutrients are available within a specific pH window. Consequently, the pH must be adjusted to a value that maximizes the availability of the ionic nutrient mixture (Figure 4). This is a trade-off, though, since various ionic nutrient forms are more accessible at varying pHs. In order to maximize nutrient availability, the hydroponic industry usually regulates the pH between 4.5 and 6.0 (an acid environment), notably in sterilised hydroponic and substrate culture systems.

On the other hand, in recirculating aquaculture systems the pH is set to a level that is more favourable for the fish growth and welfare. For fish growth the approximate set-point of pH is 7.5 which is coincidentally also the optimal pH level for microbe growth, specifically, the nitrifying bacteria, which convert fish waste to a form of nitrogen that is less toxic and more easily available to plants.

Because the components used in aquaponics have varying pH needs, there are pH-related difficulties. While recirculating aquaculture systems (RAS) for freshwater fish species normally require pH values between 7.0 and 8.0, hydroponically cultivated plants typically require pH settings between 4.5 and 6.0. The microorganisms that change potentially hazardous compounds from fish waste into less hazardous forms must also be accommodated in these environments. As a result, any pH set point is a compromise between the requirements of microbes, fish, and plants. This supports the claim that it is impossible to achieve an ideal pH for all living things within an aquaponic system, which could lead to less-than-ideal plant growth. The nutrient availability should therefore be considered, when adjusting pH of the system in a

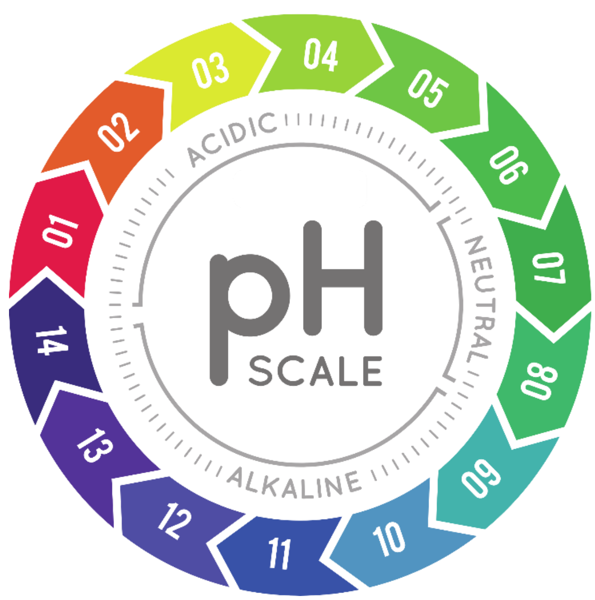

Figure 3. pH scale indicating the values of acidity-alkalinity within the range 1-14 pH.

manner where neither plant or fish growth will be influenced so that their optimal growth would be encumbered.

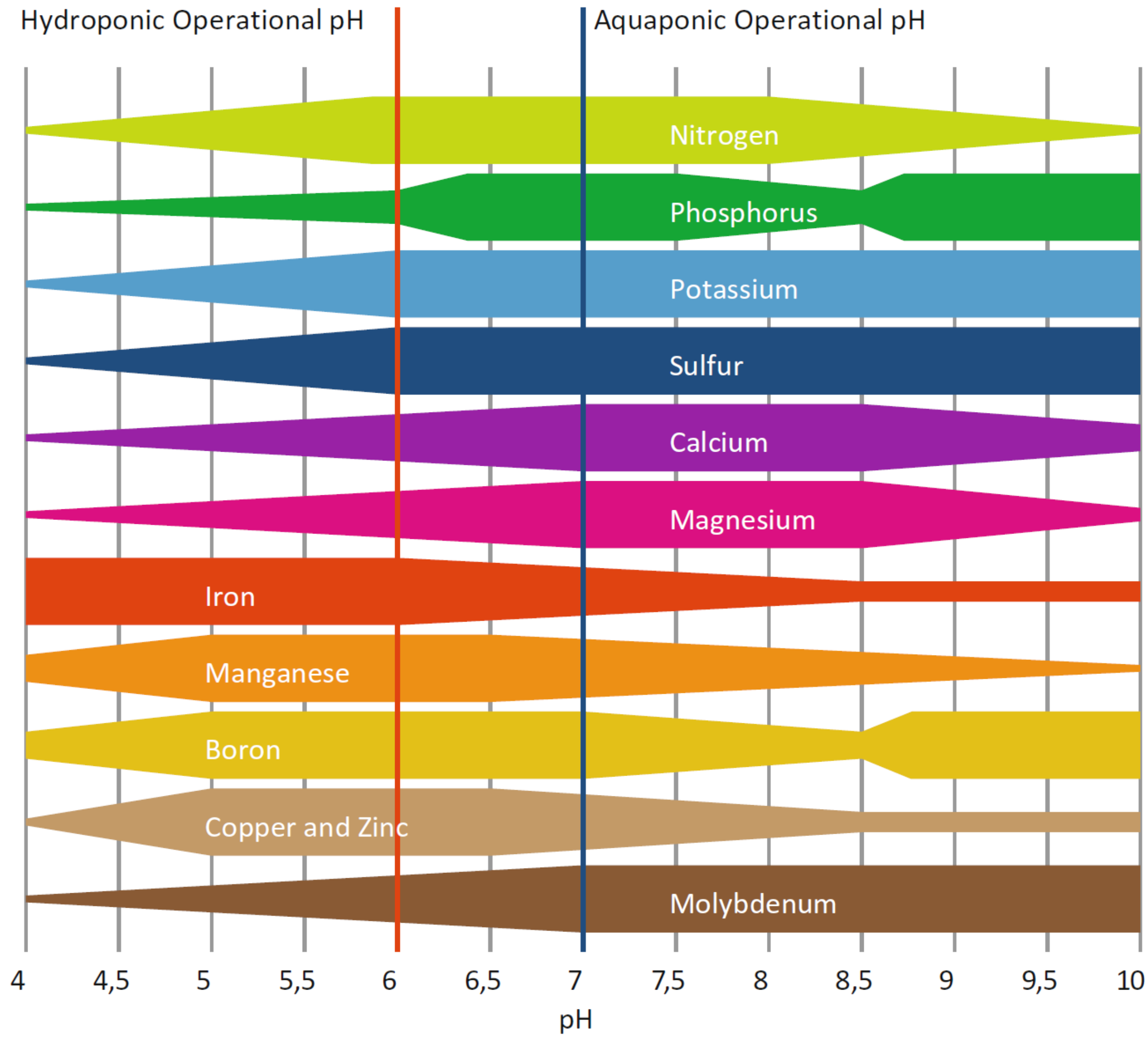

Figure 4. Nutrient availability based on the pH of the water environment[3].

Hydroponic and aquaculture pH optimal indifference is possibly one of the main challenges in aquaponics systems. The incompatibilities of pH within both systems suggests that perhaps the decoupled aquaponics systems could solve this issue. In such a system the water is not reused/recirculated back to the fish tank, but instead it is used as nutrient rich water for plants. While such solution would allow to avoid the sub-optimal pH levels, it does not consider the need for specific microbiome within the system. The water recirculation is much needed to establish a functioning biofilter microbiome, that efficiently transforms fish-waste to plant-available nutrients. Moreover, in such systems the plants can form crucial symbiosis with the bacteria, that in turn can help in assimilating the nutrients from the recirculated water. Nutrients for plants in aquaponics system are primarily produced by fish, instead of supplying them as fertiliser (as

[3] Goddek, S., Joyce, A., Kotzen, B., & Burnell, G. M. (2019). Aquaponics food production systems: combined aquaculture and hydroponic production technologies for the future (p. 619). Springer Nature.

in hydroponics systems), therefore the different species of nitrifying bacteria (*Nitrosomonas* spp. and *Nitrobacter* spp.) are a crucial element in functioning aquaponics. The intricate symbiosis between plants and microbes is the key to a successful operation and this association can even provide better plant growth rates than standard hydroponics.

