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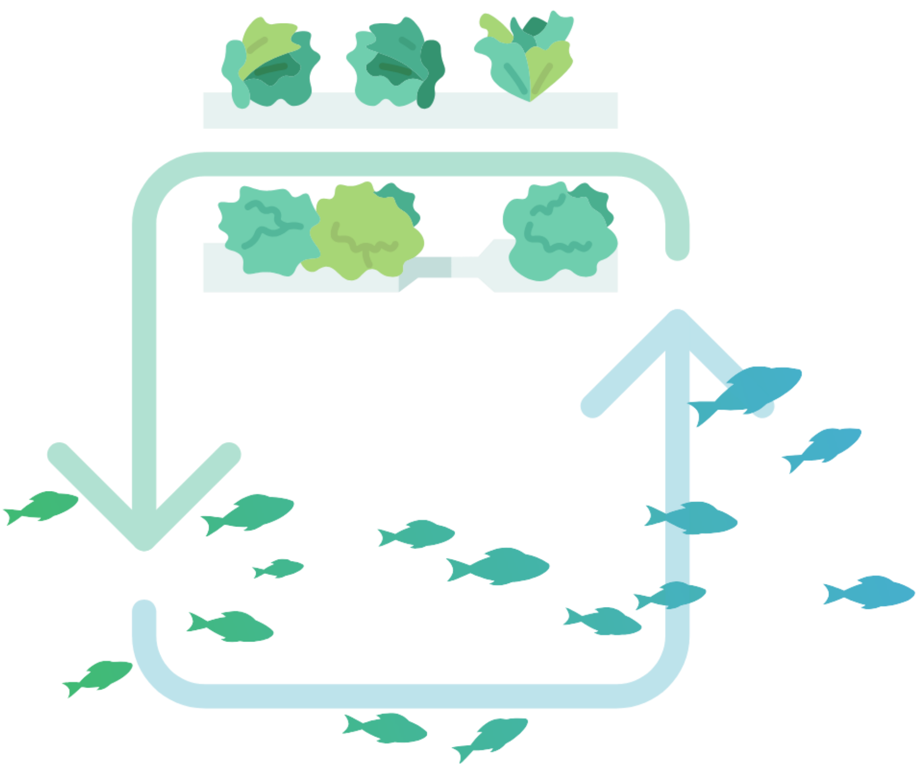
TransFarm

PLANTS IN AQUAPONICS – SELECTION, REQUIREMENTS AND LIMITATIONS



UNIVERSITY OF LATVIA

D.3.3.1. – Training materials on plants in aquaponics

Abstract (UL)

Aquaponics is a system that combines the principles of aquaculture and hydroponics. The fish through feeding release waste and through the metabolic activity of microorganisms this waste is transformed into 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 nutrients and growth conditions, 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-exists in close symbiosis to provide each other with the necessary nutrients. This report summarises the most important requirements of plants in an aquaponics system. Information on water quality parameters that are essential for plant growth, plant species most often grown in aquaponics systems, growth system types and substrates, integrated pest management and the advantages of plant production in aquaponics systems have been compiled in this report. This report includes general information for entrepreneurs and individuals interested in and those starting an aquaponics system, the reader is encouraged to explore the topics connected to plant growth in the aquaponics system by a series of reports prepared as a part of the TransFarm project.

Keywords: *TransFarm, aquaponics, plants, parameters, growth systems*

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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Saturs

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 for 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 it to grow all year round. Examples of these methods are hydroponics, where plants are grown in water, and aquaponics, which 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 relationships, 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 exchanged 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 interested in aquaponics.

The project will also investigate business models, run activities to inform consumers about the quality of the aquaponics produced, 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 University of Life Sciences** (Tartu, Estonia), **University of Latvia** (Riga, Latvia), **Campus Roslagen** and **Coompanion Norrtälje Vatten och Avfall AB** (Norrtälje, Sweden).

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

[1] UN DESA publications – World population prospects 2022

1.2. Plants in aquaponics

This report examines the fundamental elements of plant cultivation in aquaponic systems, which are symbiotic environments where plants and aquatic animals coexist. The report centres on comprehending the precise requirements of plants in aquaponic setups, the most suitable plant species for these systems, and the essential conditions for achieving optimal growth. The findings suggest that aquaponics offers a sustainable approach to plant cultivation, but its effectiveness relies on the meticulous choice of plant species, meticulous management of water quality, and maintaining a proper nutrient balance.

Plants in an aquaponics system require a balanced environment where water quality, nutrient contents, temperature and light are provided in an optimised manner. Water pH levels of between 6.00 – 7.00 are ideal fro most plants since this pH range ensures and supports nutrient availability and uptake. Plants in an aquaponics system rely on the nutrients generated by the fish (in the form of fish waste), the nutrients from the waste are then transformed into plant-available nutrients by the beneficial bacteria residing within the system. Key nutrients include nitrogen, phosphorus, and potassium as well as some minor elements like iron, calcium, and magnesium. Light for the plants is needed to ensure photosynthesis, commonly 12-16 hours of light per day is used in the vegetative period, however, longer daylight is needed while the plant is fruiting. The water temperature in and aquaponics system is between 18 °C and 26 °C – however care must be taken, since the other living organism in the system – the fish – is highly sensitive to changes and improper temperatures.

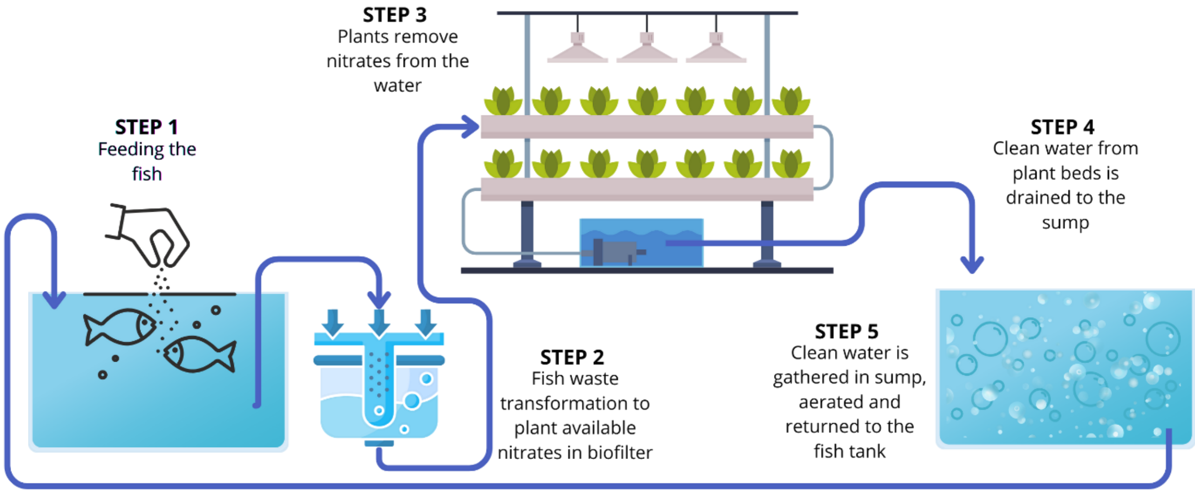


Figure 1. Generalised schematic of an aquaponics system with nutrient film plant growth channels.

Not all plants possess the same level of suitability for aquaponic systems. Typically, plants that have a moderate need for nutrients and can tolerate higher levels of humidity tend to thrive the most. Most commonly a variety of leafy greens (salads) are grown in aquaponics systems due to their fast growth rate and rather low nutrient requirements. Manny herbs grow well in aquaponics, for example, basil, mint, parsley, cilantro, dill and others. However, also plants with higher nutritional value can be grown in such a system, for example, tomatoes, peppers, cucumbers, strawberries and rooting vegetables like carrots, radishes and beets, requiring more specific media beds and growth systems to support their growth.

The efficacy of plant cultivation in aquaponic systems hinges on a harmonious environment that fulfils the precise requirements of the plants. Leafy greens and herbs are generally the most effortless and high-yielding plants to cultivate in these systems, whereas fruiting plants necessitate more meticulous handling. To achieve optimal plant growth, it is crucial to comprehend the precise demands for water quality, nutrient balance, and environmental conditions. Aquaponic systems provide a sustainable and efficient approach to cultivating a wide range of plants, especially leafy greens and herbs. Nevertheless, the effectiveness of these systems depends on the choice of plant species, as well as control of water quality, nutrients, and environmental conditions. Aquaponics, when given adequate attention and supervision, has the capacity to generate abundant quantities of fresh crops while simultaneously reducing resource consumption and environmental harm.

1.3. Soil-less vs. traditional farming

Agriculture is the basis of modern society and is the backbone of global food production. Soil-based farming is the most common and most widely used type of agriculture by far. Despite the advantages and possibilities that soil-based farming offers, the increasing global population, climate aspects and potential soil exhaustion in certain regions as well as the quality and stability of drinking water sources alternative farming methods like soil-less farming have gained attention. Soil-less farming includes such farming methods as hydroponics, aeroponics and aquaponics where the produce is grown without soil, relying on nutrient-rich fertilising solutions provided to the plant via drip-systems, flow of water or mist (aeroponics). The main aspects to be compared when evaluating traditional farming and soil-less farming are the utilisation of resources (nutrients, water, soil or substrate), crop yield growth rate of the crops (and fish in the case of aquaponics) impact on the environment (soil health, carbon footprint – growing, transportation) and of course the economic feasibility.

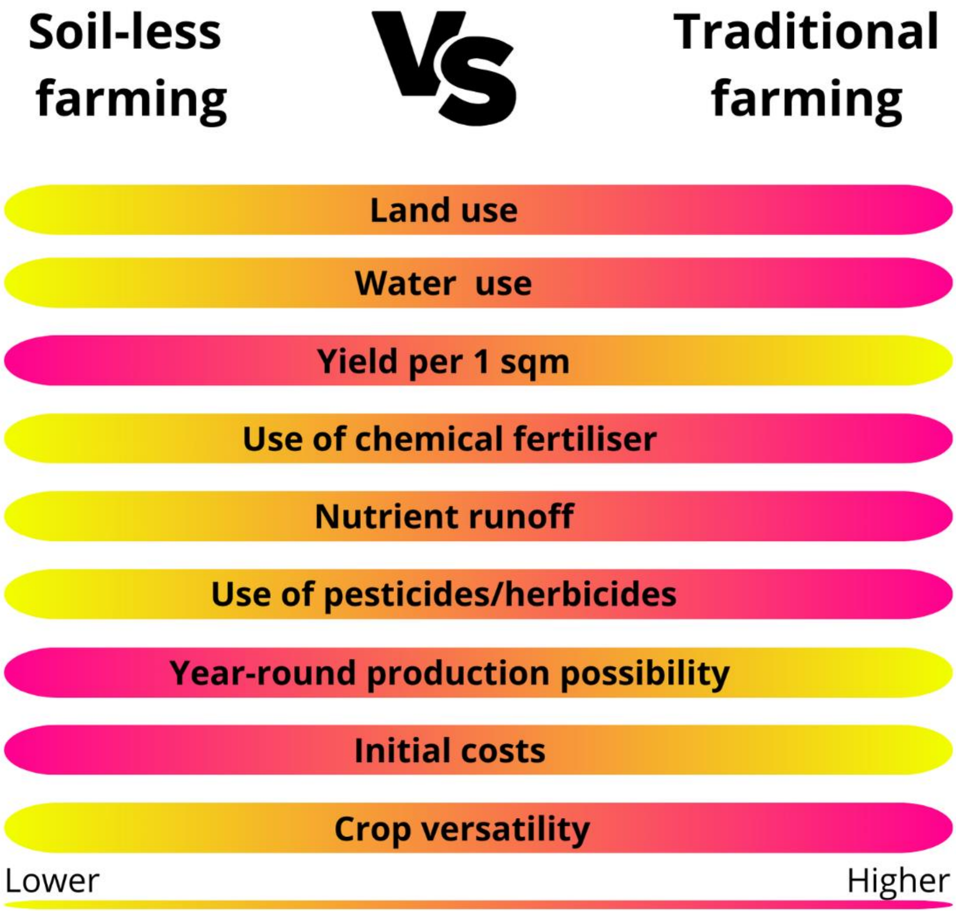


Figure 2. Comparison of soil-less and traditional farming indicating the use of resources.

The effectiveness of resource utilisation is an important factor both economically as well as environmentally. The soil-less farming methods like hydroponics and aquaponics demonstrate significantly higher water-resource efficiency than the traditional soil-based farming. In hydroponics and aquaponics, the systems are usually set up so that the water is recycled saving up to 90% of the water – the losses occur due to the evaporation of water from open plant beds of evapotranspiration through the plant's leaves. The evaporation of water from soil-based farming methods is often significantly higher due to the rapid evaporation in an uncontrolled environment and runoff. The scarcity of drinkable water in certain regions of the world puts the soil-less farming methods as more favourable alternatives to traditional farming due to the possibility of saving vast amounts of this resource.

Similarly to water also nutrients (in the form of fertiliser) are a resource that is utilised somewhat inefficiently in traditional farming – when fertilising the fields significant runoff happens meaning that with the same amount of nutrients far less produce is grown, moreover, the nutrient runoff from the fields causes eutrophication. Soil-less farming on the other hand offers the ability to precisely control the nutrient delivery that is optimised for the precise needs of each plant species and thus also the waste of nutrients is minimised.

Soil-less farming systems, due to the precise dosing of nutrients, can offer higher crop yields. Studies indicate that soil-less farming can produce up to 30% higher crop yields than traditional farming per the same area due to the controlled environment and optimised nutrient delivery. The absence of different biotic and abiotic factors that usually can encumber the growth of plants in traditional farming systems also benefits the plant in soil-less systems – it has been shown that the plant growth rate is significantly increased in hydroponic or aquaponic systems. Another aspect concerning the plant yield in soil-less systems, in general, is the ability to grow plants throughout the year by cycling different species.

The environmental impact of switching to soil-less farming would mean that the soil that is currently used for farming would be neglected which could lead to changes to soil health and changes in soil biodiversity – these are aspects crucial to agricultural sustainability and conservation. The importance of responsible, environmentally conscious farming must be considered when changing the common practices used also in farming. The carbon footprint of traditional farming can in some cases be lower than for the soil-less farming technologies. Soil-less farming systems, when high-technology solutions are used are quite energy-demanding. To avoid this such systems should be established in places where energy is cheaper or is produced by renewable technologies like wind-power or solar energy. In both cases, responsible evaluation of various aspects must be considered.

Economically the integration of soil-less farming systems requires significant initial capital – the costs of greenhouses, climate systems, nutrient delivery systems, lamps, plant beds, fish tanks, pumps etc. On the other hand, traditional farming requires more land, and water resources as well as equipment for land treating, which can be rather expensive. The operational costs for soil-less farming systems can be high due to the energy prices and possible maintenance, however, the higher yields and possibility of year-round production can offset these costs. Traditional farming from the operational costs perspective is slightly more unpredictable – factors like weather conditions (storms, loss of crop) fertiliser costs, labour, global political situation etc.

