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DEVELOPMENT OF A PILOT PLANT OF AN AQUAPONICS/HYDROPONICS SYSTEM FOR THE REDUCTION OF FERTILIZER REQUIREMENTS IN CROPS AND PARTIAL PURIFICATION OF LOW-LOAD WASTEWATER.

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I. ABSTRACT

Aquaponics is the combined culture of fish and plants in closed recirculating systems. Aquaponics is a technique for the production of plants and fish in a closed circuit without the use of soil, meaning it is based on the techniques of aquaculture and hydroponics combining their advantages and avoiding the inefficiencies that these techniques have separately. It takes advantage of hydroponics of being a closed circuit for the reduction of water consumption and it avoids the use of fertilizers present in hydroponics and the overfeeding that happens in aquaculture. This technique is possible thanks to the symbiosis that occurs between fish and plants. [1]

The remains of uneaten food, respiration, and fish waste produce ammonia, which is transformed by bacteria into nitrites and then into nitrates, a process necessary to convert these toxic compounds for both fish and plants into nutrients for the plants.

In this study a pilot system has been designed and built, implementing a 1000 L IBC tank, a 1000 L radial flow filter, a tank to regulate the water level and three culture techniques, which are **Deep Water Culture** (DWC), **Nutrient Film Technique** (NFT), and **Media Bed**. The most significant water parameters were closely monitored by measuring them weekly to regulate the evolution of the plant.

Analyses revealed that the ratio between the initial number of fish and plants was not optimal. Thus, the plants grew healthy and rapidly during the first few weeks, but the amount of fish in the system appeared to be insufficient to produce the necessary nutrients, and the plants began to deteriorate. This was partially solved by growing the fish and reducing the amount of plants in the system.

The project had an estimated budget of 16 000€. The construction itself, without considering work time, had a cost of 1 900€.

II. RESUMEN

La acuaponía es el cultivo combinado de peces y plantas en sistemas cerrados de recirculación. La acuaponía es una técnica de producción de plantas y peces en un circuito cerrado sin el uso de tierra, es decir, se basa en las técnicas de acuicultura e hidroponía combinando sus ventajas y desechando las ineficiencias que tienen estas técnicas por separado, entre otras aprovecha la ventaja de la hidroponía de ser un circuito cerrado para la reducción del consumo de agua y evita el uso de fertilizantes presentes en la hidroponía y la sobrealimentación que sucede en la acuicultura. Esta técnica es posible gracias a la simbiosis que se produce entre peces y plantas. [1]

Los restos de comida no consumida, la respiración y los desechos de los peces producen amoníaco, por medio de unas bacterias, este es transformado en nitritos y posteriormente en nitratos, proceso necesario para convertir estos compuestos tóxicos tanto para peces y plantas en nutrientes para las plantas.

En este estudio se ha diseñado y construido un sistema piloto, implementando un tanque IBC de 1000 L, un filtro de flujo radial de 1000 L, un depósito para regular el nivel del agua y tres técnicas de cultivo, que son el **modelo de raíz flotante**, **de film nutritivo** y **lecho de substrato**. Los parámetros más significativos del agua se controlaron estrechamente, midiéndolos semanalmente para regular la evolución de la planta.

Los análisis revelaron que la proporción entre el número inicial de peces y plantas no era óptima. Así, las plantas crecieron sanas y rápidamente durante las primeras semanas, pero la cantidad de peces en el sistema parecía no ser suficiente para producir los nutrientes necesarios, y las plantas comenzaron a deteriorarse. Esto se solucionó parcialmente mediante el crecimiento de los peces y la reducción de plantas en el sistema.

El proyecto tenía un presupuesto estimado de 16 000 euros. La construcción en sí, sin tener en cuenta el tiempo de trabajo, tuvo un coste de 1.900 euros.

CONTENTS

1.- INTRODUCTION

Traditional agriculture is responsible for 70% of freshwater consumption. This is because traditional agriculture techniques are very inefficient when it comes to water usage. Most of the water used to nourish the plants is absorbed into the ground and lost. The Figure 1.1 shows a method of irrigation on traditional agriculture. In addition to the water consumption, traditional agriculture implements a high amount of chemical and artificial substances necessary to feed the plants (fertilizers and pesticides), and these substances can be harmful for the human consumer or for the safety of the biomass of the ecosystem. [2,3]

Figure 1.1 Agricultural sprayer – Orange [4]

In aquaculture antibiotics are used, while in aquaponics they cannot be used because of the health of the plants and the existence of the bacterial colony that allows the nitrification process, this prevents consumers from developing resistance to antibiotics. [5]

Another problem in aquaculture is the overfeeding that is carried out in these systems because regardless of being developed in salt or fresh water, they are open systems where water is not recirculated and therefore it must be overfed to ensure that all fish have access to food, this leads to the contamination of rivers or seas where these systems are implemented, it should be noted once again that this does not happen in aquaponics. [6,7]

Aquaponics is a closed loop system, as illustrated in Figure 1.2, that maximizes the reuse of water, minimizing its consumption down to 10% of what is used in traditional agriculture. The reduction of water consumption, the non-use of fertilizers and pesticides and the greater control over the food supplied result in a lower impact on the environment making aquaponics highly efficient. To sum up, aquaponics is based in nature, in water cycles and trophic networks; it presents the perfect symbiosis between fish and plants in a closed recirculating water system, combining aquaculture and hydroponics. [8]