Case study!

Effect of pH on Cucumber Growth and Nutrient Availability in a Decoupled Aquaponic System with Minimal Solids Removal

The term "pH" refers to a measure of the acidity or alkalinity of a solution. It is a scale used to specify the acidity or basicity of an aqueous solution. Acidic solutions have a lower pH, while basic or alkaline solutions have a higher pH. At room temperature (25°C), pure water is neither acidic nor basic and has a pH of 7. The pH scale ranges from 0 to 14. In this study, pH is being studied for its effect on the yield and nutritional status of greenhouse cucumber grown in recirculating hydroponics and aquaponic irrigation water.

The article investigates the effect of pH on nutrient availability and uptake in a decoupled aquaponic system. The study was conducted using aquaculture effluent from tilapia culture tanks at four pH treatments: 5.0, 5.8, 6.5, and 7.0, used to irrigate a cucumber crop. The results showed that pH did not have a practical effect on growth rate, internode length or yield over the two growing seasons. However, availability and uptake of several nutrients were affected by pH. The solubility of calcium sulfate and magnesium oxide, which are applied to the system, increased with decreasing pH, leading to increased calcium and magnesium observed at lower pH. pH also influenced phosphorus assimilation into plant tissues, with increased phosphorus uptake at high pH. However, high pH (7.0) reduced phosphorus uptake in the apoplast. Nitrate assimilation into leaf tissue varied significantly with pH, showing highest assimilation at pH 5.8 and the lowest at pH 6.5. Calcium uptake showed the highest levels at pH 6.5. Nutrient concentrations in the aquaculture effluent were considered low compared to hydroponic solutions, but elemental analysis of leaf tissues was within the recommended ranges

Blanchard, C., Wells, D. E., Pickens, J. M., & Blersch, D. M. (2020). Effect of pH on cucumber growth and nutrient availability in a decoupled aquaponic system with minimal solids removal. Horticulturae, 6(1), 10.

2.4. Water hardness

Definition

Total water hardness is a measure of the total concentration of divalent cations, primarily calcium and magnesium, in water. It is typically expressed in units of calcium carbonate equivalent and is used to assess the water's capacity to form scale deposits and its impact on various industrial, domestic, and environmental processes.

This measurement quantifies the overall mineral content in water and is important for various applications, including water treatment, agriculture, and in assessing the suitability of water for specific uses. Total water hardness can be classified as "soft" (low hardness) or "hard" (high hardness) based on the concentration of calcium and magnesium ions present.

Water hardness can be expressed and described in two types – general hardness and carbonate hardness. General hardness does not have major impact on the aquaponics process, however, carbonate hardness, which has an impact on the alkalinity of the water, therefore it can alter the pH.

General hardness is the amount of calcium (Ca^{2+}) and magnesium (Mg^{2+}), as well as, although with lower impact iron (Fe^{+}) ions present in the water. Concentration of these ions is usually measured as mg/L or as ppm. The amount of these ions in water depends largely on the water source – higher levels of Ca and Mg are usually found in waters coming from limestone-based aquifers. Rainwater, on the other hand, has low water hardness. Both elements have major impacts on both, the fish and the plants within an aquaponics system. They serve as micronutrients for plants, and it can improve salt-loss within fish.

Carbonate hardness is the amount of carbonates (CO_2^{2-}) and bicarbonates (HCO_3^{-}) dissolved in water measured as mg/L of $CaCO_3$. Carbonates in liquids (water) have an alkaline pH. In water carbonates act as a buffer, not allowing for sharp pH changes. Hydrogen ions (H^{+}) when released by an acid produced within the aquaponics system will bind to carbonate or bicarbonate present in the water thus avoiding a rapid change in pH. Nitrifying bacteria produce nitric acid (HNO_3) which dissociates into hydrogen and nitrate ions – nitrates are assimilated by plants; however, the hydrogen ions are not and they can rapidly decrease the pH of the system. If the carbonate hardness in an aquaponics system is low, the H^{+} ions will accumulate and decrease the pH (become acidic) disrupting the functioning of the whole system, therefore it is important to have an equilibrium of the carbonate and bicarbonate concentration, since the buffering abilities of these ions.

Avoiding the depletion of carbonates and bicarbonates in an aquaponics system can be avoided by regular replenishing of fresh water from the preferred water source or by adding bicarbonates. Regulation of source water hardness can be achieved by using filtration systems set up to prepare incoming water as per the needs of each individual system. The optimal value of total hardness (sum of general and carbonate hardness) in aquaponics is 60-140 mg/L (Table 2). It is possible to add chemicals for water softening, however, increasing of water salinity or other compounds thar could potentially be harmful to fish and plants should be avoided.

Table 2. Water hardness levels based on the concentration of calcium carbonate.

Water hardness level	Concentration (mg/L)
Soft	0-60
Moderately hard	60-120
Hard	120-180
Very hard	>180

2.5. The main nutrient – nitrogen

Definition

Nitrogen is one of the most important nutrients in any living organism - it is an essential component of deoxyribonucleic acid (DNA), ribonucleic acid (RNA), it is part of amino acids which are the building blocks of protein. Nitrogen in different forms is present in the aquaponics system firstly as ammonia (NH_3) or ammonium (NH_4+); over time, bacteria will begin to establish themselves and convert the ammonia/ammonium to nitrite (NO_2-) and then to nitrate (NO_3–). Establishing a functioning nitrogen cycle is the most important process in aquaponics.

In the context of aquaponics, the components of the food chain, namely primary producers and consumers, are typically segregated spatially within the aquaculture and hydroponic compartments, respectively. Microorganisms mediate the synergistic effects that enable efficient use of nutrients.

The introduction of nitrogen into the aquaponic system occurs through the fish feed, primarily in the form of protein. This protein is consumed by the fish and then expelled as ammonia (NH_3) and ammonium (NH_4^+). An increase in the protein content of the feed leads to a corresponding increase in the availability of nitrogenous substances within the system. Approximately 30% of the protein is utilized by the fish for metabolic processes and growth, while the remaining portion is excreted by the fish as waste. Fish eliminate nitrogenous chemicals through their gills, as well as through urine and faeces, primarily in the form of ammonia, which consists of both un-ionized ammonia and ammonium ions.

Ammonia has the capacity to exist in two distinct states: un-ionized, denoted as NH_3, and ionized, referred to as NH_4^+, which is often known as the ammonium ion. The toxicity of un-ionized ammonia to fish is well-documented, whereas ionized ammonia is generally considered non-toxic to fish, especially when present in exceedingly high concentrations. The equilibrium ratio between NH_3 and NH_4+ in aqueous solutions is contingent upon the pH and temperature conditions (Figure 5). When the pH level is equal to or lower than 7.0, the majority of ammonia, specifically over 95%, will exist in the non-toxic state as ammonium ions (NH_4^+). The ratio of non-toxic to toxic ammonia is expected to exhibit a significant increase as the pH level rises. The ratio of NH_3 to NH_4^+ is influenced by water temperature, whereby warmer water conditions result in a higher concentration of NH_3, a more hazardous form, compared to cooler water conditions, at a given pH level. The solubility of ammonia in water is lower compared to that of NH_4^+ ions. As a result, NH_3 undergoes quick conversion into a gaseous state and is subsequently released from the water, resulting in the emission of a distinctive odour.