One potential answer to some of the problems facing contemporary agriculture—such as a lack of arable land, a shortage of water, and the need for more food production—is soil-less farming. However conventional farming is still necessary to maintain biodiversity and maintain the health of the soil. The most practical course for global agriculture may be to combine soil-less farming methods with sustainable soil management practices in conventional farming in a balanced manner. Integration of soil-less and traditional farming by combining the two methodologies could enhance overall agricultural sustainability and resilience. Soil-less farming could be adopted in urban areas thus providing fresher produce while traditional farming could be optimised in rural areas for sustainable land use. As the research and development to improve energy efficiency within soil-less farming is ongoing, strategies to improve and maintain the soil health of traditional soil-based farming are crucial. Overall the awareness should be promoted to educate the stakeholders on the benefits and limitations of both farming methods to encourage informed decision making.

2. Water quality and other requirements for plants

2.1. Oxygen and CO_2 management

The process of respiration in plants involves using the carbohydrates produced during photosynthesis and environmental oxygen to produce energy for the plant to develop. Respiration happens throughout the plant, while photosynthesis happens in the leaves and stems only. Plants uptake oxygen through the stomata and roots – this process occurs throughout the day, however in the dark, the process of respiration is more evident since no photosynthesis happens. Respiration is also directly connected to the ambient temperature; it is generally advisable to have lower night-time temperatures since this allows the plants to accumulate carbohydrates and synthesize other substances necessary for proper growth and development. Oxygen deficiencies are generally not very common, since air contains approximately 21% oxygen, however, it is important to ensure good airflow and ventilation of the greenhouse or the room where the aquaponic system is placed to ensure the exchange of air and optimal O2 and CO2 levels.

The rate at which photosynthesis happens is highly dependent on the CO2 levels in the environment where the plants grow. Air contains approximately 0.037% CO2 which can readily be consumed in high-intensity hydroponic or aquaponic set ups. When possible the CO2 in the growth space can be replenished by ventilation, when the air temperature allows it. During winter, when the air is too cold or in places where the average temperature is low also in spring and autumn seasons extra heating might be necessary to ensure plant growth. CO2 can be supplemented and kept constant by the use of CO2 generators – these generators use electricity or fossil fuels, which again leads to energy consumption and overall sustainability issues of the system. In winter when the exploitation of such generators where open flame is used can in fact be beneficial since burning of, for example, natural gas would produce CO2, heat and additional moisture. Another option is to use CO2 from CO2 cylinders; however, this can also increase the costs of running an aquaponics system and make it less viable.

2.2. pH

pH is one of the most important environmental factors in an aquaponics ecosystem – it influences the growth of plants, fish and beneficial bacteria, moreover, optimal pH levels determine the nutrient availability for plants. pH tolerance for most plants is between 5.5 to 7.5. Most plants prefer slightly acidic conditions; however, the bacterial and fish tolerances must be taken into account in aquaponics systems. If the pH is outside of the preferable plant range then the plants cannot uptake certain nutrients despite them being present in the water. In such cases, supplementation of suspected missing nutrients is not going to solve the issues with plant growth and development unless the pH is adjusted accordingly. The pH of the water in an aquaponics system directly affects the availability of nutrients. Every nutrient has a specific pH range in which it is highly soluble and easily accessible to plants. For instance, nitrogen, in the form of nitrate, is easily accessible within a broad pH spectrum but is most effectively taken in by plants under slightly acidic to neutral circumstances. Phosphorus, an essential nutrient for root growth and energy transportation within the plant, is most abundant in a pH range of 6.0 to 7.5. Phosphorus can become insoluble and inaccessible to plants when it falls outside of this range. Iron, manganese, and zinc are essential micronutrients for plants, as they play vital roles in activating enzymes and producing chlorophyll. The availability of these micronutrients is enhanced in slightly acidic conditions. When the pH level exceeds 7.5, these nutrients can become insoluble, resulting in deficiencies. In aquaponics, the source of the nutrient solution is the fish waste. Maintaining a balanced pH is crucial in this system to prevent a nutrient lockout, which occurs when essential nutrients are present but cannot be accessed by plants. The nutrient lockout is more common in newly established aquaponic systems that are more prone to changes since the microbial communities have not been established.

In hydroponics systems where the environment is essentially sterile, the regulation is easier than in aquaponics systems where the balance between fish, plants and microorganisms must be created. The primary difficulty in aquaponics lies in achieving and maintaining a pH level that adequately meets the needs of plants, fish, and nitrifying bacteria concurrently. Fish typically flourish in mildly alkaline environments, with a preferred pH range of 7.0 to 8.0, which may vary depending on the species. However, the majority of plants thrive in a pH range that is slightly acidic to neutral. Specifically, for hydroponic systems, the ideal pH falls between 5.5 and 6.5, while in aquaponics, it is slightly higher due to the presence of fish and bacteria.

In order to achieve equilibrium, it is commonly recommended to maintain the pH level in aquaponics within the range of 6.8 to 7.2. This range is a balanced solution that promotes the well-being of all living beings within the system. It guarantees optimal nutrient absorption by plants, maintains the health of fish, and enables efficient processing of ammonia by nitrifying bacteria.

A more detailed description of pH importance in an aquaponics system can be found in the TransFarm project report “Water quality in aquaponics”.

2.3. Light/dark cycle

Photosynthesis is the process by which all green plants are capable of producing their own food. Photosynthesis necessitates the presence of oxygen, carbon dioxide, water, and light. Inside the plant, there are tiny structures called chloroplasts that house chlorophyll, a pigment that harnesses sunlight to convert atmospheric carbon dioxide (CO_2) into carbohydrate molecules like glucose. This process liberates oxygen (O_2). There exist two distinct forms of chlorophyll, namely chlorophyll a and chlorophyll b. Chlorophyll a, the predominant photosynthetic pigment, selectively absorbs wavelengths in the blue, red, and violet regions of the visible spectrum. Chlorophyll b mainly captures blue light and is utilised to enhance the absorption spectrum of chlorophyll a by expanding the range of light wavelengths that a photosynthetic organism can absorb. Both of these forms of chlorophyll enable optimal absorption of light within the blue-to-red range of the spectrum. After being synthesised, the sugar molecules are distributed throughout the plant and subsequently utilised for various physiological functions such as growth, reproduction, and metabolism. During the nighttime, plants utilise these sugars, along with oxygen, to produce the energy required for their growth. The term for this process is respiration. It is crucial to position an aquaponic system in a location where every plant can receive ample sunlight or sufficient light from artificial sources. This guarantees sufficient energy for the process of photosynthesis. Continuous access to water is essential for the roots via the system. Carbon dioxide is readily accessible in the atmosphere, although, in highly concentrated indoor environments, plants can deplete all of the carbon dioxide within the enclosed space, necessitating the need for ventilation or additional CO_2 supplementation. Elevated levels of carbon dioxide (CO_2) enhance the process of photosynthesis, thereby stimulating the growth of plants. The concentration of CO_2 in fresh air is approximately 0.037%. However, in a tightly sealed greenhouse or grow room, the surrounding CO_2 can be depleted rapidly. For instance, in a plastic greenhouse, the concentration of CO_2 can be decreased to less than 0.02% within a mere 1-2 hours after sunrise. Plant growth will be significantly restricted at concentrations below 0.02%, and plants will completely cease to grow at concentrations below 0.01%. By elevating the concentration of CO_2 to a range of 0.075-0.15%, cultivators can anticipate a substantial enhancement of 30-50% in crop yields compared to the natural levels of CO_2. Additionally, the duration required for fruit set and flowering can be shortened by 7-10 days. Nevertheless, an overabundance of CO_2 enrichment can result in detrimental consequences. Levels exceeding 0.15% are deemed wasteful, whereas levels surpassing 0.5% are deemed harmful. Elevated concentrations will induce the closure of stomata on plant foliage, resulting in a temporary cessation of photosynthesis. As a consequence of the closed stomata, plants are unable to effectively transpire water vapour, leading to the potential scorching of leaves. In the realm of plant cultivation, the aim is to determine the amount of light that the plant absorbs throughout the day, regardless of the duration of daylight.

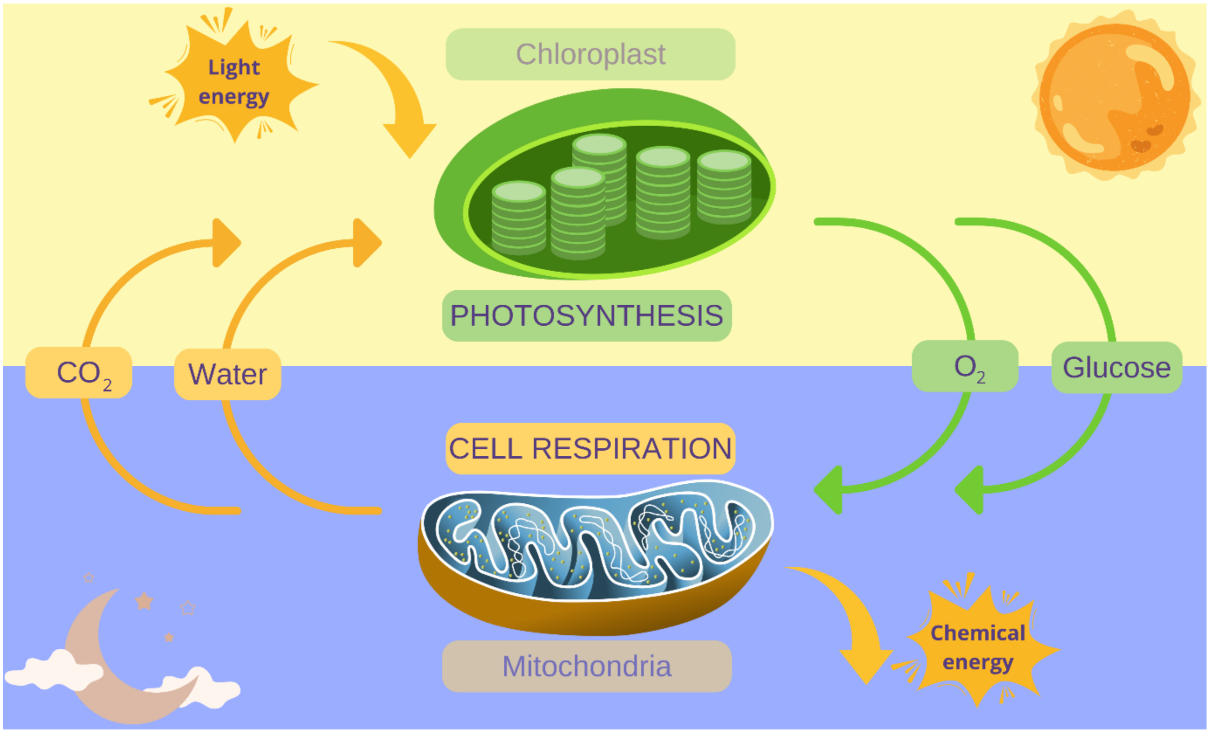


Figure 3. Photosynthesis and cell respiration of plants.

Each plant exhibits unique responses to varying levels of light, with certain species specifically adapted to thrive in full sunlight, while others thrive in shaded environments. Plants respire and generate carbon dioxide in the absence of light. As the luminosity augments, the rate of photosynthesis also increases, and at a specific luminosity level, the rate of respiration becomes equivalent to the rate of photosynthesis, resulting in no net absorption or release of CO_2. Aside from light intensity, the duration of daylight and the specific wavelengths of light also have an impact on various developmental processes, including the initiation of flowering, the elongation of plants, and the overall shape of the plant. Leafy greens and herbs typically necessitate 10-14 hours of daylight, while certain shade-tolerant plants have less demanding light needs. Excessive light exposure can trigger flowering in certain salad species, altering the taste and causing it to become more bitter. Tomatoes, peppers, and cucumbers, which are plants that produce fruit, necessitate 14-18 hours of light with a high level of intensity. In contemporary commercial hydroponic systems, the light intensity is regulated to meet the specific requirements of the plant at each stage of its growth. Artificial lighting can be used to supplement natural light in open greenhouses during cloudy conditions, resulting in significant energy savings. In aquaponics systems that are located indoors and rely solely on artificial light sources, it is crucial to carefully control the lighting conditions to ensure that the appropriate amount of light is provided for each specific stage of development.

3. Plant nutrition

Aquaponics nutrition is predicated on the synergy between aquaculture and hydroponics, facilitating a symbiotic ecosystem for fish and plants. In this system, fish excrete waste abundant in ammonia, which, although toxic in its unaltered state, transforms into a beneficial nutrient for plants through a process known as nitrification. Beneficial bacteria, including Nitrosomonas and Nitrobacter, transform ammonia into nitrites and subsequently into nitrates, a nitrogen form that plants can easily assimilate for growth. This nitrate-rich water supplies vital macronutrients such as nitrogen, phosphorus, and potassium, as well as other essential micronutrients for plant growth. Consequently, plants assimilate these nutrients and facilitate the purification of the water, which is subsequently recirculated to the fish tanks. This system's equilibrium diminishes the necessity for chemical fertilisers and promotes sustainable plant growth. For optimal plant health, supplementary nutrients such as iron, calcium, and magnesium may be necessary, as fish waste alone may not supply adequate amounts. This closed-loop ecosystem renders aquaponics an efficient and eco-friendly method for plant nutrition and food production.

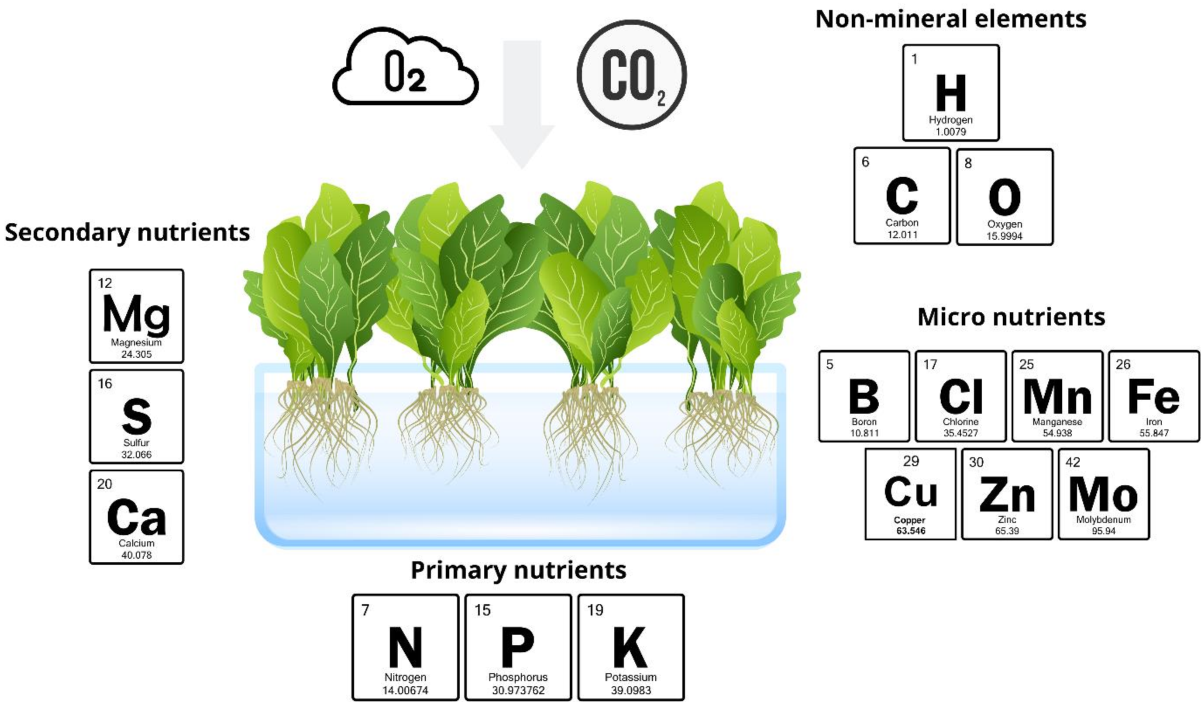


Figure 4. Compilation of the primary, secondary and micronutrients necessary for plant growth.