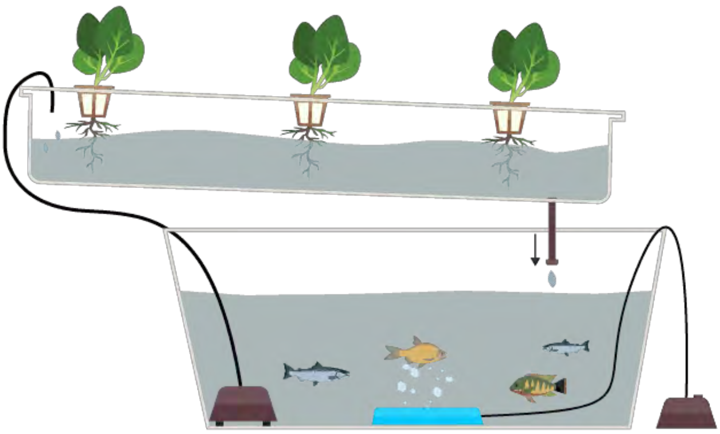

Figure 1.2 Aquaponic tank - A Complete Guide to Aquaponic Gardening. [9]

This technology makes it possible to bring food, optimize production and increase the profitability of arable land anywhere in the world. It is potentially revolutionary when we talk about third world countries that do not have fertile land for growing vegetables or that are subjected to adverse weather conditions, such as droughts, floods, tornadoes, etc., among other factors. Aquaponics allows these communities to use a very small amount of water (<10%) compared to traditional crops, to obtain food sovereignty so as to stop depending on the price requested by large food importers and to get closer to meeting some of the Sustainable Development Goals (SDGs): 1º no poverty, 2º zero hunger, 8º decent work and economic growth, 9º industry, innovation and infrastructure, 11º sustainable cities and communities, 12º responsible consumption and production and 13º climate action. [10]

The communities will benefit from the production of vegetables and fish breeding in the proximity of the urban center, thus reducing transportation costs and dependence on it and being connected to a road we ensure that we can have a continuous flow of supplies whenever necessary.

Supply of vegetables and fish as a means of food, creation of jobs, commercialization of the surplus of local consumption, independence of the climatic conditions to carry out the cultivation, thus allowing the communities a new security against adverse conditions/situations that they may suffer in relation to the lack of supply of goods, droughts or possible floods, among others.

Aquaponics, besides being profitable, is sustainable and environmentally friendly, a very important factor in third world countries where many rivers or lands are polluted due to a bad use of pesticides, fertilizers and industries with little or no respect for the environment.

1.1.- Origin of aquaponics

Nowadays there is no official agreement on the specific origin of aquaponics. Many authors attribute it to the Aztecs, based on the development on “chinampas” (view Figure 1.3), which are basically artificially originated agricultural islands. In this chinampas, crops were produced on islands, which were surrounded with canals where fish were bred. This way, these chinampas can be considered as big dimension aquaponic systems. However, other authors opt to attribute the origin of aquaponics to China or Thailand, where rice has been cultivated for a very long time, and fish are bred among the rice fields. In these fields (view Figure 1.4), fish used had the function of fertilizing fields with their solid waste, in addition of eating insects that might eat the crops or mosquito larvae that could otherwise be in the crops and would be harmful for their consumption. [11,12]

Figure 1.3 Chinampas Representation- A.C. (n.d.) [13]

Figure 1.4 Rice fields - MiRiego (n.d.) [14]

1.2.- Aquaponics' future

Modern aquaponics has emerged as a solution to the increasing demand for food production due to the growth of human population, the world's population has increased by 90% in the last 25 years, the demand for food is expected to expand up to 50% to 70% by 2050. [15]

Technology allows the development of different advances in this technique, such as aeroponics (Figure 1.5) that allows the production of vegetables with a minimum consumption of water and space, implementation of mineralization tanks to take the maximum amount of nutrients possible or the publication of new scientific studies. that. Studies of the optimal pH for fish and plants, the amount of nutrient concentration needed by each type of plant or the implementation of pure oxygen to increase the amount of fish in the system and improve productivity are studies that help us to optimize the system. It is a growing technology as Figure 1.6 suggests the increasing trend in the number of scientific publications. [16]

Figure 1.5 Aeroponics vertical farming - Germán Portillo [17]