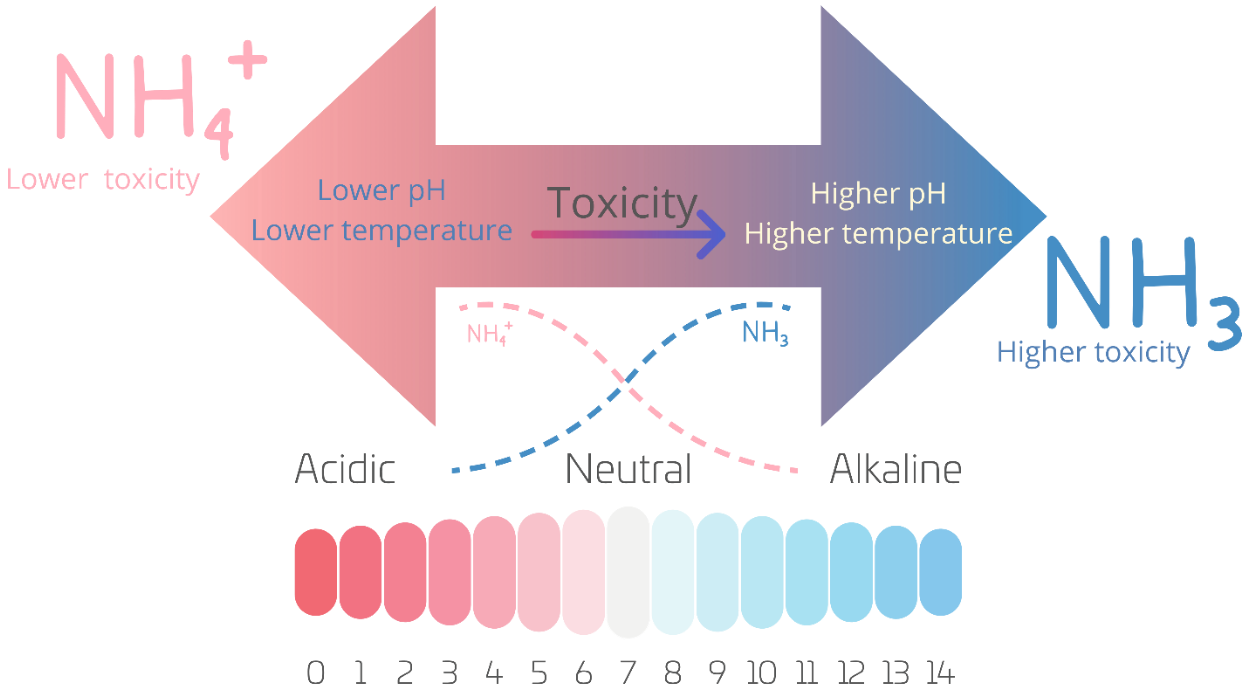

Figure 5. Ammonia and ammonium concentration relation to temperature and pH.

Although ammonium is generally considered to have low toxicity towards organisms in the system, ammonia is very harmful and hence it is necessary to eliminate it from the system or convert it into nitrate. The intermediate byproduct of the nitrification process, known as nitrite, possesses a considerable level of toxicity towards fish. It has been calculated that nitrite is approximately 100 times more harmful to fish compared to nitrate. Ammonia exerts an impact on the central nervous system of fish, whereas nitrite elicits issues pertaining to oxygen fixation. Certain species of fish have been found to exhibit a tolerance for nitrate concentrations of up to 300 mg/L and beyond. In contrast, the tolerance values for ammonia and nitrites are far lower, at 0.07 mg/L and 1 mg/L, respectively. Moreover, it is worth noting that nitrites and ammonia are not considered the most favourable nitrogen sources for plants. In fact, plants tend to exhibit a preference for ammonium and nitrates as their primary sources of nitrogen, since these compounds are more conducive to their growth and development. Elevated concentrations of nitrates in excess of 250 mg/L have been found to exert detrimental effects on plant growth, resulting in the promotion of excessive vegetative development and the potentially hazardous accumulation of nitrates inside plant leaves. This buildup poses a significant risk to human health. It is advisable to maintain nitrate levels within the range of 5-150 mg/L and to do water replacement when levels exceed this threshold. The presence of ammonia and nitrites suggests that the conversion process known as nitrification is not fully occurring within the biofilter. It is crucial to promptly address this issue by enhancing the activity of nitrifying bacteria, which can be achieved through aeration.

Definition

Nitrification is a biological process in the nitrogen cycle that is essential for converting the reduced form of nitrogen (ammonia and ammonium) into the oxidized form (nitrate), which is more stable and less toxic. Nitrate can then be taken up by plants, providing them with a source of nitrogen for growth. This process also helps in removing excess ammonia water, which is important for maintaining environmental and water quality. The nitrification process is carried out by certain types of bacteria, primarily *Nitrosomonas* and *Nitrobacter*, although other microorganisms can also be involved.

If the accumulation of ammonia excreted by fish is not prevented, it would result in the mortality of the fish. In the context of aquaponics systems, it is worth noting that the ammonia produced by fish is effectively eliminated through the activity of nitrifying bacteria. These bacteria facilitate a two-step process called nitrification, wherein ammonia is converted into nitrate nitrogen. Initially, the conversion of ammonia and ammonium to nitrite (NO_2) is facilitated by various species of bacteria, namely *Nitrosomonas, Nitrosococcus, Nitrosospira, Nitrosolobus*, and *Nitrosovibrio* spp. The aforementioned procedure necessitates the presence of oxygen, leads to the reduction of alkalinity, generates acid in the form of hydrogen ions (H^+), and results in a decrease in pH levels. During the second stage, the conversion of nitrite (NO_2) to nitrate (NO_3) is facilitated by various species of bacteria, namely *Nitrobacter*, *Nitrococcus, Nitrospira,* and *Nitrospina*. It is worth noting that nitrite is known to be particularly hazardous to fish. The current understanding suggests that *Nitrospira* is a comprehensive nitrifier, meaning it is implicated in the generation of both nitrite and nitrate. The second stage of this process also necessitates the presence of oxygen and results in a decrease in pH. Consequently, it is crucial to monitor the water hardness in order to consider the effects of nitrification and the buffering capacity of carbonates. The nitrate generated in this reaction is non-toxic and functions as a source of plant nutrients inside the hydroponic aspect of the aquaponics system (Figure 6).

Nitrification has best performance under conditions characterized by high levels of dissolved oxygen and low concentrations of organic matter, which primarily consists of uneaten fish meal and accumulated solid wastes. In the event of insufficient oxygen levels, the process of nitrification may experience a deceleration or complete cessation, resulting in the buildup of ammonia to levels that pose toxicity risks for aquatic organisms, particularly fish. The conversion of ammonia to nitrite is typically the phase in the nitrification process that imposes the greatest constraint on the overall rate. This phenomenon can be attributed to the distinct growth rates exhibited by ammonia-oxidizing bacteria such as *Nitrosomonas*, *Nitrosospira*, *Nitrosovibrio* sp., and nitrite-oxidizing bacteria including *Nitrobacter*, *Nitrospira*, *Nitrococcus*, among others. The disparate growth rates result in partial nitrification, particularly during the initial phase of system operation, leading to the accumulation of nitrite ions (NO_2^-) until the nitrifying microorganisms are fully established, a process that may require a duration of up to four weeks. The bacteria mostly inhabit biofilms that are attached to the media within the biofilter. However, they can also be observed in other compartments of the system, such as the floating-bed chambers or growth-media beds.