3.1. Nitrogenous nutrients

Aquaponics is an integrated system that combines aquaculture (growing fish) and hydroponics (growing plants). Plants in this system are responsible for the utilisation of the waste produced from fish growth and metabolism – primarily nitrogenous compounds. Understanding the functions, necessity and nitrogen needs of plants in aquaponics is essential for a balanced, healthy aquaponics system.

Nitrogen in general is a vital nutrient for all plants as it is the basic component of several biomolecules. Nitrogen is part of amino acids, which are the main building blocks of proteins. Proteins have several functions in plants, they can act as enzymes or as building blocks of the cell. Enzymes are also involved in photosynthesis, nutrient uptake and plant growth overall. Nitrogen is also a crucial component of nucleic acids (DNA and RNA), which are molecules that carry genetic information necessary for plant development, and reproduction. Chlorophyll, which is the green pigment involved in photosynthesis also contains nitrogen. Chlorophyll is responsible for converting light energy into chemical energy which enables the plant to produce carbohydrates needed for growth. Adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH) are formed from nitrogen – these molecules are responsible for energy transfer within the cell plants. These molecules are essential in photosynthesis and respiration.

Nitrogen in aquaponics comes from fish waste, however, it has to undergo several transformations before it becomes bioavailable and non-toxic to plants. Primary nitrogenous forms that come from fish are in the form of ammonia (NH_3) and ammonium (NH_4^+). Fish excrete ammonia as a by-product of protein which comes from the fish feed. In water ammonia is converted to ammonium which can also be uptaken by the plants, however, higher levels of these forms of nitrogen are toxic to both, the fish and the plants, therefore it has to be transformed further, to less toxic forms. Through a process called nitrification ammonia is transformed into, firstly, nitrite (NO_2^-) by ammonia oxidising bacteria (*Nitrosomonas* spp.) and then to the less toxic and more bioavailable nitrate (NO_3^-) by nitrite oxidising bacteria (*Nitrobacter* spp.). Nitrates are highly soluble in water and readily absorbed by plants. By supplementing the plants with enough nitrogen healthy plant growth can be ensured. Nitrogenous compounds ensure that the plants develop more leaves, stems and roots ensuring higher yields. In hydroponic and aquaponic systems plant yields are the primary source of income, therefore it is important to maintain sufficient nitrogen levels. Nitrogen deficiencies often exhibit slowed growth and exhibit chlorosis (yellowing of leaves).

In aquaponics, the plants solely rely on the water introduced and recirculated in the system where the nutrients are dissolved. Nitrogen is one of the primary macronutrients that the plants need in large quantities. While plants need this nutrient in large quantities, it can be toxic to fish, therefore maintaining a nutrient balance is crucial. Optimising nitrogen load in the system can be done by managing several factors. The number of fish in the system determines the amount of ammonia produced as does the feeding rate. The higher the stocking density, the more fish feed has to be supplemented to the fish which in turn increases the available nitrogen for plants if the biofiltration is sufficient. The feeding rate can also be adjusted; however, fish might become stressed when the feeding rates are too low or on the other hand develop diseases or overeat. The nitrogenous compound transformation can be improved by maintaining a healthy biofilter, to ensure complete transformation of ammonia and ammonium to nitrate. Nitrifying bacteria require oxygen to convert ammonia to nitrate, therefore adequate aeration is needed – oxygenation is also needed for hydroponic and aquaculture inhabitants. Since the uptake of nitrates is pH dependent an adequate level of environmental pH must be maintained – the pH necessary for plants, fish and bacteria coincide in a certain range and it can be adjusted. Temperature can also help in utilising nitrogen when excess levels of ammonia and nitrates are present by inducing faster plant growth and bacterial activity. However, the temperature must be kept constant and adjusted according to the fish and plant species in order not to suffocate the fish or induce plant wilting or bolting.

Nitrogen deficiency in plants includes yellowing of the older leaves, stunted growth and reduced leaf size. If such symptoms appear the feeding rate, stocking density or biofilter efficiency should be changed. In extreme cases the aquaponics system can be supplemented with mineral nitrogenous fertiliser, however, this is beyond the scope of an aquaponics system, which essentially makes the system a hydroponic system with a fish tank. Excess nitrogen, particularly ammonia or nitrite, can be detrimental to both aquatic organisms and vegetation. Symptoms of nitrogen toxicity in plants encompass dark green foliage, excessive vegetative growth detracting from fruiting or flowering, and possible root damage. Elevated ammonia or nitrite concentrations in fish can result in stress, disease, or mortality.

3.2. Phosphorus

Phosphorus plays a crucial role in supporting plant growth, just like nitrogen and potassium. Phosphorus is crucial in an aquaponic system as it supports plant development, energy transfer, and overall system health. Plants in this system rely solely on the nutrients found in water, which mainly come from fish waste and decomposing organic matter.

Phosphorus is a key component of adenosine triphosphate (ATP), which is the main energy carrier in all living cells. ATP stores and transfers energy in the plant, facilitating essential processes such as photosynthesis, respiration, carbohydrate and protein synthesis. Phosphorus is an essential component of nucleic acids (DNA and RNA). DNA stores the genetic blueprint of a plant, while RNA is important in converting this blueprint into proteins and enzymes. Phosphorus is therefore essential for cell division, growth and reproduction. Phosphorus is a key element in phospholipids, which form the structural basis of cell membranes. These membranes control the movement of substances in and out of cells, maintain cell integrity, and enable cell signalling and nutrient transport. Phosphorus is also involved in the formation of compounds necessary for photosynthesis. Efficient photosynthesis is essential for plants to convert light energy into chemical energy, which is then used to produce the sugars needed for growth and development. Phosphorus plays an essential role in the development and elongation of plant roots. It promotes strong root growth, allowing plants to use more water and nutrients, thus improving overall nutrient uptake and stability. Adequate phosphorus levels are important for flower and seed formation. It promotes early plant maturation, accelerates flowering and contributes to better fruiting and seed development.

Phosphorus plays a significant role in plant growth, root development and reproduction as an essential macronutrient. Insufficient phosphorus can lead to stunted growth, underdeveloped roots, delayed maturity, reduced flowering and reduced yield. It is particularly important to ensure that aquaponic plants have sufficient phosphorus for optimum growth, as they depend solely on nutrients in the water. To promote healthy plant growth and maintain optimum water quality, it is important to ensure a well-balanced nutrient profile in the aquaponic system. Excessive phosphorus can cause water quality problems such as algae blooms. Algae also need phosphorus to grow. Effective management practices maintain a balance between phosphorus availability to plants while avoiding potential ecosystem disturbances. Phosphorus is a finite resource in natural systems. Phosphorus plays a crucial role in maintaining the sustainability of aquaponics through its recycling and efficient use. Effective phosphorus management can help reduce dependence on external inputs such as phosphorus fertilisers and reduce waste.

Phosphorus in aquaponics comes mainly from fish feed. Phosphorus enters the water through the decomposition of fish waste and uneaten food. It is important to maintain adequate phosphorus levels by providing high-quality fish feed with a balanced nutrient content. The pH level of the water can affect the bioavailability of phosphorus. In aquaponic systems, it is recommended to maintain a pH level between 6.0 and 7.0 for the best uptake of phosphorus by plants. At pH levels above 7.0, phosphorus tends to form compounds that cannot dissolve, which in turn reduces its availability to plants. When organic matter, such as fish waste and uneaten feed, decomposes, it releases phosphorus into the water. The outcome of this process is influenced by fluctuations in temperature and oxygen levels. Optimum conditions for decomposition and nutrient release are higher temperatures and sufficient oxygen. However, it is important to be cautious and avoid oxygen deficiency, as this can lead to adverse chemical reactions and nutrient imbalances. Phosphorus levels are directly affected by the number of fish in the system and the amount of feed. If the fish population is more abundant and actively feeding, this can lead to elevated phosphorus levels in the water. However, if too many fish are fed or if there are too many fish, this can lead to an excess of phosphorus. This can encourage algae growth or cause other water quality problems. Phosphorus can be absorbed on the surface of the media, such as gravel or expanded clay, in aquaponics systems that use media. Keeping the media clean and the biofilters working efficiently is especially important to ensure that phosphorus can be readily absorbed by the plants. Different plants have different phosphorus requirements. For example, leafy greens generally need less phosphorus than fruit plants such as tomatoes or peppers. It is very important to understand the importance of plant choice and diversity to maintain a balanced phosphorus demand in the system.

Symptoms of phosphorus deficiency in plants include stunted growth, delayed maturity, dark green or purple foliage (especially on older leaves), and reduced flowering or fruit production. Necrotic (dead) spots may also form on the leaves. These symptoms indicate that phosphorus levels in the system are too low and need to be corrected. Excess phosphorus can cause imbalances in other important nutrients such as iron and zinc, which can lead to deficiencies. Symptoms may include chlorosis (yellowing of the leaves), especially in younger leaves, and interveinal chlorosis (yellowing between the veins while the veins remain green). Excess phosphorus can also contribute to algal blooms by reducing oxygen levels and harming fish and beneficial bacteria.

3.3. Potassium

Potassium is one of the three primary macronutrients required by plants, alongside nitrogen and phosphorus. It plays a critical role in numerous physiological and biochemical processes essential for plant health and growth.

Potassium regulates the stomatal function and water management. Stomata are small pores on the leaf surface that regulate gas and water exchange. Potassium regulates the closing and opening of stomata regulating the water uptake and retention by maintaining turgor pressure (the pressure of cell wall contents against cell walls). Potassium acts as a co-factor for various enzymes involved in metabolic processes, including photosynthesis, respiration protein synthesis and carbohydrate metabolism. These enzymatic reactions are crucial for energy production and organic compound production for plant growth and development. Potassium plays a crucial role in helping plants withstand challenging environmental conditions like drought, extreme temperatures, and diseases. It plays a crucial role in maintaining the balance of fluids within cells, preventing dehydration, and ensuring stable cellular pH levels. Resilience plays a crucial role in aquaponics, as plants often encounter diverse environmental conditions. Potassium contributes to the quality of fruit and vegetables by affecting characteristics such as colour, size, shape, taste and shelf life. It promotes the movement of sugars and starch from the leaves to the storage tissue, which is particularly important for fruit and seed development. Potassium strengthens cell walls, making plants less susceptible to disease and pest attack. It promotes the synthesis of phenolic compounds and other secondary metabolites that act as natural defence mechanisms against pathogens and insects.

In aquaponics, potassium can be obtained from the decomposition of fish feed and organic matter. However, the natural potassium content of fish feed is often insufficient to meet the needs of most plants, especially those that require a lot of potassium, such as tomatoes, peppers and leafy greens.

Therefore, additional potassium supplements such as potassium sulphate (K_2SO_4) or potassium carbonate ($KHCO_3$) may be needed to maintain sufficient potassium levels. To ensure that the potassium concentration in the water is within the optimum range (usually 20-80 mg/L depending on the plant species), it is important to check the potassium concentration regularly. This helps to prevent deficiencies or excesses that could have a negative impact on plant health or growth.

Signs of potassium deficiency can be observed through the discolouration of leaf edges, starting with a yellowing effect known as marginal chlorosis. This discolouration may further develop into brown scorching or necrosis, resulting in dead tissue at the leaf tips and edges, particularly in older leaves. Additional indicators include stems that lack strength, insufficient growth of roots, decreased blooming, and diminished crop production. Plants that lack potassium are more prone to diseases and environmental stressors. Excess potassium is not common in aquaponics, but it can cause problems when it interacts with other important nutrients like calcium and magnesium. This can lead to deficiencies in these nutrients. Excess potassium can lead to symptoms such as chlorosis, curling, or browning of leaves, especially in young leaves, and stunted growth. Severe cases of nutrient imbalances can result in a decline in plant health and vigour.

3.4. Micronutrients

Although micronutrients are needed in smaller quantities than macronutrients (nitrogen, phosphorus, potassium), they play a crucial role in the growth, development, and productivity of plants. These nutrients play important roles in enzymatic reactions, the synthesis of essential molecules, and various aspects of plant metabolism, structure, and disease resistance. When it comes to aquaponics, the nutrients in water play a vital role in supporting plant health and maximising yields.

The primary source of micronutrients in an aquaponics system is the fish feed. Fish feed contains a mixture of nutrients, including trace elements such as iron, sulphurous compounds, zinc, manganese, copper, boron etc. After the fish consume the feed, these nutrients are released into the system together with the fish waste. The nutrients are further digested by the different bacteria colonising the biofilter which makes these elements available to the plants. If the plant production of certain crops, for example, lettuce, which consumes a lot of iron is halted due to certain mineral deficiencies, the system can be supplemented by the addition of chelated micronutrients. Such supplements do not harm the fish nor the plants when used responsibly and the dosages have been carefully considered.

IRON (Fe)

Iron is an essential micronutrient that is a part of several molecules and processes, including photosynthesis. Iron is responsible for electron transport within the plant cells, specifically in the chloroplasts and mitochondria during photosynthesis and respiration, respectively. Iron is also a part of enzyme synthesis that is responsible for nitrogen fixation and energy transfer. In aquaponics the most common micronutrient deficiency is iron deficiency – this leads to interveinal chlorosis. Most commonly iron deficiencies are witnessed for leafy greens like salads and spinach and some fruiting vegetables like tomatoes and peppers.