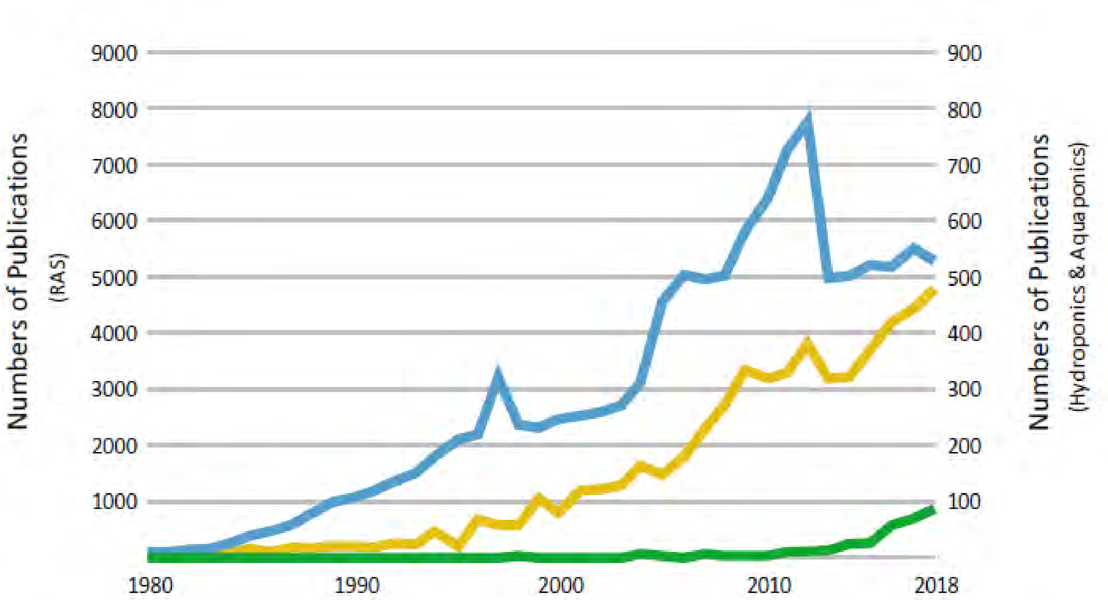

Figure 1.6 Graph showing the increasing trend in the number of scientific publications on aquaponics (green), hydroponics (yellow) and RAS (blue). [16]

An important factor in the future of this technique is that since it is a new farming method it does not have a favorable legislation since it is a combination of aquaculture and agriculture, these have different and sometimes contradictory legislations that do not help the producers and new entrepreneurs who develop these systems. [16]

1.3.- Advantages and disadvantages of aquaponics

Considering that there are technologies that produce fish and plants separately at high rates (RAS-Recirculating aquaculture systems and hydroponics), it is appropriate to combine them, giving rise to aquaponics. [18]

In RAS systems, water must be renewed to avoid a high concentration of biomass (nitrogen compounds) obtained from fish waste, which is toxic in high concentrations, these nitrogen compounds that are waste in aquaculture in aquaponics are used as a source of food for plants, generating a negative impact close to zero in the ecosystem. Therefore, aquaponics is known as a sustainable and environmentally friendly farming technology. In addition, water must be exchanged to release these wastes making aquaponics 90% more efficient in relation to water usage than aquaculture. The Figure 1.7 shows the design of an recirculating aquaculture system (RAS). [19]

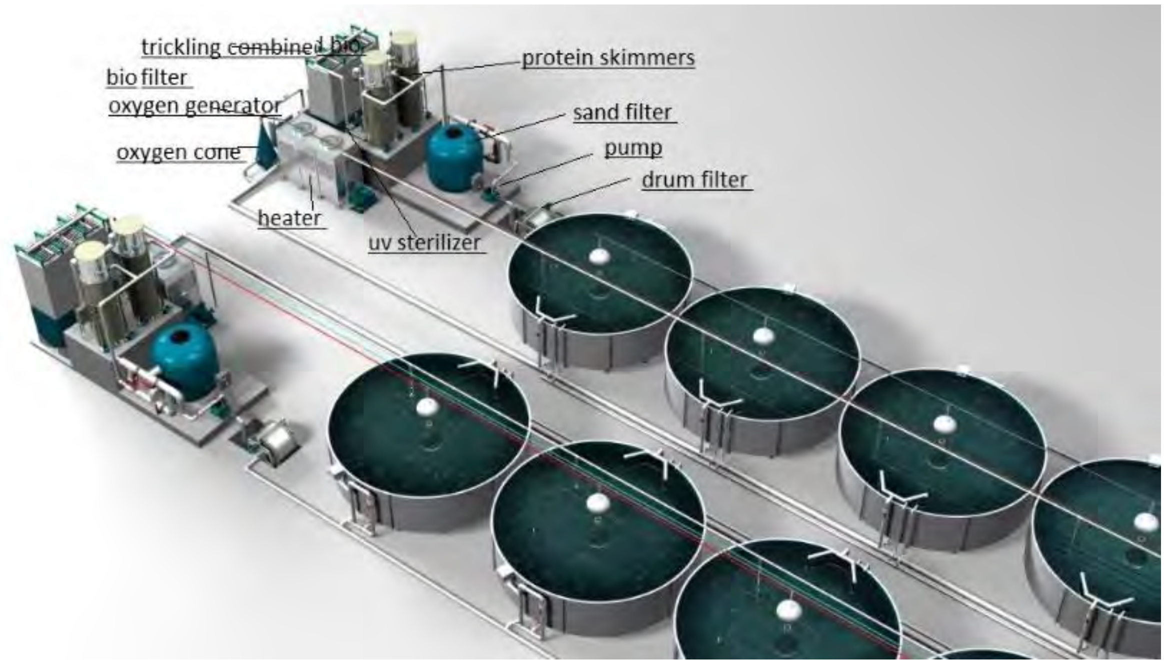

Figure 1.7 Representation of a RAS-Recirculating aquaculture systems [20]

Another advantage is the possibility of growing plants soil-less thanks to hydroponics, which allows us to grow in places where it was previously unthinkable, such as desert areas or areas with adverse environmental conditions, without having to worry about soil quality. [21]

Traditional agriculture uses techniques such as fallow to renew the nutrients present in the soil, allowing crop concentrations between 6 and 8 plants per square meter while in hydroponics / aquaponics there is no need for this time of preparation of the soil and we can cultivate all year round to obtain concentrations up to 25 and 30 plants per square meter, enabling us to grow more in less space. [22]

As aquaponics does not depend on fertile land, this technique offers us the possibility of cultivating in places where it was not possible before, such as inside cities or on the roofs of supermarkets, as shown in the Figure 1.8, among others, making the proximity to the consumer another advantage. Besides avoiding burning fossil fuels for the transportation of inputs to the cities and post-harvesting damages in the transportation process and obtaining better quality and fresher products.