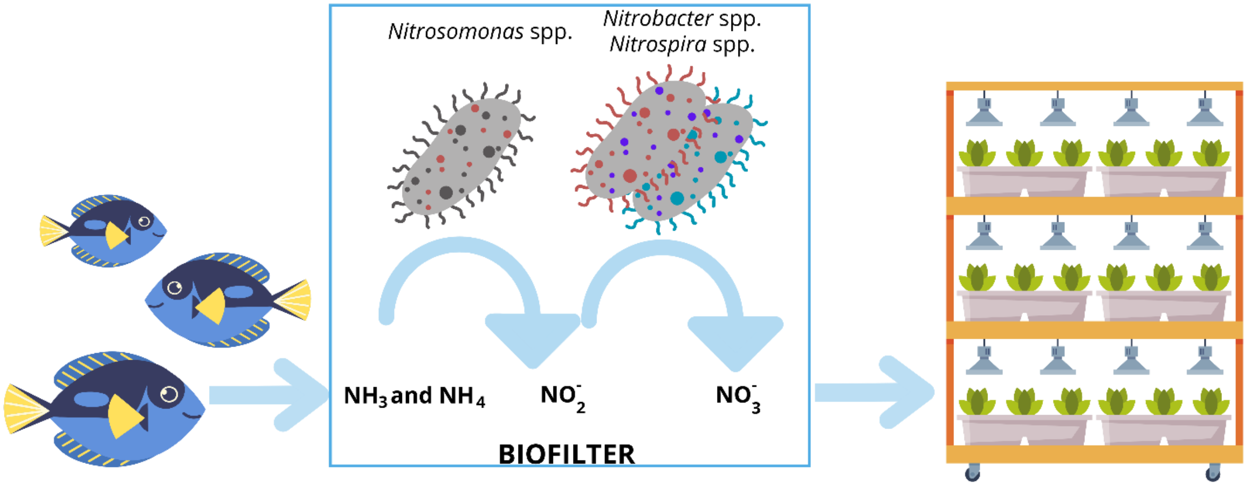

Figure 6. Bacterial species within the biofilter that are involved in the nitrification process.

The process of eliminating ammonia and nitrite in aquaponics systems is commonly known as biofiltration (Figure 6). Biofiltration serves as the crucial connection between the piscine element and the hydroponic element within an aquaponics framework. The activity of nitrifying bacteria experiences a significant reduction when exposed to elevated concentrations of ammonia. Ammonia possesses antimicrobial properties and has the potential to hinder the activity of nitrifying bacteria when present at concentrations exceeding 4 mg/L, hence diminishing their efficacy. The situation can potentially deteriorate exponentially when an insufficiently sized biofilter becomes overwhelmed by ammonia, leading to the demise of bacteria and further escalation of ammonia levels. The absence of a robust and operational biofilter in the fish production component would result in the accumulation of waste products, insufficient generation of plant nutrients, and impaired system performance.

A biofilter serves as a habitat for the colonization of nitrifying microorganisms (Figure 7). In certain instances, the utilization of a distinct biofilter may be unnecessary in raft and medium-filled bed aquaponics systems due to the potential adequacy of available surfaces like as rafts, media, tank walls, and other components for bacterial colonization. Nevertheless, it is worth noting that a majority of these systems continue to employ a form of biofilter in order to facilitate the decomposition of organic substances and enhance the presence of micronutrients and dissolved oxygen within the water. In the context of nutrient film technique systems, the inclusion of a distinct biofilter is indeed important. An excessively big biofilter does not pose any harm to an aquaponic system. While it is true that having a large biofilter may result in extra expenses, having excess biofiltration capacity has proven to be beneficial in preventing system failures in numerous instances.

Figure 7. Biofilter for an aquaponics system at Campus Roslagen, Norrtälje.

Assuming that the key water quality factors, including pH, dissolved oxygen, temperature, and surface area, are adhered to, it may be reasonably inferred that the bacteria are both present and operating effectively. The significance of bacteria in aquaponics necessitates the assessment of their general health at any given moment. Bacteria are microscopic organisms that cannot be observed with the naked eye, necessitating the use of a microscope for visual detection. A straightforward approach exists for monitoring bacterial function, which involves assessing levels of ammonia, nitrite, and nitrate. This method yields valuable insights into the overall health of the bacterial colony. In a well-functioning and balanced aquaponic system, it is imperative to maintain ammonia and nitrite levels within the range of 0-1 mg/L. The presence of either indicates a potential issue with the nitrifying bacteria. There exist two prevalent explanations for the occurrence of this phenomenon. Initially, it can be observed that the biofilter's capacity is insufficient to accommodate the current quantity of fish and fish feed. Hence, an inequilibrium exists, resulting in an over population of fish. In order to address the issue at hand, one potential solution is to either augment the dimensions of the biofilter or decrease the fish population, or alternatively, modify the feeding regimen for the fish. Occasionally, this issue may arise when the initial equilibrium of the system is disrupted due to the growth of the fish and their increased feeding, which exceeds the capacity of the biofilter that remains unchanged in size. Furthermore, in the event that the system is proportioned, it is plausible that the bacteria themselves may be experiencing impaired functionality. This observation may suggest a potential issue pertaining to the quality of the water.

The phenomenon of bacterial colony formation during the initial setup of an aquaponics system is commonly referred to as bio-filter establishment or cycling. Cycling is a fundamental initial procedure in the establishment of an aquaponics system. The completion of the cycle is contingent upon the establishment of a robust community of nitrifying bacteria. Without this crucial step, the growth of plants becomes unattainable, and the environment may become detrimental to the well-being of the fish. It is advisable to initiate a cycling process of the system without the presence of fish until a stable microbiome is established within the biofilter. Commercial combinations of microbial community starters are readily accessible for the purpose of enhancing the creation of nitrifying bacteria communities. This, in turn, leads to a reduction in the required duration for these bacteria to reach an adequate population size inside the system and the biofilter.

Denitrification refers to the process by which nitrate (NO_3^-) is transformed into nitrite (NO_2^-), nitric oxide (NO), nitrous oxide (N_2O), and ultimately into nitrogen gas (N_2) in environments characterized by an absence or extremely low quantities of dissolved oxygen (Figure 2), therefore being anoxic and anaerobic in nature. Denitrification is a biological process executed by denitrifiers, which encompass distinct taxonomic groups of archaea and facultative heterotrophic bacteria. Due to its higher potency as a greenhouse gas compared to CO_2, it is imperative to minimize the formation of N_2O in order to optimize the rates at which N is assimilated into plant biomass.

3. Microorganisms in aquaponics

Aquaponics is a symbiotic system consisting primarily of fish, nitrifying microorganisms, and plants. Nevertheless, as time progresses, numerous additional organisms may play a role in shaping and influencing this particular environment. Certain creatures, such as earthworms, can play a beneficial role by aiding in the breakdown process of fish waste. There exist certain organisms, specifically different crustaceans, residing within the biofilters, which can be classified as benign entities that do not actively contribute to or detract from the overall functioning of the system. Various organisms pose dangers in aquaponics, including parasites, pests, and other types of bacteria. It is challenging to entirely eliminate these organisms due to the inherent non-sterile nature of aquaponic systems. To mitigate the potential escalation of these minor risks into hazardous infestations, it is imperative to adopt an optimal management approach that involves cultivating robust and resilient fish and plants. This can be achieved by diligently maintaining highly oxygenated conditions and providing ample access to all necessary nutrients. In this manner, organisms are able to defend against infection or sickness by utilizing their own robust immune systems.