ZINC (Zn)

Zinc is a cofactor for several enzymes involved in DNA transcription, and hormone regulation (auxins). It plays an important role in maintaining the integrity of cell membranes and in carbohydrate metabolism. Zinc is also involved in the synthesis of chlorophyll and some carbohydrates; zinc levels affect the uptake and use of water by the plant. Tryptophan synthesis is regulated by zinc, which is a precursor of auxins. Deficiencies in zinc reduce plant growth rate, distort leaves and reduce elongation of the internodes. Depending on the plant species, the need for zinc can vary, plants like beans, corn, and wheat have higher zinc requirements for optimal yields.

SULPHUR (S)

Sulphur plays a vital role in the growth, metabolism, and overall health of plants in aquaponics. It is essential for synthesising amino acids, proteins, vitamins, and coenzymes, which are crucial for plant development. This substance is crucial for the creation of chlorophyll and the process of photosynthesis. It also helps plants efficiently use nutrients, particularly nitrogen, and improves the taste, smell, and ability to fight off diseases in crops. When there is a lack of sulphur, it can result in chlorosis, which is the yellowing of young leaves. This can also cause stunted growth and hinder the flowering process. Regular monitoring and balanced nutrient management are crucial for maintaining plant health and optimising yields in aquaponics. Sulphur is sourced from fish feed, sulphate-containing supplements, and decomposing organic matter.

MANGANESE (Mn)

Manganese is a vital element involved in photosynthesis; it plays a direct role in the water-splitting process during photosynthesis. Manganese activates several enzymes that are important in plant metabolism, for example, enzymes involved in nitrogen uptake and synthesis of fatty acids. Lignin, a structural cell wall component, is also formed with the help of manganese. Crops like soybean, wheat and oats are especially dependant on manganese supplementation. Deficiency of manganese is characterised by interveinal chlorosis, especially in young leaves.

BORON (B)

The formation of cell walls and their stability is regulated by boron – it helps in the cross-linking of pectin (a type of polysaccharide found in plants). Boron is involved in the translocation and metabolism of carbohydrates. Boron also plays a significant role in the regulation of plant hormone levels, seed and fruit development and pollen germination. Deficiency of boron is expressed as developmental issues with the cell walls leading to brittle stems, misshapen fruits and seed infertility or deformation. Boron is particularly important for root vegetables, fruiting vegetables and legumes.

COPPER (Cu)

Copper is an important micronutrient that is essential for the electron transport chain. Copper is involved in the activity of several enzymes, especially those involved in photosynthesis and respiration. Lignin synthesis also happens in the presence of copper, which strengthens the vascular tissue. The plant's defence system against pests and the production of secondary metabolites (phenolic compounds) is regulated by enzymes that are activated by copper. Copper deficiency can cause distorted leaves, plant tissue death on the leaf tips, disturbed flowering and increase susceptibility to fungal diseases. Copper is especially vital for cereal crops and legumes, where disease resistance is very important.

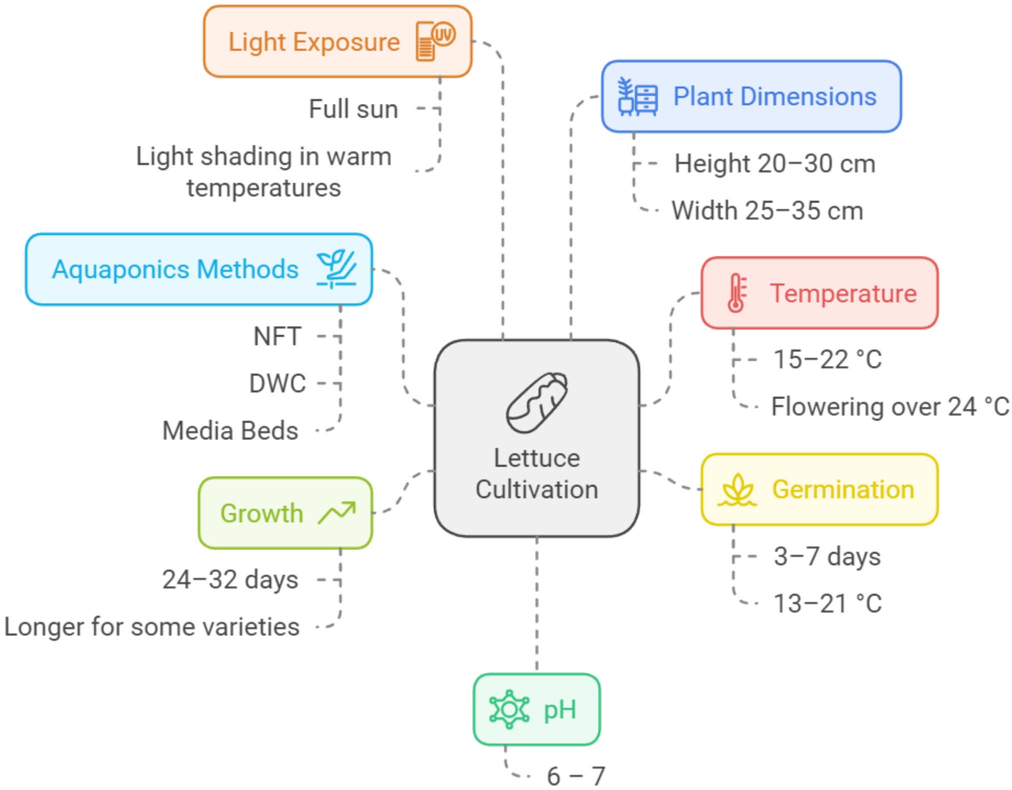
MOLYBDENUM (Mo)

Molybdenum is involved in the plants' nitrogen metabolism – it is a component of nitrate reductase and nitrogenase. It also helps in the synthesis of amino acids, the building blocks of protein. If molybdenum is in low concentration or unavailable to the plants, especially legumes, the nitrogen fixation can be disrupted thus reducing the growth rate. Also, plants like cauliflower or broccoli can show distinct signs of molybdenum deficiency by having a distorted leave shape.

4. Selection of the plant species

4.1. Leafy greens

Lettuce



Growing lettuce in aquaponics

Lettuce has a low nutrient demand and is a high-demand crop, which makes it suitable to grow for commercial purposes. Lettuce is a winter crop, water temperatures over 26 ◦C will cause a bitter taste. The process consists of three phases: germination, transplanting and maintenance/care. The medium should be humid rather than wet since it's the type of environment that seeds prefer.

Germination & transplanting

Lettuce should take between 3 to 7 days to germinate in temperatures between 13 to 21 ◦C.
Once the lettuce seedlings are about three weeks old and have 2 to 3 true leaves, it's safe to transplant them into the aquaponic unit.
It is advisable to give them a little extra phosphorous in the second or third week before transferring them over. This will give them a little more root growth and will "harden" the plants so they're not stressed.
When growing outside, it is good to gradually expose the lettuce seedlings to normal growing conditions — such as colder temperatures and direct sunlight — 3 to 5 days before you officially transplant them. This should give them plenty of time to adjust to the elements. Moreover, plant

hardening, through exposing seedlings to colder temperatures and direct sunlight, for 3–5 days before transplanting results in higher survival rates. When transplanting lettuce in warm weather, place a light sun-shade over the plants for 2–3 days to avoid water stress.

Figure 5. Lettuce grown in aquaponics deep water culture.

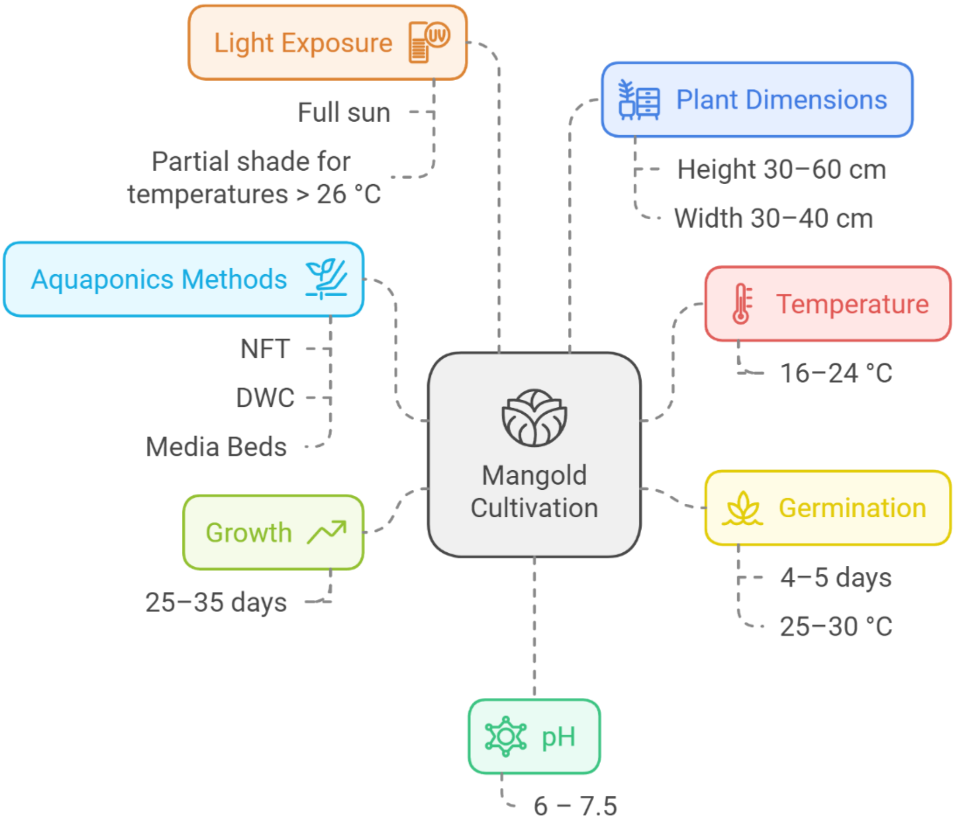
Maintenance and care

In order to obtain lettuce that is both crisp and sweet, it is necessary to cultivate plants at a rapid rate by ensuring elevated nitrate levels within the growing environment. When the temperatures of both air and water rise throughout the season, it is advisable to utilize bolt-resistant (summer) varieties. When cultivating in media beds, it is advisable to plant new lettuces in areas where they will receive partial shade from taller neighboring plants.

Harvesting

The commencement of harvesting is possible once the heads or leaves have attained sufficient size for consumption. When targeting markets, it is recommended to remove the entire plants and roots upon reaching the desired market weight (250 – 400 g) during the harvesting process. Remove the roots and transfer them into a compost bin. It is advisable to commence the harvest in the early morning hours when the leaves are in a state of crispness and contain ample moisture, followed by prompt chilling.

Swiss chard/ Mangold

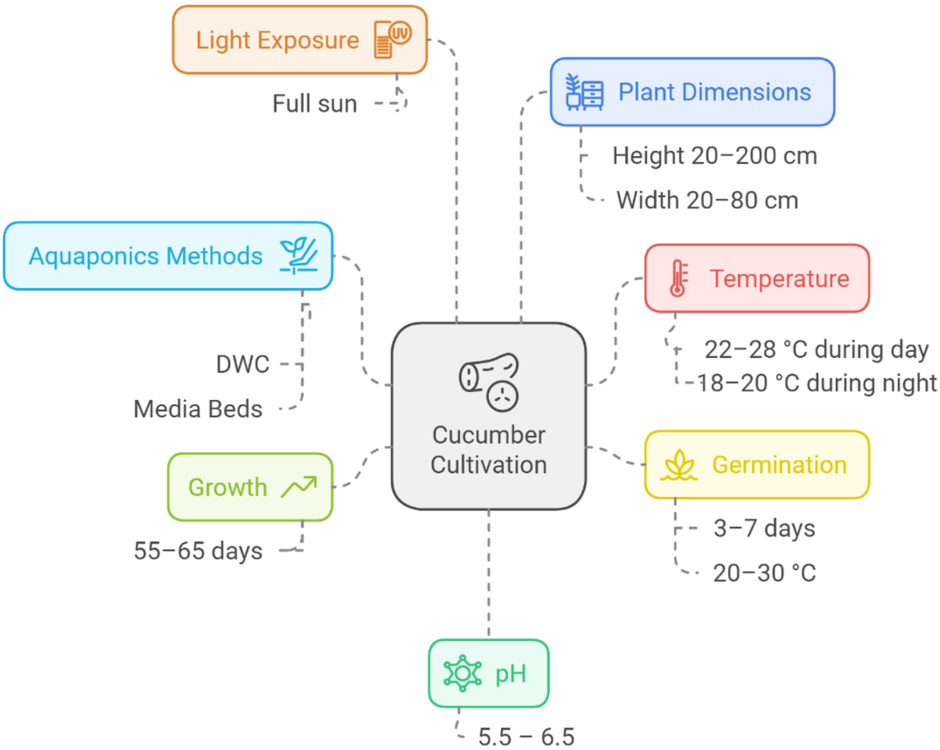


Growing instructions
Swiss chard seeds produce more than one seedling; therefore, thinning is required as the seedlings begin to grow. As plants grow and become old during the season, older leaves can be removed to encourage new growth.

Harvesting
Swiss chard leaves can be consistently harvested as soon as they reach the appropriate size. The elimination of larger leaves facilitates the development of fresh ones. Avoid damaging the growing point in the centre of the plant at harvest.

Figure 6. Mangold grown in aquaponics media bed with expanded clay.

4.2. Cucumbers



Growing cucumbers in aquaponics
Cucumbers thrive with prolonged periods of high temperatures, humidity, abundant sunlight, and warm nights. The ideal growing temperatures range from 24 to 27 °C throughout the day, accompanied by a relative humidity of 70 to 90%. A substrate temperature of approximately 21 °C is suitable for

manufacturing. Plants cease growth and production at temperatures between 10 and 13 °C. Cucumbers necessitate substantial amounts of nitrogen and potassium; therefore, the selection of plant quantity should take into account the nutrients present in the water and the biomass of the fish stock.Growing cucumbers in aquaponics involves a series of steps from transplanting to harvesting. It's also important to provide appropriate plant care, including proper pruning, pollination and pest management.

Figure 7. Cucumber grown in hydroponic nutrient film growth channels.

Transplanting

Cucumber seedlings can be transplanted into the aquaponic system when they are 2-3 weeks old, generally at the 4-5 leaf stage. At this stage, they are robust enough not to suffer the stress of the transition and begin drawing nutrients from the aquaponic system.