Figure 1.8 Rooftop farm in Singapur – Comcrop [23]

Some disadvantages of aquaponics are the relatively high initial cost and the knowledge you need to initiate the system. There still is a lot of investigation and standardization needed on this subject, and these systems are relatively more complex compared to other productive systems, since there is need to be vigilant of both fish and plants. The complexity of this practice might be an obstacle for a new user, as some training is needed.

Aquaponics starts to be considered an efficient fish and plants production system, especially useful for places where the access to this food is limited or the access to water is difficult. Being the concept of aquaponics perfectly developed, in the nineteen-nineties (90s) different models were optimized to be put into practice. One of the most extended ones was that of James Rakocy, an investigator from the University of the U.S. Virgin Islands, who is nowadays considered the father of modern aquaponics. His model, a system called UVI, shown in Figure 1.9, is currently the most extended worldwide. [16]

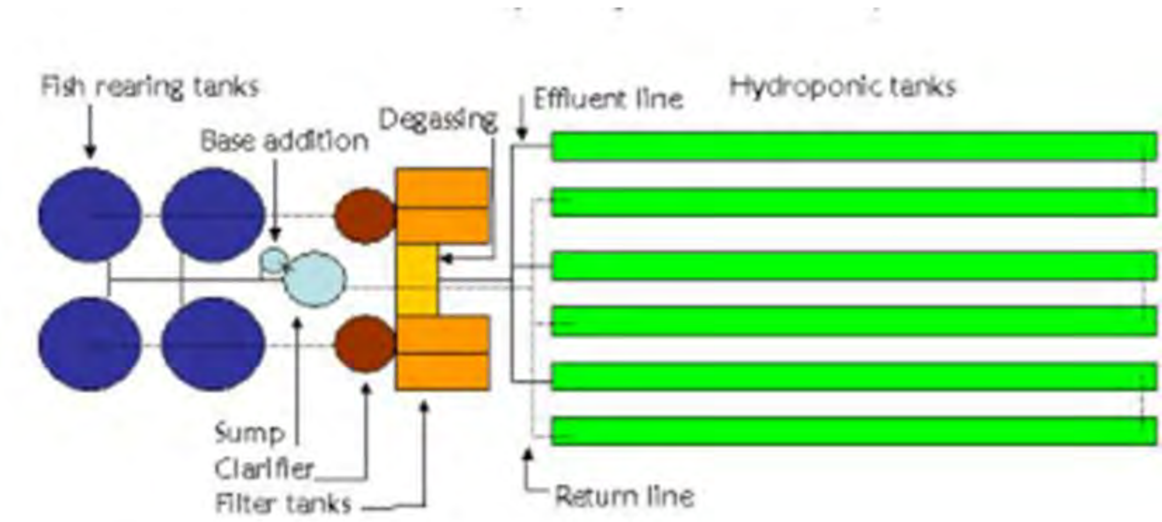

Figure 1.9 UVI aquaponic system – University of the Virgin Islands [24]

The UVI system is grossly composed of three subunits: fish tanks, the spaces designated for biofiltration and water cleaning, and hydroponic canals. In an aquaponic system, the water completes a continuous cycle, running through a closed system, from the fish tank, then being mechanically and biologically filtered and finally nourishing the plants before going back again into the fish tanks.

In hydroponic plants, it is necessary to add mineral fertilizers to obtain plant nourishment and growth, such as nitrate, phosphate, potassium among others. Meanwhile, in aquaculture it is necessary to perform regular water changes, usually daily, to control the accumulation of waste derived from fish feed and depositions. Combining both techniques, aquaponics seeks to generate a system that takes advantage of the benefits while minimizing some of the most important disadvantages of each practice. [25,26]

1.4.- Water quality parameters and treatments

Both nitrification and denitrification process are important for the biological treatment of tributaries. Nitrites and nitrates turn into nitric oxide (NO) and nitrous oxide (N_2O), which finally turns into nitrogen gas, suitable for an innocuous evacuation to the atmosphere. These processes occur in the following way:

1.4.1.- Nitrification process

Fish release ammonia into the water through their respiration and wastes, which can be directly absorbed by plants in certain amounts but is very toxic for fish at very low levels. [27]

The Figure 1.10 illustrates the nitrogen cycle in an aquaponic system. It consists in the biological oxidation of ammonium into nitrate by aerobic microorganisms that use molecular oxygen (O_2) as electron receptor, meaning oxygen works as an oxidant. Ubiquitous bacteria species replace hydrogen ions with oxygen ions, producing nitrate from ammonia. Nitrate is far less toxic for fish than ammonia and is the preferred source of nitrogen for plants. [28]