3.1. Algae

Definition

Algae are a varied collection of photosynthetic organisms that live predominantly in aquatic conditions but may also thrive in terrestrial and even severe environments. They range in size from microscopic single-celled organisms to vast multicellular organisms. Because algae lack many of the specialized structures and tissues found in plants, such as roots, stems, and leaves, they are not categorized as plants.

Algae include taxonomic categories consisting of green algae, red algae, brown algae, and diatoms, among others. They are distinguished by their ability to gather light energy via chlorophyll and other pigments, converting carbon dioxide and water into organic compounds, typically sugars, via photosynthesis.

An aquaponic system's performance may be negatively impacted by algal development. Because they are photosynthetic organisms, algae can develop quickly and easily in water when given light. Algal growth is generally affected by the pH, DO and nitrogen contents of the water within the system. It is nearly a given that they will arise in an aquaponic system because they naturally occur in all water sources. In aquaponics systems, algae are frequently seen, although they are typically managed by adjusting the temperature, photoperiod, and light intensity throughout the day. Algal growth can be an indication of unutilised nitrogen present in the system, meaning that fish produce more nitrogenous compounds than the plants downstream can uptake.

Algal morphology encompasses a variety of forms, including single-celled creatures called phytoplankton and multicellular varieties called macroalgae. Fast-growing phytoplankton can quickly multiply and tint water green, but macroalgae create long filamentous strands that can adhere to tank bottoms. Algal development can alter the water's chemical composition and cause problems for the pumps and filters' operating mechanisms. Algae compete for nutrients with other organisms within the system, they can utilise nitrates and ammonium as their nitrogen sources, depending on species. They create oxygen in the daytime and use it for energy at night. In extreme circumstances, anoxic water resulting from algae consuming oxygen during the night might kill fish, since high levels of DO are being consumed. Filamentous algae can also get very big and are frequently difficult to decompose. This indicates that an accumulation of algae may harm the pumps and filters, posing a risk to the system's functionality and potentially requiring costly repairs.

The majority of the time, visual inspection of aquaponics system parts such fish tank walls, the areas surrounding pumps and filters, and plant roots is all that is needed to monitor the growth of algae (Figure 8). To avoid unnecessary growth of algae it is important to cover the parts of an aquaponics systems with light-blocking material or lids, this will also prevent evaporation of water throughout the system. Since the light sources (the lamps) used for plant growth are often close to the water, it is important to design the system in a way that light won't be directly shining on water. Leaving exposed water without coverage in, for example, nutrient-film beds or the collection tank can rapidly increase the growth of algae and therefore fast uptake of nutrients, leaving the cultured plants with less feed. Since the fish tank will most likely be exposed to light, it is inevitable that algae growth will develop within the system, it is therefore required to clean the system once the algal growth becomes more visible.

Figure 8. Algal growth on aquaponics microgreens growth channel that is exposed to light (right), algal growth in deep water culture parts not covered with Styrofoam (left).

Case study!

Co-cultivation of microalgae in aquaponic systems

In this study, the function of *Chlorella* sp. microalgae in the floating-raft aquaponic system for ammonia management is assessed. During the aquaponic systems' operation, the yields of algal biomass, vegetables, and the elimination of the systems' essential nutrients were tracked. The systems produced 4.15 ± 0.19 g/sq.m·day (dry basis) of algae when they were operating at full capacity, which is modest because the growth conditions are mainly designed for the production of fish and vegetables. Nevertheless, it was discovered that algae could regulate ammonia since they prefer ammonia nitrogen over nitrate nitrogen, and they could also counteract the pH drop brought on by nitrifying bacteria.

The aquaponic system's algal component offers numerous benefits that have been demonstrated. Algae can contribute oxygen, balance pH levels, and regulate ammonia levels in the system during regular operations. Because algae contain more nitrogen than vegetables, they can remove nitrogen more efficiently than vegetables, while having lower production that is equivalent to that of vegetables and economically unfavorable to growers. Furthermore, algae compete with vegetables for growing space and the entire nitrogen pool rather than for nitrate nitrogen. Algae play a special function in the aquaponic system's water treatment process and, if conditions permit, can be added at the end of the system to remove even more ammonia. When it comes to removing nitrogen overall, algae are more effective than vegetables.

Addy, M. M., Kabir, F., Zhang, R., Lu, Q., Deng, X., Current, D. & Ruan, R. (2017). Co-cultivation of microalgae in aquaponic systems. Bioresource Technology, 245, 27-34.

3.2. Other bacteria

Heterotrophic bacteria

Aquaponics involves the participation of a significant bacterial community, with many microorganisms evolving a symbiotic relationship. The bacterial group commonly referred to as the heterotrophic group is known as *Pseudomonas* spp. Table 3 shows the bacterial species responsible for this process. The bacteria in question employ organic carbon as their primary source of food and are mostly engaged in the process of decomposing solid waste derived from fish and plants. The solid fish wastes are metabolized by heterotrophic bacteria through a process known as mineralization. This process facilitates the release of crucial micronutrients that can be utilized by plants in aquaponics systems. The heterotrophic bacteria, together with certain naturally existing fungi, aid in the decomposition of the solid component of the fish waste. By doing so, the nutrients that are trapped in the solid waste are released into the water. The process of mineralization is crucial since it enables plants to access nutrients that are not readily available in solid form. In order to facilitate absorption by plants' roots, it is imperative that the wastes undergo a process of molecular breakdown into simpler constituents. Heterotrophic bacteria possess the ability to derive nutrients from a wide range of organic substances, including but not limited to solid fish waste, unconsumed fish food, decaying plants, withering plant leaves, and even deceased bacterial organisms. Aquaponic units offer a variety of food sources for bacteria, since it is an open system in terms of the input materials that are not sterile. The utilization of biosolids as a medium for the growth of heterotrophic bacteria might lead to an escalation in their concentration, which may ultimately lead to heightened oxygen demand and diminished performance of the biofilter. In contrast to nitrifying bacteria, heterotrophs exhibit a far higher rate of multiplication, estimated to be 40 times faster. Heterotrophic bacteria necessitate comparable environmental conditions for growth as nitrifying bacteria, particularly in environments with elevated amounts of dissolved oxygen. The heterotrophic bacteria exhibit colonization across all constituents of the unit, with a notable concentration in regions where solid waste tends to accumulate. These organisms engage in a symbiotic relationship with other bacteria to facilitate the decomposition of solid waste. The presence of this community can effectively mitigate the accumulation of solid waste.

Sulphate reducing bacteria

Nitrifying and mineralizing bacteria (heterotrophic bacteria) play a beneficial role in aquaponic systems, however certain strains of bacteria can have detrimental effects. One example of a detrimental bacterial group is the sulphate-reducing bacteria. These bacteria are typically located in environments devoid of oxygen, known as anaerobic conditions, where they get energy through a redox reaction involving sulfur. Table 3 shows the bacterial species responsible for this process. The issue lies in the fact that this particular process yields hydrogen sulphide (H_2S), a highly hazardous substance for aquatic organisms such as fish. Sulphur reducing bacteria are widely distributed, inhabiting various aquatic environments such as lakes, saltmarshes, and estuaries across the globe. Moreover, they play a significant role in the natural sulfur cycle. These bacteria are accountable for the olfactory perception associated with hydrogen sulfide, like the smell of rotten eggs, as well as the pigmentation of sediments, characterized by a grey-black hue. One of the challenges encountered in aquaponics is the accumulation of solid wastes at a rate that surpasses the capacity of heterotrophic bacteria and their associated community to efficiently process and mineralize them. This imbalance can result in the development of anoxic conditions that promote the growth of sulphate-reducing bacteria. In systems with high fish density, the substantial production of solid waste by fish surpasses the capacity of mechanical filters to be effectively cleaned in a timely manner. Consequently, this situation promotes the proliferation of bacteria and the subsequent generation of their harmful metabolites. In many instances, expansive aquaponic systems have a degassing tank as a means to safely discharge hydrogen sulphide back into the atmosphere. The process of degassing is deemed unnecessary in systems of smaller scale. Nevertheless, even within limited-scale systems, the identification of a noxious aroma resembling that of decaying eggs or untreated wastewater necessitates the implementation of suitable measures for effective management. The growth of these bacteria is restricted to anoxic environments. Therefore, in order to mitigate their proliferation, it is imperative to ensure sufficient aeration and thorough flow of oxygenated water and enhance mechanical filtration to impede the buildup of sludge.