Growing instructions

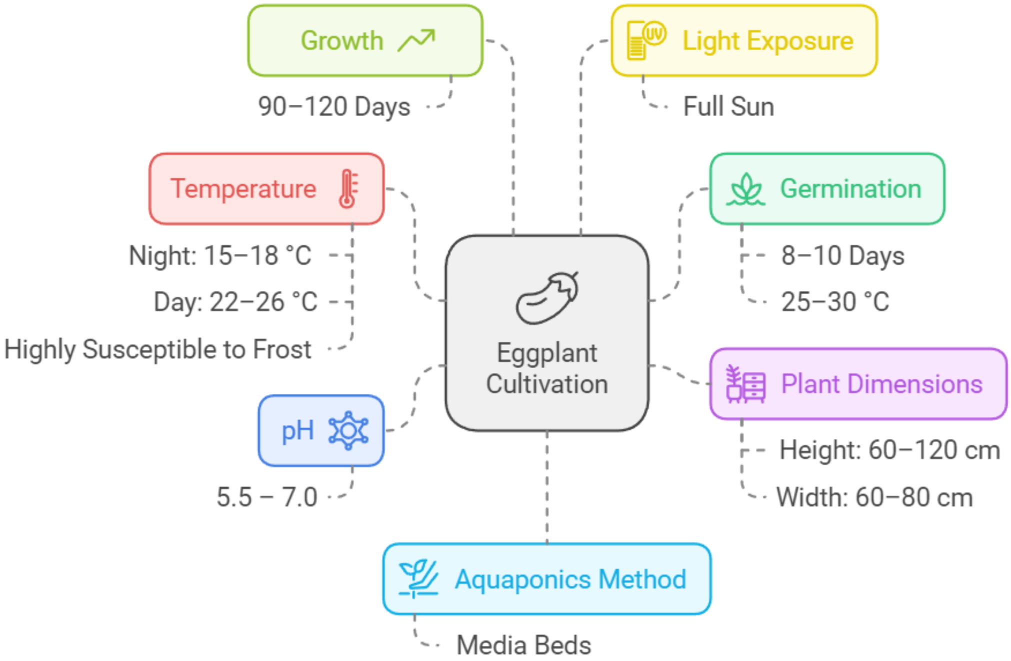
Cucumber plants grow very quickly and it is a good practice to limit their vegetative vigour and divert nutrients to fruits by cutting their apical tips when the stem is two metres long; removing the lateral branches also favours ventilation. Subsequent plant elongation can be achieved by retaining only the two most distal buds emerging from the main stem. Plants are stimulated to enhance output through the systematic harvesting of fruits that reach a marketable size (> 180 g for slicing types). The existence of pollinating insects is essential for effective fertilisation and fruit development. Cucumber plants require support for optimal growth, which also ensures sufficient aeration to mitigate foliar diseases such as powdery mildew and grey mould. Owing to the high incidence of pest occurrences in cucumber plants, it is important to plan appropriate integrated pest management strategies (see Chapter 6) and to intercrop the plant unit with plants that are less affected by the possible treatments used.

Harvesting

Once transplanted, cucumbers can start production after 2–3 weeks. In optimal conditions, plants can be harvested 10–15 times. Harvest every few days to prevent the fruits from becoming overly large and to favour the growth of the following ones.

4.3. Nightshades

Eggplant



Growing eggplant in aquaponic units

Eggplant is a summer fruiting vegetable that grows well in media beds owing to the deep growth of the root systems. Plants can produce 10–15 fruits for a total yield of 3–7 kg. Eggplants necessitate elevated levels of nitrogen and potassium, necessitating meticulous management decisions about the quantity of plants cultivated in each aquaponic unit to prevent nutritional imbalances.

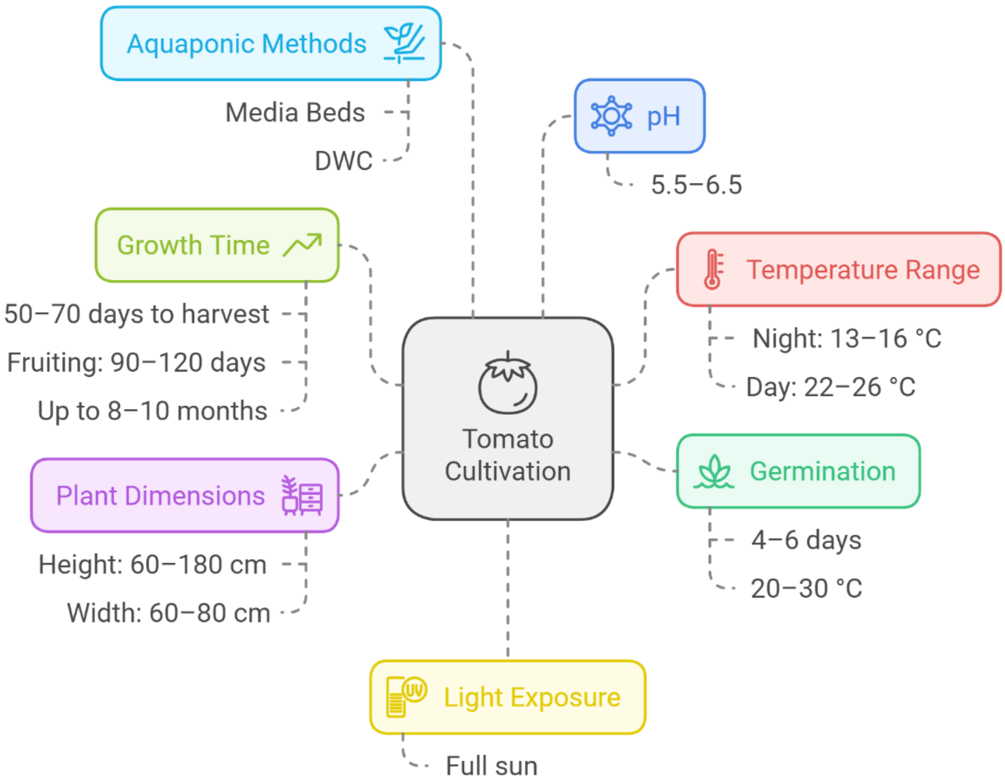
Figure 8. Eggplant grown in hydroponics with a drip system.

Growing instructions

Seeds germinate in 8–10 days in warm temperatures (26–30 °C). Seedlings can be transplanted at 4–5 leaves. Plants can be transplanted when temperatures rise in spring. Towards the end of the summer season, begin pinching off new blossoms to favour the ripening of the existing fruit. At the end of the season, plants can be drastically pruned at 20–30 cm by leaving just three branches. This method interrupts the crop without removing the plants during the unfavourable season (winter, summer) and lets the crop restart production afterwards. Plants can be grown without pruning; however, in limited spaces or greenhouses, management of the branches can be facilitated with stakes or vertical strings.

Harvesting
Start harvesting when the eggplants are 10–15 cm long. The skin should be shiny; dull and yellow skin is a sign that the eggplant is overripe. Delayed harvest makes the fruits unmarketable owing to the presence of seeds inside. Use a sharp knife and cut the eggplant from the plant, leaving at least 3 cm of the stem attached to the fruit.

Tomatoes



Growing instructions
Set stakes or plant support structures before transplanting to prevent root damage. Transplant the seedlings into units 3–6 weeks after germination when the seedling is 10–15 cm and when night-time temperatures are constantly above 10 °C. In transplanting the seedlings, avoid waterlogged conditions around the plant collar to reduce any risks of diseases. Once the tomato plants are about 60 cm tall, start to determine the growing method (bush or single stem) by pruning the unnecessary upper branches. Remove the leaves from the bottom 30 cm of the main stem to favour better air circulation and reduce fungal incidence. Prune all the auxiliary suckers to favour fruit growth. Remove the leaves covering each fruit branch soon before ripening to favour nutrition flow to the fruits and to accelerate maturation.

Figure 9. Tomatoes grown in nutrient film growth channels.

Harvesting
For the best flavour, harvest tomatoes when they are firm and fully coloured. Fruits will continue to ripen if picked half-ripe and brought indoors. Fruits can be easily maintained for 2–4 weeks at 5–7 °C under 85–90 % relative humidity.

Potatoes

pH: 5.5 – 6.5
Temperature range: 15-20 °C
Growth time: 70 - 90 days

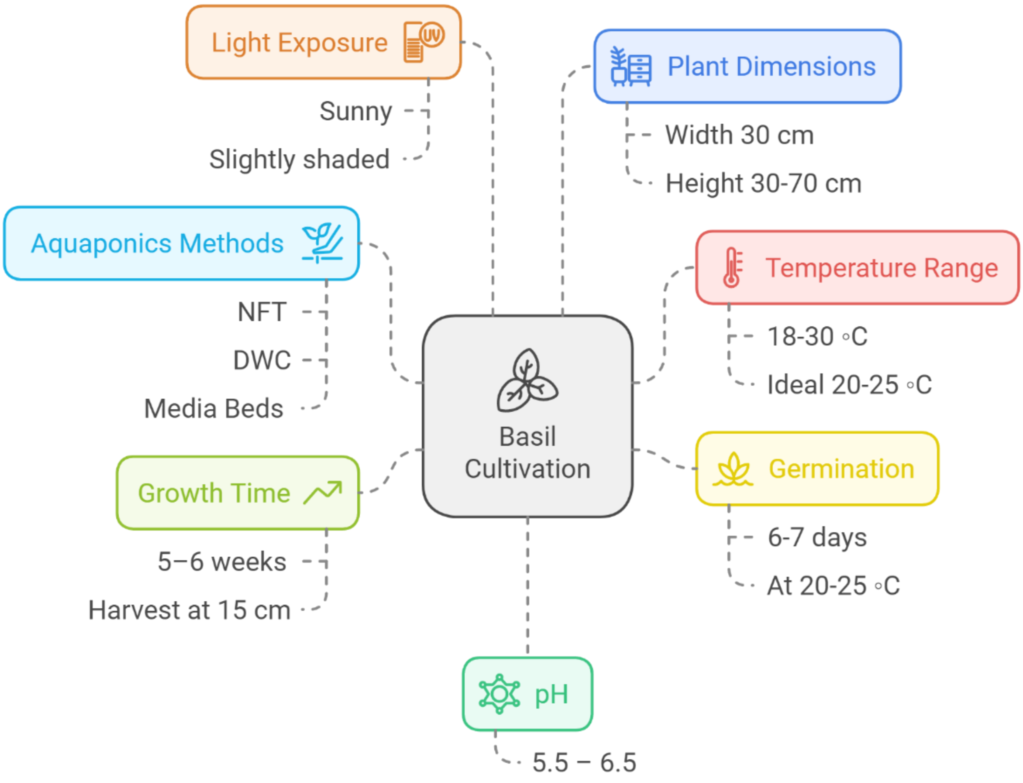
Potatoes are included in this report because they can be grown aeroponically. It is important to choose the right potato variety that can thrive in an aeroponics system for a good outcome.
These varieties are designed to grow in soilless environments and produce a better yield than the traditional soil-based method.

Maintenance and care
It is important to keep clean every component of the system to prevent harmful bacteria and diseases. Common potato pests, such as aphids, beetles, and whiteflies, should be properly addressed and controlled.

Harvesting
The ideal time to harvest potatoes is when the plants start to yellow and die back.
Harvesting is a very easy process. Simply remove the plant from the system and pluck the potatoes off the roots.
After harvesting, the potato should be cured to improve its flavour and storage life. This process involves placing the potatoes in a cool, dark, and well-ventilated area for 10 to 14 days.

4.4. Herbs and spices

Basil



Growing basil in aquaponics

The process consists of three phases: germination, transplanting and maintenance/care. The medium should be humid rather than wet since it's the type of environment that seeds prefer.

Germination & transplanting

When using seeds put the seeds in a growing medium (rock wool, coconut fibres, natural sponge, peat). At 20-25 ◦C it should take 6-7 days to the seeds to germinate.
Seedlings can be transplanted when the plant has 4-5 true leaves.

Maintenance and care

Basil enjoys warm temperatures to grow and it can be placed directly under the sun. However, when daily temperatures are higher than 27 ◦C plants should be ventilated and/or covered with shading nets to prevent tip burning. Basil can be affected by various fungal diseases, including Fusarium wilt, grey mould, and black spots, particularly under suboptimal temperatures and high humidity conditions. Air ventilation and water temperatures higher than 21 °C, day and night, help to reduce plant stress and incidence of diseases.

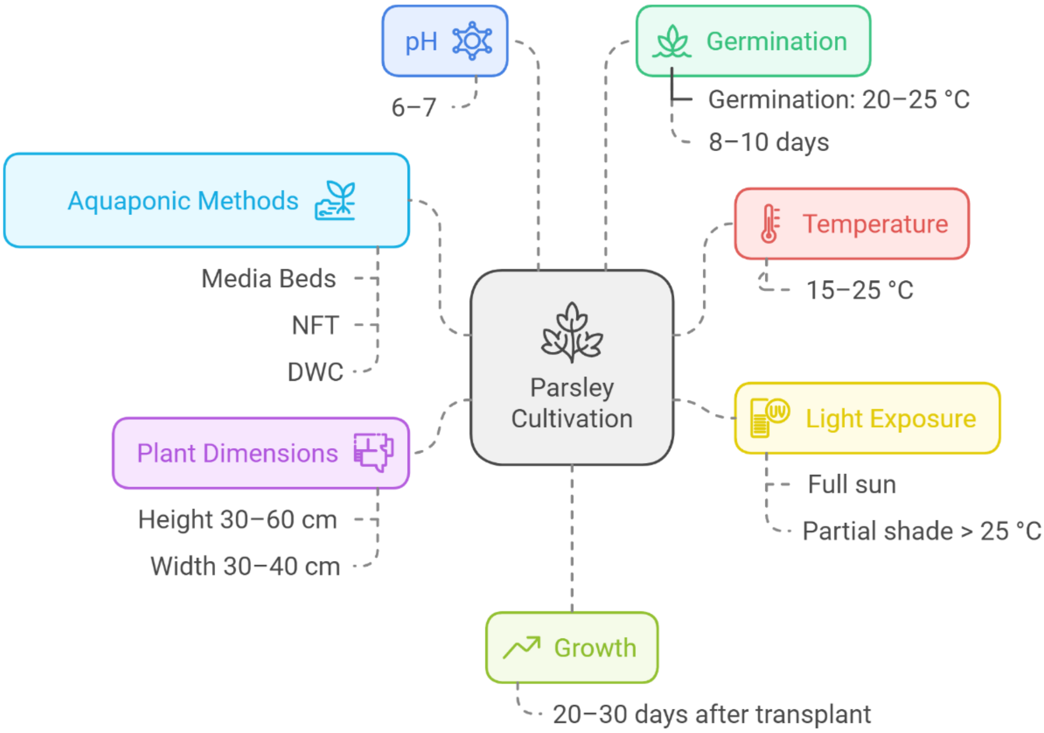
Figure 10. Basil grown in deep water culture.

Harvesting

The harvest of leaves starts when plants reach 15 cm in height and continues for 30–50 days. To do this it is necessary to cut about 5 mm over a node. Care should be used when handling leaves at harvest to avoid leaf bruising and blackening.

It is recommended to excise flowering tips during plant development to prevent bitterness in leaves and promote branching. Basil blooms attract pollinators and beneficial insects; hence, retaining a few flowering plants can enhance the garden's overall health and provide a continuous supply of basil seeds.

Parsley



Growing parsley in aquaponic units

Parsley is a very common herb grown in both domestic and commercial aquaponic units owing to its nutritional content (rich in vitamins A and C, calcium and iron) and its high market value. Parsley is an easy herb to grow as the nutrient requirements are relatively low compared with other vegetables.