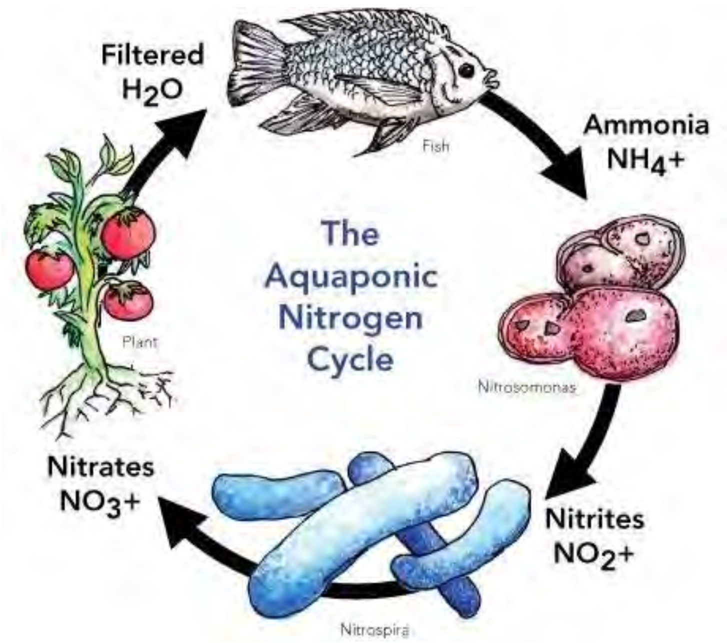

Figure 1.10 Aquaponic Nitrogen Cycle-Hungerford [29]

Nitrifying (autotrophic) bacteria play a very important role in an aquaponic system. These bacteria turn fish excretions, which enter the system as ammonia, into nitrates, which fertilize plants. Nitrification in aquaponics is a two-step process and involves two types of nitrifying bacteria:

I. **Conversion of ammonia into nitrites**

   This process is developed by Nitrosomonas. When there is an overload of food waste, an excess of ammonia appears in water. The Nitrosomonas bacteria convert ammonia into nitrites. Nitrites are toxic for the fish, and therefore it is not desired for these to stay in the system. [30]

II. **Conversion of nitrites into nitrates**

   This process is developed by Nitrobacter. These bacteria feed on nitrites which are converted into nitrates after being consumed by Nitrobacter. Plant growth is stimulated when they absorb nitrates. An excess of nitrites can be harmful for fish, to keep plants and fish healthy, nitrites must be turned into nitrates. [30]

Nitrifying bacteria take time to reproduce and stablish colonies; this process could take days, weeks or even months. These bacteria are strictly aerobic since the process is basically an oxidation.

Ammonia-Nitrogen (NH_3-NH_4^+) + BACTERIA + O_2 → NO_2^- + BACTERIA + O_2 → NO_3^- [31]

1.4.2.- Denitrifying process

Denitrifying process consists in the conversion of nitrates into nitrogen gas by heterotrophic bacteria, in absence of oxygen and presence of organic carbon (anaerobic conditions). Nitrate serves as an oxygen acceptor. De-nitrification requires an oxidable substrate that acts as a source of energy; hence it can be developed by both heterotrophic and autotrophic bacteria. [31]

On his research "Aquaponic System Design Parameters: Fish to Plant Ratios (Feeding Rate Ratios)", 2012, Dr Lennar explains that in systems that implement media beds, these serve as a mechanical filter, screening solid waste from the fish, which can present a risk. This portion of the bed could convert to an anaerobic phase if the beds are not designed and sized correctly to handle and adequately treat the accumulated fish solids using an aerobic (oxygen rich) approach. Anaerobic conditions surge with very low (close to zero) oxygen concentration, anaerobic bacteria will process fish waste solids from the inside mass to the outside. In his method, Dr. Rakocy uses a controlled anaerobic denitrification, as the netting containing the de-nitrifying bacteria can simply be removed from the system and cleaned if desired. [32]

Zones of anaerobic activity in the system produce denitrification, which produces alkalinity, causing the pH to rise. If the pH is too high, it can be necessary to add an acidic agent.

If the addition of pH lowering agents is necessary in an aquaponic system, it can be a sign that anaerobic conditions are prevailing, meaning the solids entering the system are not quicky and efficiently broken down and mineralized. [32]

The overall chain of nitrogen species associated with de-nitrification may be represented as following:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

1.4.3.- Filtration mechanisms

Both mechanical and bio-filtration play a vital role in the system as these two processes make it possible to achieve healthy levels in the different parameters of the water.

Mechanical filtration is essential in any type of recirculating water system to allow the separation and removal of suspended solids, whether these are floatable or not, generating a series of objectives and benefits. These suspended particles are mainly composed of fish fecal matter and feed remains, as well as other microorganisms, such as bacteria, fungi and algae that develop in the system. Suspended particles vary in sizes from micrometers up to centimeters and have different densities, which distributes them among different heights in the system´s water. Generally, a sedimentation method is used for large particles (over 100µm) and other types of mechanical filtrations take care of smaller particles. [16]

Solid waste, if not removed from the system, could expel toxic gases by accumulating and being decomposed by anaerobic bacteria (de-nitrification), and these solid particles could also reach the roots of the plants, clogging them and this way avoiding a correct nutrient absorption. Apart from removing solid waste, mechanical filtration fulfills the purpose of retaining and periodically accumulating them in a determined sector where mineralization will naturally begin. [30]

There are several types of mechanical filters but the most used are the radial flow filter and the swirl filter, the schematics of these filters can be seen in Figure 1.11, because the mechanical filters normally used in aquariums composed of sponges that retain solids, collapse easily due to the high amount of fish waste found in these systems.