Denitryfying bacteria

The denitrification process is facilitated by a group of microorganisms that are considered undesirable. Table 3 shows the bacterial species responsible for this process. These bacteria, akin to sulphate reducers, inhabit anaerobic environments. They facilitate the conversion of nitrate, a highly sought-after plant nutrient, into air nitrogen, rendering it inaccessible to plants. The process of denitrification has the potential to result in a significant reduction of nitrogen, ranging from 25% to 60%. These bacteria are widely distributed in various environmental settings and hold significant ecological importance. Nevertheless, the presence of these bacteria in aquaponic systems can potentially reduce efficiency by depleting the nitrogen fertilizer. Insufficient oxygenation frequently poses a challenge in the context of expansive floating beds, particularly those characterized by elongated channels. The occurrence of a potential issue may be indicated when plants exhibit symptoms of nitrogen deficits, even in the presence of a balanced system, and when the quantity of nitrate in the water is exceptionally low. In the context of large-scale aquaponics systems, it is possible to include a distinct denitrification tank. Nevertheless, it is recommended to prioritize the thorough elimination of nitrates by plants, thereby converting these precious nutrients into biomass rather than allowing their release as gas.

Table 3. Bacterial species and their functions within an aquaponics system[4]*.*

Microbiological process	Genera
Nitrification	
-Ammonia oxidisation	*Nitrosomonas*, *Nitrosococcus*, *Nitrosospira*, *Nitrosolobus*, *Nitrosovibrio*
-Ammonia oxidisation by archaea	*Trosopumilus*, *Nitrososphaeras*
-Nitrite oxidation	*Nitrobacter*, *Nitrospira*, *Nitrococcus*, *Nitrospina*
-Complete ammonia oxidation	*Nitrospira*
Denitrification	*Dokdonella*, *Thermomonas*
Mineralisation	*Pseudomonas*, *Flavobacterium*, *Sphingobacterium*, *Arcobacter*
Anaerobic ammonium oxidation (Anammox)	*Brocadia*
Sulphate reduction	*Fusibacter*, *Bacteroides*, *Desulfovibrio*, *Dethiosulfovibrio*
Organic phosphorus mineralisation	*Modestobacter*
Iron cycling	*Acidibacter*
Nitrogen fixation	*Pontibacter*, *Pseudonocardia*

[4] Kasozi, N., Abraham, B., Kaiser, H., & Wilhelmi, B. (2021). The complex microbiome in aquaponics: significance of the bacterial ecosystem. Annals of Microbiology, 71(1), 1-13.

Harmful bacteria

Undesirable, harmful or pathogenic bacteria encompasses those that induce diseases in plants, fish, and people. Additional information regarding fish and plant pathogens can be found in the studies titled "Fish in Aquaponics - Selection, Requirements, and Limitations" and "Plants in Aquaponics - Selection, Requirements, and Limitations." In general, the establishment and implementation of effective agricultural techniques play a crucial role in the mitigation and reduction of bacterial infections within aquaponic systems. The prevention of pathogens within the system can be achieved through various measures. First and foremost, it is crucial to prioritize good worker hygiene practices. This includes maintaining proper personal cleanliness and adhering to appropriate sanitation protocols. Additionally, it is essential to implement strategies to prevent rodents from contaminating the system through fecal matter. In the case of large-scale, greenhouse-based aquaponic systems, it is important to ensure that wild mammals, as well as domestic animals such as dogs and cats, are kept away from the system to minimize the risk of pathogen introduction. Furthermore, it is imperative to avoid using water that is contaminated or has not been adequately prepared. Lastly, it is crucial to recognize that any live feed utilized in the system can potentially serve as a carrier for introducing foreign microorganisms, for example worms used as fish feed from an another source. Also, if saplings are delivered and used in an aquaponics systems, care should be taken that viral or bacterial contamination is not transferred from the plant nurseries, since different types of substrates are used for growing them, for example soil or compost, which often contains also pathogenic organisms. It is of particular significance to refrain from utilizing rainwater collected from roofs contaminated with avian excrement, unless the water undergoes appropriate treatment procedures. One significant concern associated with warm-blooded animals is the potential transmission of *Escherichia coli*, whereas birds are frequently carriers of *Salmonella* spp. These pathogenic bacteria can infiltrate the environment through animal fecal matter. Furthermore, it is imperative to ensure that the aquaponic water does not come into touch with the foliage of the plants, following the preventive measures. The implementation of this measure serves to mitigate numerous plant illnesses and minimize the risk of fish water contamination in relation to human produce, particularly when the produce is intended for raw consumption. It is imperative to thoroughly cleanse vegetables prior to consumption, regardless of whether they were grown by aquaponic or conventional methods. In the context of aquaponics, it is widely recognized that the prudent use of common sense and adherence to proper hygiene practices serve as effective measures in preventing the occurrence and spread of infections.

The implementation of biosecurity measures can effectively mitigate the risk of introducing pathogenic germs. One recommended practice involves the implementation of quarantine measures for newly acquired fish or plants prior to their introduction into the system. Additionally, it is essential to uphold rigorous standards of hygiene in equipment and handling protocols. The implementation of regular system maintenance practices, such as the cleaning of filters and the maintenance of appropriate flow rates, can effectively mitigate bacterial problems by promoting the establishment and maintenance of a robust and balanced ecosystem.

3.3. Fungi

Definition

Fungi in aquaponics are a varied collection of eukaryotic microorganisms from the fungi kingdom that play a role in the biological activities of the system. Fungi are commonly found in the growth media and biofilter components. They have a crucial function in breaking down organic matter that comes from uneaten fish feed, fish waste, and decaying plant material. Fungi, acting as decomposers, aid in the transformation of intricate organic molecules into more basic ones, so releasing nutrients like nitrogen and phosphorus. Effective control of fungal populations is crucial for sustaining a harmonious and flourishing aquaponics system, promoting optimal plant development and fish well-being. Pathogenic fungus in aquaponics can primarily endanger both the plant and fish components of the system.

Fungi are essential for the decomposition of intricate organic substances and the replenishment of nutrients through recycling. Cellulolytic fungi such as *Aspergillus*, *Penicillium*, and *Trichoderma* expedite the natural process of breakdown. Such fungi species like *Candida albicans*, *C. parapsilosis, Aspergillus flavus*, *A. niger*, *Rhizopus*, *Fusarium* spp., *Trichoderma* and *Penicillium* spp. have also been found in aquaponics system – these species have no effect on the well-being on fish. Water molds, although mainly saprophytic, possess the capability to colonize various substances and establish parasitic associations with living hosts, which significantly impact biological productivity.

Fungi thrive in dim, damp environments, where they release hydrolytic enzymes to extract nutrients from deceased organic matter, utilizing it as a source of carbon and energy to sustain their development and reproduction. Rich nutrient media yield a greater abundance of hydrophobic spores compared to poor nutrient media. Effective control of fungal populations is crucial for sustaining a harmonious and flourishing aquaponics system, promoting optimal plant development and fish well-being.