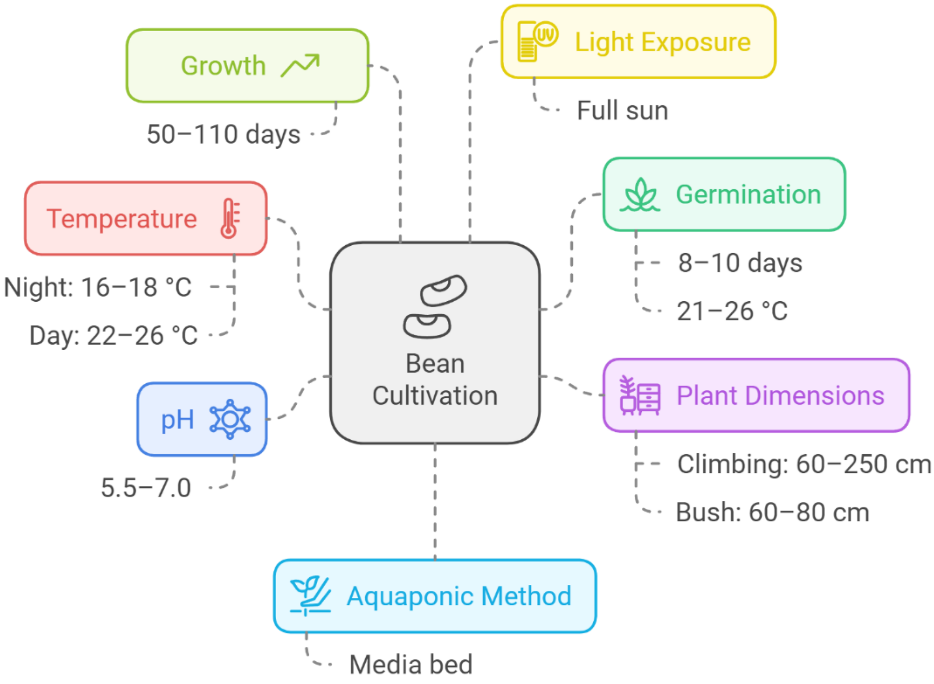
Growing instructions

The main difficulty when growing parsley is the initial germination, which can take 2–5 weeks, depending on how fresh the seeds are To expedite germination, seeds may be immersed in warm water (20–23 °C) for 24–48 hours to soften the seed coats. Subsequently, eliminate the water and plant the seeds in propagation trays. Emerging seedlings will resemble grass, featuring two slender seed leaves positioned opposite one another. After 5–6 weeks, transplant the seedlings into the aquaponic unit during early spring.

Harvesting

Harvesting begins once the individual stalks of the plant are at least 15 cm long. Harvest the outer stems from the plant first as this will encourage growth throughout the season. If only the top leaves are cut, the stalks will remain and the plant will be less productive. The parsley dries and freezes well. If dried, plants can be crushed by hand and stored in an airtight container.

4.5. Beans



Growing beans in aquaponic units
Both climbing and bush bean varieties grow well in aquaponic units, but the former is recommended for less use of space, which maximizes aquaponic bed use. Climbing types can produce 2 to 3 times more pods than bush variants. Beans have little nitrate requirements but possess a moderate necessity for phosphate and potassium. The nutrient requirements of beans render them an optimal selection for aquaponic cultivation, while excessive nitrate levels may impede flowering. Beans are advised for newly built units due to their ability to autonomously repair atmospheric nitrogen.

Growing instructions for pole beans
For media bed units, seed directly into the grow bed 3–4 cm deep (making sure the bell siphon is out so the water level is high during germination). Beans do not transplant well, which makes them hard to grow in NFT pipes. Any supporting pole should be placed before seed germination in order to avoid root damage. In sowing, care should be taken to avoid future cross-shading with other plants. Beans are susceptible to aphids and spider mites. Although low occurrences of such pests could be controlled with mechanical remedies, attention should be paid to the choice of companion plants to avoid cross-contamination if any treatment has to be carried out.

Harvesting
Snap bean varieties (green or yellow wax beans) - Pods should be firm and crisp at harvest; the seeds inside should be undeveloped or small. Hold the stem with one hand and the pod with the other to avoid pulling off branches that will produce later pickings. Pick all pods to keep plants productive.
Shell beans (black, broad or fava beans) - Pick these varieties when the pods change colour and the beans inside are fully formed but not dried out. Pods should be plump, and firm. Quality declines if they are left on the plant for too long.
Dried beans (kidney beans and soybeans) - Let the pods become as dry as possible before cooler weather sets in or when plants have turned brown and lost most of their leaves. Pods will easily split when very dry, making seed removal an easy process.

5. Cultivation practices

5.1. Substrates used for seedlings

Aquaponics is a sustainable agricultural method that combines aquaculture and hydroponics. It depends on the meticulous nurturing of seedlings to promote robust plant development. The selection of substrate and pot type is crucial during the initial phases of plant growth, as it directly impacts the health of the roots, the absorption of nutrients, and the ease of transplanting. This chapter offers an analysis of the various substrates and pot types frequently employed in aquaponics. Its objective is to assist practitioners in making well-informed choices that optimise seedling health and system effectiveness.

Coconut fibre (coir)

Coconut fibre or coir is derived from the coconut industry when the inside coconut is separated from the outside shell. In hydroponics as well as aquaponics it is used due to its fibrous structure, which ensures aeration of plant roots and ability to retain water. The high water retention of coconut fibre allows the young seedling to remain in moisture and helps in avoiding drying out of the young roots while the aeration ability allows the roots to avoid being waterlogged and developing rot.

Coconut fibre is a relatively inert material in the sense that it does not hold a lot of nutrients or pH-varying substances. To avoid this, it is crucial to start supplementing the seedling with the necessary plant nutrients – often mild fertilisers are used or water from the aquaponics systems when appropriate. Compared to other substrates that are mineral-based, coconut fibre is a sustainable material which is renewable and serves as an environmentally friendly alternative.

Coconut coir is highly suitable for a diverse array of seedlings, particularly those that are susceptible to excessive watering. The substrate's capacity to sustain a consistent moisture environment renders it adaptable for aquaponic systems of various sizes, ranging from small to medium-scale. Coconut fibre for seedling is usually in the form of plugs which are sold in large quantities and must be hydrated before use. In many hydroponic and aquaponic systems, these plugs are the preferred media for seedling production. Coconut fibre is biodegradable as opposite to the mineral substrates. Despite this being the most used potting material it has to be noted that the fibres in the plugs are loose and when sufficiently strong water flow is applied to the pot/seedling, the fibrous material can be washed off and carried throughout the system. In cases where the fibres are carried throughout the system, it is advisable to install a mechanical filter to remove them.

Figure 11. Coconut fibre derived from coconut husks, coconut plugs for seedlings.

Perlite

Perlite is a light material with a volcanic origin, it is a glass-like mineral that has been expanded by heating the material. The material is characterised by high porosity; therefore it serves as an excellent medium for root aeration. The characteristic of lightweight and porous structure makes this an excellent substrate for seedlings, which require high oxygenation at the roots. Compared to coconut fibre, which is an organic material, perlite does not decompose or alter the pH of the environment it is placed in, providing stability over several growth cycles.

Perlite, however, has low water retention capacity meaning that the seedling grown in this substrate would require more frequent watering or constant irrigation. For young seedlings, which have not established a proper root system this can be a disadvantage, as more risk of drying the roots and stressing the seedlings can occur. Perlite during the manufacturing process is expanded in heat and may contain small dust particles which could be dangerous when handling the material – the dust particles can be inhaled. Also, these small particles can potentially clog the filters and damage the water pumps in excessive amounts. Avoiding the spreading of dust particles within the system is possible by thoroughly washing the material before use. Perlite is best used in combination with other substrates to provide the porosity and aeration advantages of this material, for example, coconut fibre – this would also provide water retention advantages provided by the coconut fibres. Combining different substrates with perlite gives the advantage of supporting various plant species in the early stages of growth.

Figure 12. Perlite used for seedling germination.

Vermiculite

Vermiculite is a biotite mineral, which, similarly to perlite, is expanded by heating. It is a widely used substrate for seedlings or as a mixing agent for other substrates, however, it can be used as the sole material. Vermiculite has excellent water retention properties, ensuring that seedling roots receive a steady supply of moisture and nutrients. This characteristic is particularly important in the first stages of seedling growth – the high moisture content allows for seeds to imbibe and start growing and later ensures adequate development of the root system. Vermiculite also has the ability to absorb nutrients and ensure slow release for the plant.

Vermiculite is a lightweight substrate, however, over time this substrate can break down and start compacting, thus reducing the aeration potential for the roots. Compacting makes the material dense and potentially creates anaerobic conditions, which can suffocate the roots and cause rotting. When using vermiculite as the sole substrate for seedlings, it is important to ensure proper drainage, since the water retention might cause anoxic conditions. To mitigate the effect of vermiculite compacting it can be mixed with perlite. This combination will provide a balanced environment providing the effects of moisture retention and aeration for healthy seedling development.

Figure 13. Vermiculite used for seedlings and plant transplantation in hydroponic systems.

Rockwool

Rockwool is a man-made substrate created from basalt rock and recycled slag that is spun into fibres at extremely high temperatures. This substrate, due to its uniformity and structure is widely used in large-scale hydroponic and aquaponic systems, among other uses in the construction industry. Rockwool's ability to retain water reduces the need for irrigation during the seedling stage allowing for consistent plant development. Since this substrate is created at such high temperatures it is essentially sterile, which is an advantage as it is free from microbial pathogens and other pests that could potentially harm the seedlings.

Rockwool is a light material, which is easy to handle, however, considering the inherent alkalinity of the substrate, pH must be carefully monitored to avoid nutrient lockout. The transplantation of seedlings that have been grown in rock wool is rather straightforward – the rock wool plugs can be placed into net pots and placed directly into the DWC or NFT systems for further plant development. Rockwool is not biodegradable and there are no current solutions for its recycling, it cannot be reused. Handling of rockwool, especially in large quantities can cause skin irritation since the small fibres can easily detach from the rockwool plugs and plates when being transferred. Considering the advantages and consistency of rockwool substrates they are used in commercial applications for large-scale hydroponic production.

Figure 14. Rockwool cubes used for seedling preparation and transplantation in hydroponic systems.

Peat Moss

Peat moss is a substrate harvested from peat bogs, this is a natural resource and can be found across the Northern Hemisphere, for example in Scandinavia and the Baltics. This substrate has superior water retention, which makes it a suitable material for seedling germination. Peat moss itself contains nutrients, it is a material that is formed from *Sphagnum* moss over an extended period, the nutritional value for plants supports the early development stages. Peat moss is acidic in nature and can lower the pH of the growing environment, in cases where raw peat is used it should be neutralised. Commercially available neutralised peat products are available.

Plants that prefer slightly more acidic soil are usually grown in peat moss substrates. Despite this material being a popular choice for small-scale growers, environmental concerns may arise – peat mining is an unsustainable process which can degrade the peat bog ecosystem. This is a biodegradable material, and it cannot be reused. In a circulating aquaponics system, a small fraction of peat might clog up pumps and other pieces of equipment, so when using this substrate special filters should be set up.

Figure 15. Loose peat moss, peat moss planters and plugs for seedling growth.

5.2. Types of Pots for Seedling Propagation and plant growth in aquaponics

The selection of pots for seedling propagation in aquaponics plays a crucial role in the ease of transplanting and overall plant health. Three primary types of pots are commonly used: net pots, biodegradable pots, and plastic trays, each offering distinct advantages and challenges.

Net Pots

Net pots are small plastic pots with perforated walls that allow water and nutrients to flow freely around the plant's roots. The net pot has an open structure which allows for free aeration thus minimising risks of root diseases and encouraging healthy root growth and development. Net pots are reusable, they can also be sterilised in between the growth cycles providing economic benefits of the use of this type of pot. The primary advantage of net pots is that they are very easy to use, the seedlings that have been prepared in peat or coconut plugs or rock wool blocks can simply be placed into the net pot and transferred to the growth system. The roots grow through the perforated sides of the pot rather easily. The transplantation process does not induce any damage to the plant roots and the open structure of the pot allows for rapid development of the root system once placed in the grow bed, Nutrient Film Technique or Deep-Water Culture. Net pots can be slightly more expensive than biodegradable pots or plastic trays, however, the fact that they can be reused must be considered. Net pots are particularly well-suited for aquaponic systems that involve continuous water flow, such as Nutrient Film Technique or Deep-Water Culture systems, where high root aeration is essential.

Figure 16. Net pots are used in aquaponics and hydroponics in deep water cultures and nutrient film channels.

Biodegradable Pots

Biodegradable pots are made from biomaterials such as peat, coconut fibre, and paper and they offer an environmentally sustainable option for seedling propagation. These pots can decompose naturally over time thus reducing waste and eliminating the need to remove the plant when transplanting into its growth environment. Ideally, biodegradable pots are sturdy enough to withstand soaking water while still keeping the structure, at the same time the pot walls must be fragile enough so that the plant roots can easily penetrate through the walls. The most important advantage of biodegradable pots is their sustainability, however, in excess moisture and increased microbial activity, these pots can degrade too quickly. Biodegradable pots usually hold large amounts of water and if insufficient drainage is possible they can develop mold and start rotting. Biodegradable pots are ideal for seedlings that are to be transplanted directly into media beds or soil, particularly in systems where minimizing environmental impact is a priority. Since these pots degrade so easily and can disintegrate if disturbed, it is not advisable to use used in DWC or NFT systems.

Figure 17. Biodegradable peat moss planters.

Plastic Seedling Trays

Plastic seedling trays are compartmentalised trays for seedling growth. As the name suggests they are usually made out of plastic and can be reused for several growth cycles. Trays can be recycled after the exploitation quality is insufficient, sometimes the seedling trays are made out of recycled plastic. These trays are generally resistant to wear and therefore are used for high-volume seedling production where efficiency and uniformity are necessary. By combining substrate solutions, such as coconut fibre plugs or rock wool blocks with the plastic trays, it is possible to create a streamlined process for seedling production. In such a system large number of seedlings can be propagated simultaneously. One of the main benefits of plastic trays is their ease of handling and the possibility to organise and move the trays efficiently. The limiting factor in such trays is the space within each compartment that is designated for root development. If the seedlings are not transplanted at the right time and left to overgrow it is possible that root-bound seedlings will develop.

Figure 18. Plastic trays used for germination of seeds and seedling preparation.

Choosing the appropriate substrates and pot types for seedling propagation in aquaponics is a multifaceted decision that is influenced by many factors, such as the type of plant, the design of the system, and environmental sustainability. Substances such as coconut coir and vermiculite are preferred due to their ability to retain water, however, perlite and rock wool provide good aeration of roots. The selection of containers, such as net pots, biodegradable pots, or plastic trays, influences the ease of transplanting and the overall health of the plants in the long run.