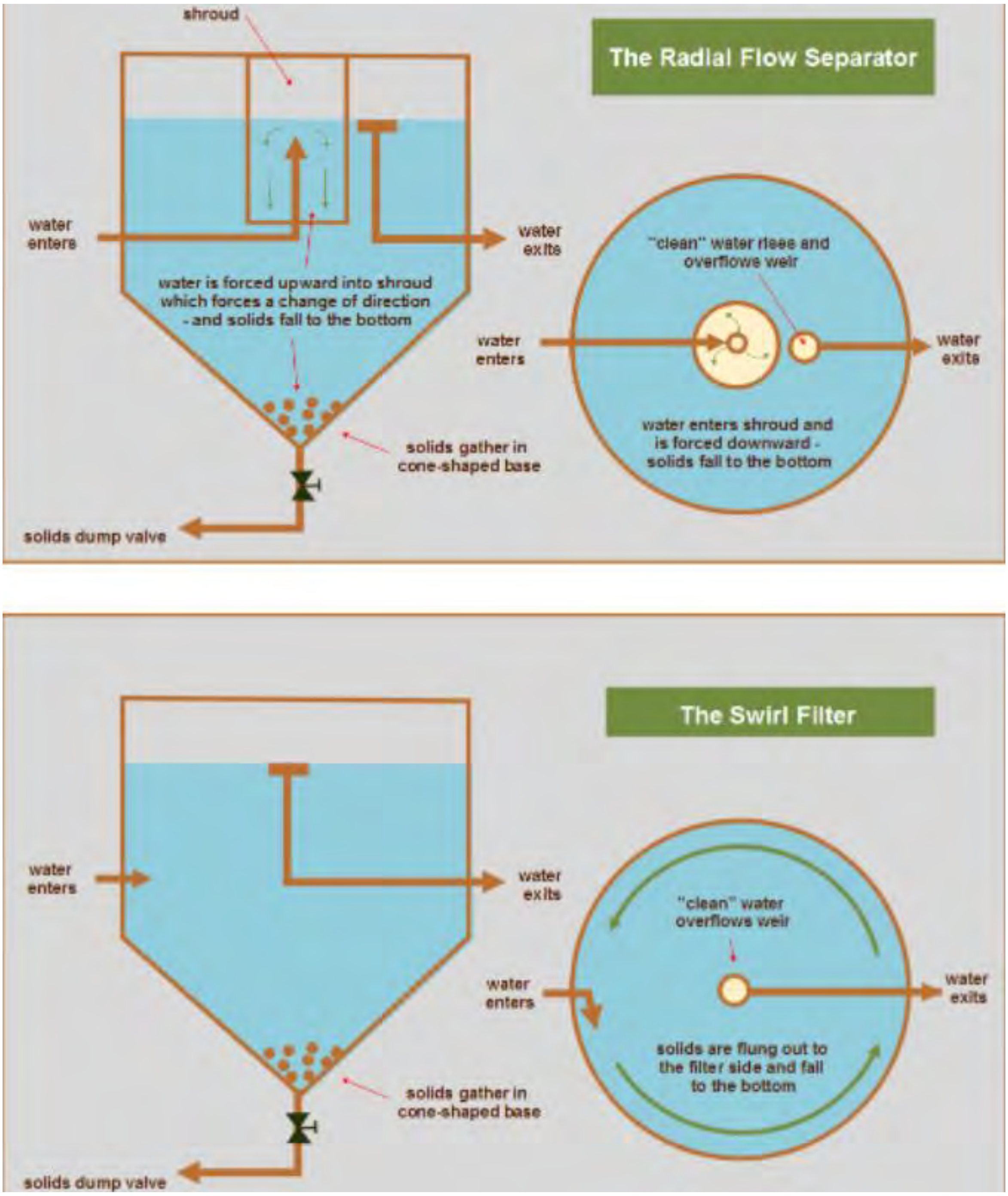

Figure 1.11 Schematics of a swirl filter and a radial flow filter [33]

The biofilter is where the bio-filtration takes place where the bacteria transform the ammonium into nitrates. There are several models although the best in relation to space used and performance is the moving bed filter which is filled with bioballs (balls of porous material that provide a large surface for the growth and maintenance of the bacteria) and aerated to ensure that the bacteria have enough oxygen and to avoid that possible wastes remain adhered to the surface of the bioballs and do not allow the bacteria to perform their function. This filter is shown in Figure 1.12. [34]

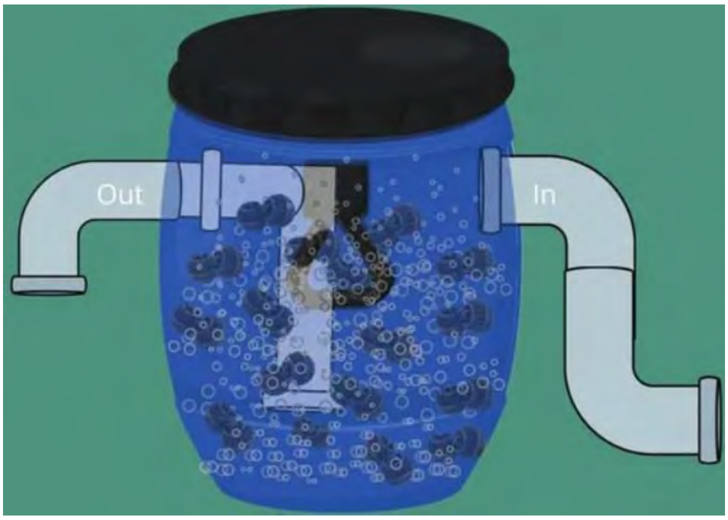

Figure 1.12 Aquaponics' Biofilter - JayLea [35]