Fungi within aquaponics system are more associated with plant or fish diseases. Indoors aquaponics systems are prone to fungal diseases, for example powdery mildew, which spreads quickly throughout the whole plant population, for example cucumbers and salad. Since aquaponics systems that are held indoors create humid environment it is of utmost importance to maintain appropriate humidity and ventilation within the room to avoid rapid spread of fungal diseases. Fungicides could be used in cases of fungal outbreaks, however, most of the fungi that infect, for example plants, show visible symptoms when the plant has already been fully infected and the plants must be discarded. In order to avoid fungal disease special care must be taken to avoid bringing in infected soil, plants or other items that would introduce pathogenic fungi that could cause loss of produce.

Case study!

Potential use of entomopathogenic and mycoparasitic fungi against powdery mildew in aquaponics

It has been determined that entomopathogenic and mycoparasitic fungi are safe biological control agents for a variety of pests. This study determined how well the mycoparasitic fungus *Trichoderma virens*, entomopathogenic fungi *Lecanicillium attenuatum*, and *Isaria fumosorosea* inhibited the growth of *Podosphaera xanthii* (powdery mildew). Additionally, by introducing the three fungal biocontrol agents into aquaponic water and observing their development and survival, potential negative consequences on the system were observed. The results demonstrated that at 107 CFU/ml, the three biocontrol agents substantially reduced the powdery mildew. *L. attenuatum*-treated leaves showed a noteworthy 85% disease reduction under greenhouse conditions (65-73% relative humidity-RH). With a disease severity of 32% under 65-73% RH, *I. fumosorosea*-treated leaves exhibited the lowest levels of disease severity. Furthermore, it was observed that *L. attenuatum* spores were the most persistent on the leaves; under 65-73% RH, the spore population rose from 7.3 CFU to 9.54 × 10^3 CFU/mL. On the other hand, after 96 hours, the spores of the three tested entomopathogenic fungi in hydroponics water drastically decreased by more than 99%. After 96 hours, the initial *L. attenuatum* spore concentrations of 10^7 CFU/mL were lowered to 4 × 10^3 CFU.

FIGURE 4 Efficacy of microbiological agents, *L. attenuatum* on cucumber leaves artificially infected with powdery mildew. **(A)** leaves treated with 0.05% tween 80 solution (control) after 20 days of the treatment, and **(B)** leaves treated with *L. attenuatum* after 20 days. Both treatments were applied 48 hours before the inoculation of *P. xanthii*. Other pictorial presentation showing a comparisons of TVI and IFR-treated leaves can be found in the Figure 1 of the supplementary material.

Folorunso, E. A., Bohata, A., Kavkova, M., Gebauer, R., & Mraz, J. (2022). Potential use of entomopathogenic and mycoparasitic fungi against powdery mildew in aquaponics. Frontiers in Marine Science, 9, 992715.

4. Sources of water

Water is the key medium used in aquaponic systems because it is shared between the two major components of the system (fish and plant components), it is the major carrier of the nutrient resources within the system and it sets the overall chemical environment the fish and plants are cultured within. The water source used will have an impact on the water chemistry of the unit. Therefore, it is a vital ingredient that may have a substantial influence over the system. In an aquaponic system, the source of water and what that source water contains chemically, physically and biologically have a major influence over the system because it sets a baseline of the most important water quality parameters. New water sources should always be tested for pH, hardness, salinity (concentration of dissolved salts), chlorine (if tap water is used) and for any pollutants (heavy metals, microbial contamination) in order to ensure the water is safe to use.

Tap water

Municipal water sources are frequently treated with various chemicals to eliminate germs. Chlorine and chloramines are the predominant compounds employed in water treatment. The presence of these chemicals in the aquaponic ecosystem poses a threat to the well-being of fish, plants, and bacteria, since they have poisonous properties. These chemicals are specifically employed to eliminate bacteria in water, but their usage has negative consequences on the general health of the aquaponic environment. Chlorine test kits can be obtained, and if elevated amounts of chlorine are identified, the water must undergo treatment before to usage. An uncomplicated approach involves storing the water prior to usage, so facilitating the dissipation of all the chlorine into the atmosphere. This process can take more than 48 hours, although it can happen more quickly if the water is vigorously aerated. Chloramines exhibit greater stability and have a lower tendency to be released. However, off-gassing is typically sufficient in small-scale systems that utilize municipal water. An advisable rule of thumb is to refrain from replacing more than 10% of the water without conducting a test and eliminating the chlorine beforehand. Furthermore, the quality of the water will be contingent upon the composition based on where the initial water is obtained.

Most commonly in European Union the water sourced from tap is prepared so that it is safe to consume, meaning it will have sufficient quality also for an aquaponics system. Drinking water in Europe is sourced from lakes, rivers or groundwater sources and it goes through a series of steps to purify it so that it agrees with the drinking water directives. Drinking water is filtered through sand, gravel and membrane filters to remove particles, bacteria and other impurities, afterwards the water is disinfected using chlorination, UV irradiation or ozonation. The pH level of tap water, if necessary, is adjusted and the quality is monitored throughout the process until the consumer is reached. The strict standards set by the regulatory bodies suggest that tap water is one of the most suitable water sources for small-scale aquaponics systems.

Underground water sources

The quality of water taken from wells will largely depend on the material of the bedrock and sources of infiltration into the aquifer. If the bedrock is limestone, then the water will probably have quite high concentrations of hardness, which may have an impact on the pH of the water. High general hardness concentrations are found in water sources such as limestone-based aquifers and/or river beds, as limestone is essentially composed of calcium carbonate ($CaCO_3$). Water sourced from limestone bedrock wells/aquifers will normally have a high carbonate hardness of about 150–180mg/litre. Water hardness is not a major problem in aquaponics, because the alkalinity is naturally consumed by the nitric acid produced by the nitrifying bacteria. However, if the hardness levels are very high and the nitrification is minimal because of small fish biomass, then the water may remain slightly basic (pH 7–8) and resist the natural tendency of aquaponic systems to become acidic through the nitrification cycle and fish respiration. In this case, it may be necessary to use very small amounts of acid to reduce the alkalinity before adding the water to the system in order to prevent pH swings within the system.

Quality of the water obtained from drilled wells largely depends on the geomorphological composition of each specific region. Certain regions might have water with increased salinity or dissolved mineral contents. Certain regions may have elevated levels of iron or sulphates. In such cases a series of specified filters should be used to remove these ions from the input water. The cost of such systems can increase the overall operational costs therefore it should be carefully evaluated whether other sources of water would be more viable for aquaponics use. Filtration systems must be replaced once the maximum purification capacity has been exhausted, thus the costs could be increased even more on regular basis. Aquifer water should be tested in certified/accredited laboratories before use if any suspicion arises (water has iron, sulphur smell), to ensure the quality of input water.

Rainwater

Rainwater is a highly beneficial water supply for aquaponics. The rainwater typically maintains a neutral pH and contains minimal levels carbonates and dissolved minerals, as well as negligible salinity. This composition is ideal for system replenishment and prevents the accumulation of salinity over time. Nevertheless, in certain regions, for example, in eastern Europe, eastern United States of America, and parts of southeast Asia, the pH of precipitation will have a slightly more acidic pH, however, it should not affect the water quality. It is often advisable to collect and store rainwater while also raising the total water hardness by addition of minerals, in order to improve the buffering capacity. Furthermore, the implementation of rainwater harvesting will effectively decrease the operational expenses of the unit, while also promoting greater sustainability. Rainwater is usually collected in septic tanks that dug into ground to maintain cool temperature and ensure that no light gets to it, to prevent algae growth. Rainwater typically does not contain microorganisms, however the containers or tanks used to store rainwater may facilitate the growth of microorganisms. Care should be taken when using rainwater – the collection system should be prepared so that no contact with wild animals is possible as well as other sources of possible contamination, for example, leaves from nearby trees, factory presence that produce fine particles with their emissions. Another important aspect to consider when using rainwater is to consider its seasonal availability and taking into account temperature differences, avoiding adding large quantities of water to system with significantly different temperature (colder or warmer).