To achieve the best results in seedling propagation, it is recommended to use a combination of substrates that can effectively maintain moisture while also providing adequate aeration. This approach allows for customisation based on the specific requirements of different plant species. An example of combining coconut coir with perlite is to create a substrate that facilitates both water retention and root oxygenation. Likewise, the selection of a pot should be in accordance with the growing system and environmental factors, such as opting for biodegradable pots in systems that prioritise sustainability.

6. Types of production systems in aquaponics

6.1. Media beds

In aquaponics, media beds are the main production type that allows the growth and stabilisation of plant roots and acts as a biofiltration medium. Media beds are vital to plant growth and system health and can be filled with a variety of substrates, such as expanded clay, gravel, lava rock, and coconut coir. Selecting a media bed substrate is crucial for aquaponic practitioners because it has a big impact on water quality, plant health, and system upkeep. Water from the fish tank is pumped to the media bed on one end and the water flows through the media bed due to an incline, the water is then returned to the sump or fish tank via a collector at the end of a bell siphon or sometimes simply pumped back. Optionally the media bed can be set up as an ebb and flow system where the plant is submerged for a period of time and then drained allowing the roots to breathe (flood-drain cycling). Types of media bed substrates can be evaluated based on their physical properties, impact on water quality, ease of use, cost, and overall performance in aquaponics systems.

Figure 19. Media beds filled with expanded clay, lava rock, gravel and perlite-soil mixtures.

Expanded clay (Lightweight Expanded Clay Aggregate – LECA)

Expanded clay is the most commonly used media bed substrate. It is made from clay that has been heated at elevated temperatures causing it to expand and create a porous structure. This material is rather neutral (pH), easy to reuse and is widely used in small to medium-sized aquaponics systems.

Pros	Cons
Lightweight – LECA is easy to handle and transfer within the system	Cost – more expensive than other substrates
Porous – the pore in this material allows for aeration of roots and water retention	Dust – LECA holds a lot of dust from the production process, to use it must be thoroughly washed to avoid damage to pumps and contamination of the system
Neutral pH – the pH is not affected by this substrate also after prolonged use	Low surface area – Although porous the surface area is low compared to other substrates; less area for bacteria to adhere
Reusability – by washing and disinfecting (with hot water) this material can be reused in multiple growing cycles	

Figure 20. Expanded clay used in aquaponics media beds.

Gravel

Commonly used, inexpensive substrate for media beds composed of crushed granite, quartz, basalt or other minerals. Used in larger systems in outdoor set-ups and greenhouses where durability is crucial.

Pros	Cons

Cost – cheap and readily available	Weight – heavy substrate, might require special reinforced growth media beds
Surface area – some of the minerals have high surface area improving the growth of beneficial bacteria	Changes in pH – some types of gravel can alter the pH, especially limestone-based gravels, pH monitoring becomes more important
Durability – does not break down after several growth cycles, can easily be reused	Damage to plant roots – crushed stones can have sharp edges that can potentially damage plant roots

Figure 21. Different types of gravel used in aquaponics media beds.

Lava rock

Lava rock is a naturally occurring volcanic rock that is highly porous and lighter than gravel. Used in medium to large-scale systems.

Pros	Cons
Weight – lighter than gravel, heavier than LECA	Damage to plant roots – sharp edges, handling can be difficult
Porosity – support biofiltration	Dust – thorough washing before use is needed
Cost – cheaper than LECA, higher surface area	Quality consistency – depending on the source the quality can differ, not a standardisable material
Neutral – does not affect the pH of the system	

Figure 22. Lava rock used in aquaponics media beds.

Coconut fibre

Coconut fibre (coir) is a fibrous material created from the husks of the coconuts, used as growth medium for seedlings as well as in medium beds of various kinds. Most commonly used for seedling, however, sheets of this material can be used in aquaponics systems that produce microgreens.

Pros	Cons
Renewable – a byproduct of coconut industry, environmentally friendly	Structural support – enough support for seedlings and small plants, cannot support larger plants by itself
Water retention – holds moisture well	Decomposition – since this is a material with biological descent, it is biodegradable. The degradation products might clog up parts of system
Neutral – does not affect the pH of the system	Salt content – might require washing before use to avoid unnecessary mineral addition to the system
Weight – light material, easy to handle	

Perlite and Vermiculite

Perlite is a type of volcanic mineral (glass) that expands when heated, while vermiculite is a magnesium-aluminium- iron silicate mineral that is heated to expand. This is a light substrate used in small-scale systems for seed germination, not used for large media beds since it can be easily carried throughout the system due to flaking and having small dust particles.

Pros	Cons
Light – very light material, easy to handle	Erosion – the material can break down into smaller pieces overtime and be carried throughout the system
Aeration –the plant roots are well aerated	Compaction – overtime the material can compact reducing the aeration, material is not reusable therefore
Inert – does not affect the pH or the nutrient contents of water	Cost – while neutral and light the material is more expensive especially when large quantities are needed

Several other media bed materials have been suggested in scientific literature, however, the drawbacks of some of the materials do not put them as perspective substrates to be used in real-life solutions. For example, polonite, is a mineral used in water treatment, particularly for phosphorus removal. This mineral has an alkaline nature, meaning that it can potentially raise the pH of the system to pH 9, which is suitable for neither the fish nor plants. Also, sand has been suggested as a possible material for media beds, however, the compaction of sand does not provide sufficient aeration of the plant roots, and the flow of the water is limited.

6.2. Deep water cultures

Deep water culture (DWC) is a growing system where plants are grown on a floating raft that is made out of Styrofoam or another buoyant material in a large tank of water. The root system in this type of culture is submerged in oxygen and nutrient-rich water. The water in such a system is circulated from one end of the water tank to the other end ensuring that the water in the basin is exchanged frequently. The water from the fish tanks is pumped or fed through gravity to the DWC bed and then recirculated back to the fish tank. Aeration of water under the DWC rafts is ensured by the use of diffusers or air-stones. The plants before placing into the DWC are grown in the substrate, placed in a mesh-pot and then put into the holes of the floating DWC raft.

In this system the roots of the plants are fully submerged in the water therefore constant aeration is crucial to avoid anoxic conditions. Usually, the air-stones or diffusers are placed throughout the DWC basin – lack of oxygenation can cause rot of the roots or other oxygen deficiency-related issues. The increased aeration used in this method is beneficial not only for the plants, but it also ensures that the water is highly saturated with oxygen ensuring fish needs. The large volume of water in this system is beneficial when the nutrient levels fluctuate, the water quantity can act as a buffer. Since the roots are submerged in water, it provides the plant with a constant flow of nutrients. Most commonly different types of salads are grown using this method, however, also tomatoes, cucumbers, and peppers can be grown due to the continuous nutrient flow.

DWC systems are rather straightforward from the complexity point of view, however, the maintenance due to the increased need for aeration can make it more difficult to run. As the roots remain in the water the system is more resilient to power outages and the large volume of water can sustain plant growth for a period. A drawback can be considered the needed volume of water initially to start the system as well as the surface area in which evaporation occurs. Since such a system requires extensive aeration, DWC is more energy demanding than, for example, the nutrient film technique, however, when maintained and balanced, the system can provide higher crop yields, and a larger variety of plants can be grown.

The DWC system offers a flexible and sturdy setting that accommodates various types of plants, including larger ones and those that produce fruits. Aeration necessitates additional water and energy resources, but it provides stability and resilience, making it an ideal choice for cultivators seeking to achieve a wide range of crop production or those with larger-scale systems.

Figure 23. Aquaponics deep water culture channels.

6.3. Nutrient film technique

Nutrient film technique (NFT) is a growing system where the plants are grown in long, narrow channels, usually tubes , with a flow of nutrient-rich water, that continuously flows over the roots in a thin stream. In this system, the plant roots are only partially submerged in the water keeping most of the root system exposed to air. The water from the fish tank (sometimes the sump) is pumped into the NFT tubes and allowed to flow through the set channels back into the sump and then recycled back to the fish tank. Most often this technique is used by creating a vertical stack of tubing pumping the water to the highest point and allowing gravity to feed the lower tubes before returning the water to the sump or fish tank. Similarly to DWC, the plants are placed into net pots that are fitted into the holes made on the top of the flow channel. The roots extend into the channel where they come in contact with the flowing nutrient-rich water. The use of NFT allows for vertical set-up and is lighter in construction than DWC or media beds.

Roots in NFT systems are exposed to air, and only a small part of the root system is submerged in the thin layer of water at the bottom of the channel. The water must be oxygenated as well; however, it is not as crucial as for the DWC. It is advisable to add extra air stones or diffusers at the sump or water collector after the NFT channels to ensure that the water is enriched with oxygen before returning it to the fish tank. The flow of water is much quicker in NFT than it is in DWC, therefore the nutrient uptake by plants can be considered rather efficient – what limits the nutrient uptake is the fact that only a portion of the roots is submerged into the water therefore the whole root system is unable to uptake the nutrients. Comparably the growth rate of NFT plants would be slightly lower than those in

DWC. Plants with smaller and shallower root systems would be more suitable with an NFT system, for example, leafy greens (lettuce, spinach, herbs). Also, larger plants can be grown, however, if the NFT channels are narrow then the root system can quickly overgrow the channel and block the flow and nutrient availability for plants downstream of the NFT channel.

NFT systems are relatively simple and easy to set up and maintain, there is less water as well as pumps or aerators to manage. However, because the water film is so thin and any disruption in the system would mean that the roots of the plants would quickly dry out, backup pumps should be installed together with an emergency off-grid uninterruptible power supply. NFT is more water-efficient than the DWC, relying on quicker re-circulation of the water within the system. Less evaporation occurs in this system since the surface area of exposed water is lower. Considering the need for fewer pumps of different kinds, NFT is also more energy efficient.

NFT is particularly well-suited for cultivating small, rapidly expanding plants such as leafy greens. It provides a high level of efficiency and simplicity, but it necessitates oversight to prevent root desiccation and nutrient imbalances. It is most suitable for cultivators with restricted space and individuals seeking to cultivate particular varieties of crops.

Figure 24. Aquaponics nutrient film channels.

6.4. Drip systems

The drip system is a system where the plant is usually planted into a substrate, most commonly rock wool. A small diameter pipe is connected to a water tank and an automatic watering system is attached to it. A probe with a water outlet coming from the nutrient tank is placed in the rockwool close to the plant's roots. The drop irrigation is not continuous and is activated only several times per hour. Excess nutrient solution drips through the substrate and is gathered for recirculation. As compared to NFT and DWC in this system the roots are never submersed in water.

Drip systems are used in large-scale hydroponic greenhouses where vegetables are grown commercially. Commercially available solutions for systems with thousands of plants are available. Despite the proven efficiency of drip systems in hydroponic-based greenhouses, this system is not necessarily well combined with the aquaponics system as a stand-alone solution. The flowthrough of an aquaponics system is much larger than a drip system can ensure. On the other hand, the flow could be ensured by increasing the number of plants, however, then the nutrient balance would be insufficient for the number of plants. Balancing such a system is not possible, therefore such a system could be used in combination with an NFT or DWC system thus expanding the possibilities and variety of plants that could be grown with an aquaponics system – also plants that do not like so much water could be grown when using drip systems.

7. Plant health and diseases

7.1. Integrated pest management

Integrated pest management or IPM is a sustainable, widely adapted approach to controlling pests and integrates a variety of strategies to minimize the negative effects on the environment, human health and the aquaponics system. Aquaponics is a closed-loop system which consists of plants, fish and microorganisms and the use of synthetic chemicals or pesticides can disrupt one of the elements and thus influence the viability of the whole system negatively. Since 2014 professional plant growers have been encouraged to use the IPM by the Europa Parliament to mitigate the use of pesticides. IPM focuses on the long-term prevention of pests and the damage to the crops they can cause through several approaches – biological control, ecosystem manipulation, farming practice modification and the use of pest-resistant plant varieties. In a closed system, the IPM is especially crucial, since the pests can spread rapidly if not taken care of. Aquaponics in general is slightly more resilient than hydroponics since higher microbial diversity is available in the system influencing the rhizosphere and enhancing the nutrient uptake. Once again, balancing the system can greatly improve the resilience of the whole system help in maintaining healthy crops and improve the cultivation yields.

IPM consists of several mutually beneficial solutions that can increase the productivity and resilience of the system, for example, physical and mechanical solutions (physically fencing the crops from possible influence and introduction of pests), biotechnology-based methods (varieties that are resistant to the most common diseases), biological pest control (use of organisms that are natural predators of the pests in question, and in some cases, as a last resort effort, chemical products. As opposed to organic farming where only natural products can be used for chemical control (inorganics, essential oils, naturally derived constituents) in IPM also synthetic pesticides that are not toxic to other parts of the system (fish, plants, microorganisms) can be used.

Most commonly different plants suffer from microbial pests that cause powdery mildew, for example. Such diseases are carried into the system due to poor hygiene or infected plants/seedlings/seeds that are used within the system. Once such a breakout occurs, it is very difficult to eliminate the cause without discarding the plants, so special care should be taken to choose resistant plant varieties and certified seedlings/seeds from trusted vendors. Insect pests are problematic due to the fact that they cause direct harm to the plants, and they can act as vectors (carriers) of different plant diseases, both viral and microbial. The occurrence of pests in aquaponics and hydroponics systems are benefited from the highly controlled environment within the growth space – the constant temperatures, and moisture. On the other, this same environment allows for the use of beneficial organisms that are natural predators of the harmful insects. For example, ladybird larvae can be used as natural predators against aphids, fly parasitoids can be used against whiteflies, gall midges can be used against aphids and several entomopathogenic nematodes, bacteria and fungi species are beneficial in dealing with pest breakouts.

Due to the density of fish and plants in aquaponics, the spread of disease can happen rapidly. If the disease or the spread of pests has not been treated in time, likely, the whole part (fish, plants or microbiome) of the system should be discarded or chemically treated. In such cases, the system balance is interrupted, and it can take a long time to reach the balance again, therefore the IPM should be applied proactively to avoid system disruption.