Biofilter maturation consists in the population of said filter with nitrifying bacteria so that every small piece of it is full of bacteria among its surfaces. Nitrifying bacteria are found in the environment, hence, to accomplish the biofilter maturation, it only is necessary to create favorable conditions for these bacteria to enter the system and massively reproduce. [16]

There are two methods to accomplish maturation of the biofilter, chemical and biological. The chemical method consists in the addition of sodium bicarbonate into the system and elevating the pH to an optimal level for bacteria (between 7 and 7.5) by the addition of calcium or potassium hydroxide. This method is the most effective but requires excessive precaution. Biological maturation consists in the addition of fish into the system for these to produce ammonium, which nourishes bacteria allowing it to grow. [32]

In the first weeks of the implantation of an aquaponics plant, the bacteria begin to reproduce and form colonies. In this period, the total nitrogen in the system rises linearly, while the ammonia nitrogen rises at the beginning to then lower as nitrites and nitrates start to rise. Nitrites will increase faster than nitrates until these first reach a maximum after which the rise in nitrates concentration will accelerate and the nitrites concentration will lower until reaching zero. After the maturation of the biofilter and proper formation of the colonies, the nitrates would form the totality of the nitrogen in the system. It can be said that the system has matured when the ammonium and nitrite levels are low, and the nitrate levels climb sharply. This process is shown in Figure 1.13. [30]

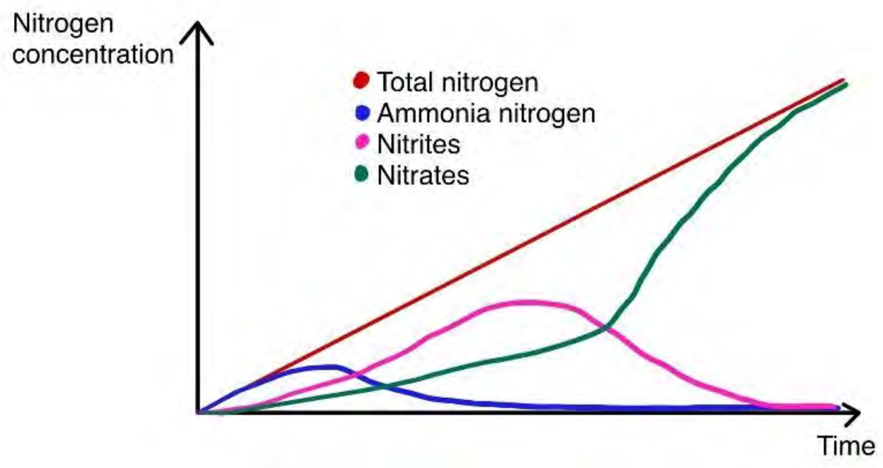

Figure 1.13 Evolution of nitrogen concentration and composition - Note. Adapted from "Aquaponics 5 – From Biology to Hardware," (24)

After this maturation, which typically takes around 50 days, the total nitrogen levels, consisting almost completely in nitrates, stay essentially constant. Once the biofilter has matured and the system has reached equilibrium, it is very stable, meaning it is hard for the conditions to deviate and parameters to fluctuate. [30]

1.4.4.- Water quality parameters

While each parameter itself has importance, it is also crucial to consider the correlation between them, since these can interact in a complex way.

a. **Nitrate*:*** Nitrate is an essential and desirable nutrient in an aquaponic system, as it is a vital nutrient for plant growth. It has high value as a fertilizer. Nitrate is quickly absorbed by plants through the roots, and plants can store this nutrient without it being toxic for them. [16]

   If nitrate levels are excessive (over 150 mg/L) it could be because not enough plants are being cultivated to absorb all the nitrates produced by the nitrifying bacteria. This could be solved by adding more plants to the system or reducing the amount of fish feed introduced into the system.

   Nitrate is often measured to analyze the nitrogen concentration levels in the water and therefore evaluate if these concentrations are optimal for plant nourishment. However, nitrogen can be found in various ways in the system because of the possible de-nitrification processes occurring, and plants require other nutrients (such as calcium and potassium) without which they will experience deficiencies. Nitrate concentrations in aquaponic systems containing media beds do not represent the total amount of nitrogen available for the plants. Aquaponics systems also contain a large amount of dissolved organic nutrients, especially nitrogen, and nitrate measuring does not consider the levels of dissolved organic nitrogen in the system.

   It is common to find older leaves to turn pale green, a phenomenon known as chlorosis, reduction in growth and accelerated aging in the plants when these have a nitrogen deficiency. However, excess nitrogen in plants rises growth rates and crop cycles length. [16]

Optimal **nitrate levels** for comet goldfish are **under 30 mg/L**. [36]

b. **Nitrite:** Another form of nitrogen in the water are nitrites. Nitrites are very **toxic for fish** in concentrations that surpass 1 mg/L. Plants can tolerate higher levels of nitrate than fish, so the limit in the desired concentrations will always be set to the fish's necessities. [12]

c. **pH:** pH measures the concentration of hydrogen ions in the water (H^+). This parameter determines the alkalinity or acidity degree of the water. Solutions with a pH above 7 are alkaline and those below 7 are acid, a solution of pH 7 is considered neutral. pH is defined as the base 10 logarithm of the hydrogen ions activity. [37]

This parameter influences many other processes, it is especially significant (along temperature) in the determination of the percentage of un-ionized ammonium (NH_3) in the total ammonia nitrogen, which indicates the percentage of toxicity of the water. [38]

Achieving an optimal pH level is quite crucial in aquaponics, yet it can be complex given the three living organisms in the system (fish, plants, and bacteria). Each of these organisms has its own optimal range for pH, if the pH in the system gets out of these levels, plants and fish will have low growth rates, fish could get sick, and it could even kill any of the living organisms in the system.