5. Water treatment for aquaponics

Disinfection of water

Both bacterial and viral organisms can provide significant challenges in aquaponics systems. While the system operates in a cyclical manner and is theoretically capable of sustaining itself, there are instances when the risk of pathogens can increase. The most prevalent techniques for water disinfection are ozone treatment and UV irradiation. UV radiation, when emitted at a specific intensity, has the ability to degrade the DNA of biological entities such as pathogens and single-celled organisms. In aquaponics, the UV light is typically contained within a compact section of pipe located between the mechanical filtering unit and the biofilter, or positioned before the sump tank. To achieve optimal performance, it is crucial to position the UV lamp downstream of the mechanical filtration system to prevent obstruction by suspended materials. Ozone (O_3) can effectively reduce infections and other undesirable organisms. When ozone comes into contact with water, it undergoes a process called splitting, resulting in the formation of oxygen molecules (O_2) and a reactive oxygen species known as a free oxygen radical ($O_2^{\bullet-}$). This radical chemically reacts with and oxidizes organic compounds. In addition, the ozone molecule's radical O also targets and eliminates bacteria, plankton, and filamentous algae by attacking their biological cell walls. Nevertheless, ozone exhibits significant reactivity and might potentially damage the nitrifying bacteria present in the biofilter, as well as adversely affect the fish gills when excessively administered. Consequently, the dosage must be continuously regulated. A combined solutions where ozone and UV treatments are combined exist – this helps in removal of residual ozone more effectively. Special ozonation devices will add extra expenses and additional monitoring of its functionality, dosages, as well as necessity for separate tank where de-ozonation would take place before releasing the water back into the system.

Chemical agents can be employed for targeted interventions to decrease the levels of microorganisms in the water. Hydrogen peroxide (H_2O_2) is frequently utilized, however, excessive dosages can result in significant harm to the well-being of fish and can cause harm to the microorganisms in the filter. Hydrogen peroxide is mostly utilized for disinfecting vacant tanks and other equipment during periods of system inactivity, when there are no fish or established biofilters present.

Since all of the above mentioned disinfection methods can have impact on overall health of an aquaponics system, including fish, plants and the microorganisms colonizing the biofilter, it is advisable to avoid using these solutions in smaller-scale units, since the cumulative effects of disinfection aids can damage the intricate symbiotic mutualism. When starting an aquaponics system it is advisable to firstly establish conditions that can be considered hygienic and in some way aseptic. The room should be disinfected and hygienic practices put in place (hand, shoe sanitation, protective clothing etc.) in order to avoid the need for disinfection methods that can cause damage to an already established system.

5.1. Regulation and troubleshooting of water quality

Water quality in an aquaponics system is an essential set of parameters that directly affect the health and wellbeing of all the involved organisms within the system – the plants, fish and microorganisms. Below the most common issues related to the water quality have been compiled including the possible solutions and ways to regulate the parameter in question (Table 4).

Table 4. Water quality parameters and troubleshooting.

Parameter	Problem	Solution
Dissolved oxygen	Low levels of dissolved oxygen	• Reduce the stocking rate of fish • Increase aeration (more air-stones, larger pumps) • If ambient temperature has risen then more aeration is needed due to the oxygen dissolution in water • Exchange the fish population (larger fish consume more oxygen)
pH	pH too low (acidic)	• Gradually add $NaHCO_3$ (dissolved in water) until optimal pH is reached • Add bicarbonates • Add fresh water (based on the water hardness)
	pH too high (basic)	• Add acid (H_3PO_4) to sump tank
Temperature (water)	Temperature too high	• Cover the water reservoirs, tanks with insulation materials if in direct sun • Install water cooling unit

	Temperature too low	• Insulate the water holding reservoirs and tanks • Install water heater with regulated temperature
Nitrogenous compounds	Nitrite or ammonia peak	• Stop or decrease the feeding rate of fish • Dilute the water within the system with fresh input water • Increase aeration in biofilter • Increase the surface area of biofilter
Water hardness	Water hardness too low/too high	• Too low – use additives to raise the hardness (limestone) • Too high – treating and filtering of the input water
Micronutrients	Plants start wilting	• Based on the damage of the plant leaves add mineral fertiliser as needed • Regular monitoring of water quality to avoid plant deficiencies
Algae growth	Green algal growth	• Shade the exposed water by covers, minimize water exposure to light

5.2. Testing and monitoring of water quality

The frequency of monitoring varies based on the specific metric being observed. It is advisable to conduct daily testing of start-up systems during the initial stocking of plants and animals in order to promptly make necessary adjustments. For instance, in order to address elevated ammonia levels, one can decrease feeding volumes, enhance aeration, or dilute the water. After achieving equilibrium in nutrient cycles (after a minimum duration of 4 weeks without notable variations in parameters), regular weekly monitoring is typically satisfactory for upholding favourable water quality. However, if there is a suspicion of a problem (such as changes in the fish's look or behaviour, or deficiency indications in plants), it is advisable to continue more frequent monitoring of the water quality. Hence, it is imperative to conduct daily surveillance of the well-being of the fish and plants to promptly identify any potential issues. Maintaining a comprehensive record of monitoring metrics is crucial. This includes observing the fish's appearance and behaviour (normal or abnormal), assessing the plants' condition (healthy or ill), and measuring water chemistry parameters such as pH, dissolved oxygen, ammonia, nitrites, and nitrates. By following this approach, the underlying cause of a prospective issue can be readily discovered, and if the problem reoccurs, the previously effective solution can be promptly implemented. Table 5 summarizes the most important water quality parameters and most frequently used testing/monitoring approaches.

Table 5. Water quality testing and monitoring activities.

Parameter	Monitoring activities
Dissolved oxygen	• Monitor fish, functioning of air pumps • DO reading can be obtained by using measuring kits (cheaper, not as reliable, single measurements)

	• DO readings from sensors on site or set-up for online monitoring (more expensive, more reliable, continuous measurements) • Once the system, the feeding rates and fish have been established measurements can be taken more rarely
pH	• pH test strips (cheap, not as accurate) • pH sensors – portable models (not very expensive) Continuous monitoring pH sensors – slightly more expensive, has the online option • Measurements can be done daily or ideally constantly to monitor changes
Temperature (water)	• Analogue thermometers • Digital thermometer with an online option • Monitoring of temperature is done continuously • Temperature probes often come together with other measuring devices (pH, DO)
Nitrogenous compounds	• Kits for measuring nitrite, ammonia, nitrate • Spectrophotometric analysis • Sensors for measurement of nitrates • Measurements done weekly or few times a week
Water hardness	• Test strips and titrimetric analysis • Largely depends on water source and therefore the hardness within the system doesn't have to be monitored as often
Micronutrients	• Micronutrient concentrations are difficult to monitor in-house • Once plants start showing signs of micronutrient deficiency it means that the nutrients have been exhausted from the system • Monthly analysis of micronutrients are advisable, usually done by accredited laboratories
Algae growth	• Visual inspection – green slime on walls of containers/tanks, floating beds

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