Prevention methods in IPM include –

- → Physical barriers and traps
    - Nets to prevent insects from moving within the greenhouse/room where the aquaponics system is set up
    - Sticky fly traps
    - Separating the different compartments of the system
- → Water treatment
    - If appropriate using the UV, ozonation
    - Heat treatment of water
    - To promote plant and microorganism growth the system can be supplied with soluble fertilisers
- → Hygiene
    - Sanitation of the equipment
    - Personal hygiene of the employees
    - Clothing of the employees
    - Rules for the hygiene of visitors, protective clothing
    - Disinfection in between crop rotations
    - Disinfection of tools
- → Environmental conditions
    - Humidity adjusted for cultivation
    - Temperature adjusted for cultivation
    - Ventilation
- → Agricultural practices
    - System balance to provide optimal nutrition to plants
    - Plant spacing
    - Tolerant and certified seed material or seedlings
    - Separate rooms for germination and cultivation
    - Regular monitoring of plants
    - Grafting
- → Disease and pest-suppressing organisms
    - System balance to aid beneficial bacteria
    - Insects that are natural predators of pests
    - Companion planting
    - Use of natural pesticides if needed

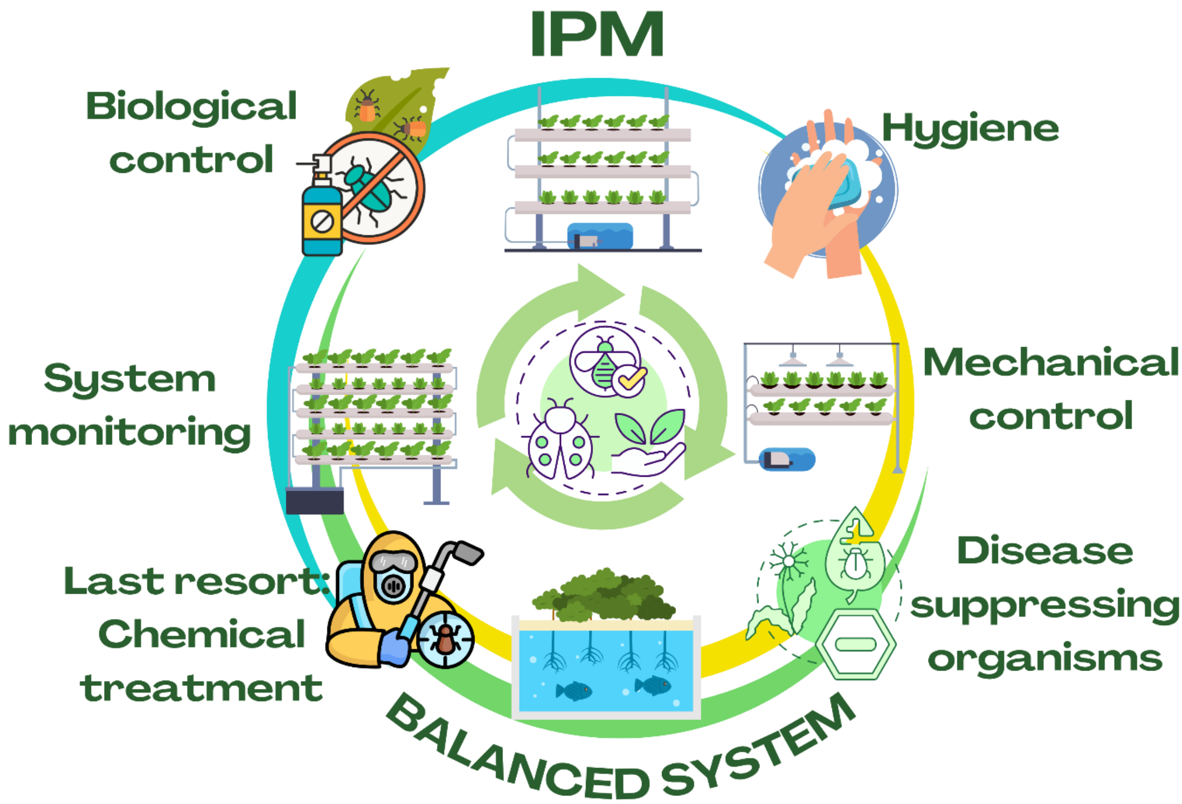


Figure 25. The most important factors for implementation of integrated pest management.

Interventions involving chemical goods may be warranted; however, severe rules must be taken into account. Botanical pesticides should be prioritised whenever feasible, as they are derived from biological sources. Certain extracts from microorganisms are safe for fish and can be utilised in aquaponics. One is a toxin derived from *Bacillus thuringiensis*, effective against caterpillars, leaf rollers, and other lepidopteran larvae. Another is *Beauveria bassiana*, a fungus that penetrates the insect's integument and is efficacious against various pests, including termites, thrips, whiteflies, aphids, and beetles. Numerous chemical synthetic fungicides and insecticides, as well as certain products authorised in organic agriculture, are toxic and detrimental to aquatic organisms. An application is only advisable for young plants before their transplantation into the aquaponic system. If chemical control is the final option, the specific toxicity of the product to fish must be meticulously evaluated. Aquaponics is a sophisticated ecosystem comprising various bacteria, fungi, and higher species, exhibiting significant potential for natural power resistance. Maintaining the natural balance of this environment through appropriate preventive actions, as previously outlined, is essential. This should minimise the need for direct pest management approaches.

7.2. Pests and diseases

Plant pests in aquaponics

Aphids (Aphidoidea)

Aphids are small, soft-bodied insects that frequently infest aquaponics systems by consuming plant sap. They can proliferate swiftly and establish extensive colonies that undermine plants by depleting them of vital nutrients. Aphids are typically located on the undersides of leaves or the apices of growing plants. Aphids in aquaponics can lead to issues including the transmission of plant viruses and the inhibition of plant growth. Effective control measures encompass the introduction of beneficial insects, such as ladybugs, or the application of organic insecticidal soaps, ensuring their safety for the aquatic life within the system.

Figure 26. Aphids on plant stems and under the leaves.

Whiteflies (Aleyrodidae)

Whiteflies are another prevalent pest in aquaponics, particularly in warm and humid conditions. These tiny, winged insects consume plant sap and excrete honeydew, fostering the proliferation of sooty mould. Whitefly infestation can result in stunted plant growth, chlorosis of leaves, and diminished yields. They may also serve as vectors for plant diseases, disseminating detrimental pathogens among plants. Aquaponics employs adhesive traps, biological controls like parasitic wasps, and adequate air circulation in the cultivation area to mitigate humidity.

Figure 27. Whiteflies on the plant leaves.

Spider mites (Tetranychidae family)

Spider mites are small arachnids that can pose a significant threat to aquaponic systems, particularly in arid and elevated temperature environments, typically when plants requiring higher temperatures are grown. They typically construct webs on the undersides of leaves, where they extract nutrients from plant cells by puncturing the tissue and syphoning the cellular contents. Spider mite infestations cause leaves to become mottled or crunched, ultimately leading to yellowing and abscission. These pests are challenging to manage because of their swift reproductive cycle. Aquaponics can be regulated through the utilisation of natural predators, such as predatory mites (*Phytoseiulus persimilis*), and by sustaining appropriate humidity levels to establish less conducive conditions for their proliferation.

Figure 28. Spider mite colonies and their webs on plant leaves.

Thrips (Thysanoptera)

Thrips are diminutive, elongated insects that feed by puncturing plant cells and extracting their contents. They exhibit significant mobility and can disseminate rapidly throughout an aquaponics system. Thrips damage manifests as silver streaks or spots on foliage, and severe infestations can inhibit plant growth and diminish yield. Besides causing direct harm, thrips are recognised for their role in transmitting plant viruses. To manage thrips in aquaponics, cultivators frequently employ predatory insects like minute pirate flies (Orius spp.) and utilise reflective mulch to deter them.

Figure 29. Thrips in the core of the plant and on the leaf surface.

Fungus gnats (Sciaridae)

Fungal larvae are diminutive, dark flies commonly present in aquaponics systems characterised by elevated humidity levels. Their larvae consume organic matter, including plant roots, which can inhibit plant growth and heighten vulnerability to root diseases. Fungal larvae can disseminate plant pathogens, including Pythium, responsible for root rot. Ensuring adequate water drainage, minimising organic debris accumulation, and employing biological controls like beneficial nematodes (*Steinernema feltiae*) are essential for managing fungus gnats.

Figure 30. Fungus gnats on sticky trap surface and on plant leaves.

Leaf miners (Agromyzidae)

Leaf miners are the larvae of diverse insects, typically flies, that penetrate plant leaves and consume the tissue between the layers. This leads to discernible wavy markings or blemishes on the leaves, which may diminish photosynthesis and compromise plant vitality. While leafminer damage seldom results in plant mortality, it can diminish crop quality and yield. In aquaponic systems, leaf beetles are typically managed through biological controls like parasitic wasps (*Diglyphus isaea*) or neem oil, both of which are safe for fish and plants.

Figure 31. Damage to the leaves by leaf miners.

Plant diseases in aquaponics

Powdery mildew (Erysiphales)

Powdery mildew is a fungal affliction marked by the presence of white, powdery lesions on the surfaces of plant foliage. Aquaponics typically impacts plants cultivated in humid conditions with inadequate air circulation. While powdery mildew is not immediately lethal to plants, it can compromise their vitality by disrupting photosynthesis, leading to diminished growth and yield. To avert powdery mildew, it is essential to regulate humidity levels, ensure adequate spacing between plants for optimal air circulation, and apply organic sulphur-based fungicides as needed. Introducing advantageous fungi that compete with powdery mildew can also enhance aquaponic systems.

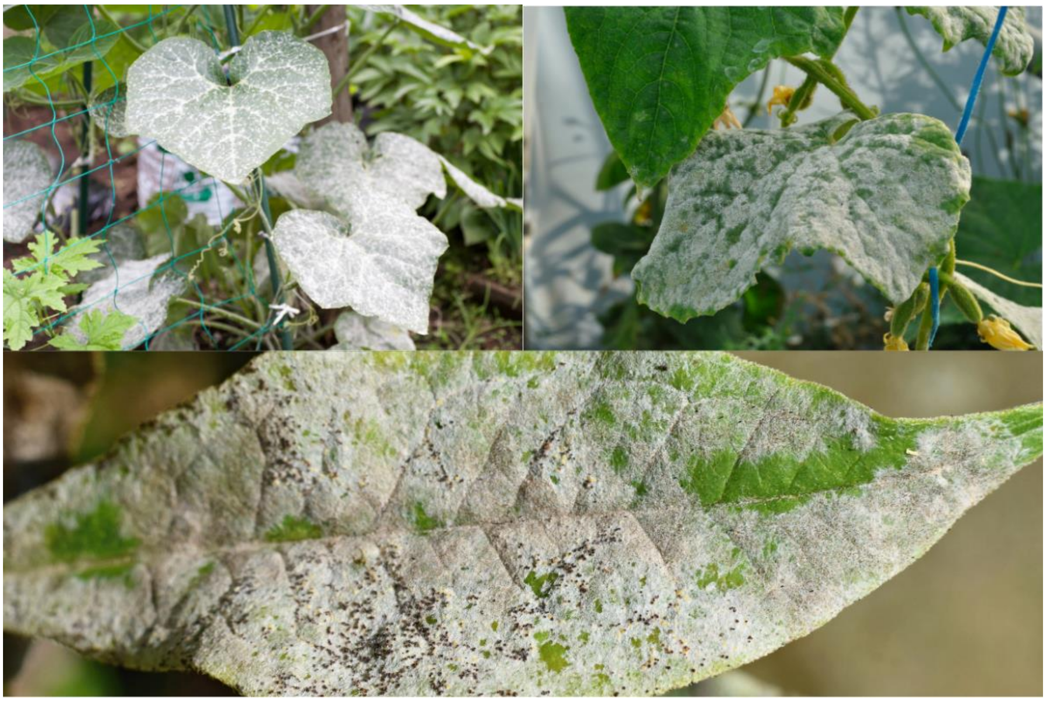


Figure 32. Powdery mildew-infested leaves.

Root rot caused by Pythium species.

Root rot, frequently induced by waterborne pathogens like Pythium, is among the most severe diseases affecting aquaponics. It transpires when plant roots are subjected to overly saturated conditions that induce decay. Infected roots become brown and crustaceous, resulting in stunted growth and wilting of plants. Root rot can rapidly disseminate throughout an aquaponic system, impacting numerous plants simultaneously. Prevention entails sustaining optimal water quality, ensuring proper aeration in the root zone, and preventing excessive watering. Beneficial microorganisms like Trichoderma can assist in managing Pythium in aquaponic systems.

Downy mildew (family Peronosporaceae)

Downy mildew is a fungal-like affliction that impacts aquaponic vegetation, particularly leafy greens such as lettuce and basil. It flourishes in cool, humid environments and presents as yellowish lesions on the upper surface of leaves, accompanied by fuzzy grey or white growths on the underside. Downy mildew can inflict considerable harm on crops, leading to hindered plant growth and diminished yields. To mitigate the dissemination of the disease, management of downy mildew entails enhancing air circulation, decreasing humidity, and eliminating infected plant matter. Copper-based fungicides, deemed safe for aquaponic systems, can aid in the prevention of disease outbreaks.

Figure 33. Downy mildew infestation on plant leaves and fruit.

Bacterial leaf spot caused by Xanthomonas species.

Bacterial leaf spot is a disease induced by bacteria of the genus Xanthomonas, impacting various plants, particularly green foliage and herbs. It appears as diminutive, water-saturated lesions on foliage that ultimately become brown or black. The disease can disseminate swiftly, particularly in high humidity conditions, and significantly impact plant health. In aquaponics, bacterial leaf spot can be mitigated by refraining from overhead irrigation, adequately spacing plants to facilitate air circulation, and employing copper-based bactericides. Consistent system cleaning to eliminate plant debris is crucial for preventing bacterial proliferation.

Figure 34. Bacterial leaf spot damage on plant leaves.

To minimise the risk of illnesses and pests in aquaponics, it is vital to keep the ecosystem in a state of equilibrium and good health. This begins with the correct design of the system, which includes providing appropriate ventilation, controlling humidity, and maintaining a sufficient distance between plants in order to avoid the spread of airborne and fungal infections. When water quality factors such as pH, ammonia, nitrites, and dissolved oxygen are monitored, it helps avoid stress in both plants and fish, which in turn reduces the vulnerability of these organisms to different infections. To efficiently control pests without causing any damage to the fish or plants, it is possible to use integrated pest management (IPM) strategies. These activities include the introduction of beneficial insects (such as ladybirds or predatory mites) and the utilisation of organic therapies such as neem oil. When it comes to preventing disease outbreaks, it is essential to do routine inspections of fish and plants, as well as to remove diseased items as soon as possible. Several solutions to fight these mentioned pests and diseases exist, however, it has to be carefully evaluated whether the use of them is really necessary and whether the synthetic pesticides are certified for use in an aquaponics system. The quarantining of new plants and fish, the maintenance of system cleanliness, and the management of waste buildup are other important responsibilities in decreasing the danger of illness and ensuring that an aquaponic ecosystem provides a flourishing environment.

Pathogens affecting fish

In aquaponics, plants face threats from pests and diseases, while the aquatic organisms in the system are likewise vulnerable to pathogens. In aquaponics, fish ailments encompass fungal infections, parasitic infestations (such as Ich), and bacterial diseases like columnariasis. Ensuring optimal water quality is essential for mitigating stress in fish, thereby preserving their immune function and reducing their vulnerability to disease. Standard preventive measures encompass isolating newly acquired fish, sustaining ideal water temperatures, and minimising ammonia and nitrite concentrations. Consistent observation of fish behaviour and physical health can facilitate the early detection of disease symptoms. More information on fish pathogens can be found in the TransFarm report “Fish in aquaponics – selection, requirements and limitations”.

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