The optimal pH value for freshwater fish is close to 7.4 for most. The most optimal pH levels for plants is between 5.5 and 6.5 for optimal nutrient availability for uptake, and nitrifying bacteria require a pH close to 7.5 in order to effectively perform the conversion of ammonia into nitrates. [28,39,40]

Hence **optimal pH** in an aquaponic system **is about 7.5**. A pH along this level will keep bacteria working at plain capacity while allowing plants to have total access to the nutrients essential for their growth. However, the average standard pH level required for hydroponic plant cultures is 5.5, which is clearly different from the 7.5 pH required for aquaponic systems, this issue is broadly argued to be one of the most significant compromises in aquaponic science when it comes to water quality. [39]

Nevertheless, offer plants the ability to gain access to nutrients in a series of manners not possible in systems that rely solely on pH settings to allow access to nutrients, as standard hydroponic systems do. That's the reason why the roots of the plants on an aquaponic system are greater than on hydroponic systems. This means that with these microbes present in the water, which work at pH levels of 6.5-8.0 like nitrifying bacteria, plant growth is still advanced and efficient despite the pH being raised above what is generally applied in hydroponic or substrate culture techniques. [28]

Quick changes in the pH levels can be very damaging for fish, even mortal. If the pH quickly lowers, it can kill beneficial bacteria, stopping the bio-filtration. [16]

Some factors that cause pH to decline are:

- The **nitrifying process has an acidifying effect** in the system´s water by releasing hydrogen ions.
- A high fish density can increase the systems acidity, since they produce carbon dioxide when breathing, producing the carbonic acid by subsequent contact with the water.
- The water initially added into the system has a lower pH value, which can cause problems as the nitrifying process develops.
- The cultivating mechanisms and materials used in the construction of the system.
- The type of plants being cultivated.

Low pH levels diminish the nitrifying process and will create stressful conditions for the fish which can often cause illness and even death. [30]

Some methods to rise pH levels are:

- Adding a mix of calcium carbonate and potassium carbonate into the water.
- Changing the water in the system.
- Adding sodium hydroxide into the water.
- Implementing alkaline cultivating media, such as limestone.

On the other hand, if the pH is too high, it can stop the nitrifying process, causing a low growth rate for the plants, and increasing ammonia levels in the system. The most common cause for the accumulation of the pH levels in aquaponics is the accumulation of carbonate in the system, this phenomenon often appears when the hardness of the water is high, or it can be a result of the cultivating media/mechanisms or materials used. On the good side, higher pH levels reduce the ammonium´s toxicity, as it predominates in its ionized (NH_4^+) form. [16]

It is usual to encounter high pH levels in newly implemented aquaponic systems, where the bacteria have not finished reproducing and forming colonies. [41]

Some methods to lower the pH in the system are:

- Allowing the necessary time for recently built systems to have stablished bacteria colonies (bio-filter maturation). After the biofilter has completed its maturation, the pH will naturally decrease. [16]

- Using certain acids, such as phosphoric acid, which is safe and effective. Or using lemon or vinegar. [42]
- Adding dry oak leaves into the water which release tannins into the water. [43]
- Adding peat into the system. [43]
- Implementing a reverse osmosis filter.

d. **Total Dissolved Solids (TDS):** Total dissolved solids are the sum of all minerals, metals and salts dissolved in the water, organic and inorganic, and are a good indicator of water quality. This parameter would mostly be harmful for fish if the optimal levels were exceeded. It is recommended that **TDS** stay **under 250 mg/L** for goldfish. [36,44]

The nature of total dissolved solids is mainly from agricultural and urban runoffs, clay-rich mountain waters, leaching of soil contamination, and discharge from industrial or sewage treatment plants. As an aquaponic system is normally developed on a controlled environment and the water is obtained from sewage treatment plants this is going to be the principal nature of TDS in our system. Anyway, if our system obtains the water from an effluent accordingly on the location, this measurement would change depending of factors as agricultural and urban runoffs, the season because of the possible mountain thaws or spring storms, among others. Making the control of this parameter very difficult [45]

e. **Temperature:** Temperature determine the metabolic rate of the fish. Growth rates get higher with temperatures (staying between the tolerated range for the fish) until reaching an optimal level. At the optimal temperature, metabolic processes and energetic requirements rise, increasing the conversion of feed into flesh. [16]

Temperature is inversely proportional to oxygen solubility in the water, which plays a very important role in the biological processes of the system. A rise in temperature also increases the fishes' oxygen demand. Significant temperature fluctuations should be avoided as much as possible, seeking maintaining stable oxygen levels. [16]

The optimal temperatures for the fish and plants chosen should be similar, in this sense, it is advised to work with species acclimated to local climate conditions, both fish and plants. Greenhouses are a good tool when working small scale by appeasing the intensity of temperature fluctuations. It is also an option to shift fish and plants species in the system according to the season to handle changes in the production. [16]

Optimal water temperature for fish is usually between 22ºC and 32ºC for warm water fish, and between 10 and 18 for cold water fish, but the optimal temperature may vary depending on the specific fish species. For example, the comet goldfish require between 16ºC and 30ºC and nitrifying bacteria between 14ºC and 34ºC. [16,46]

f. **Ammonia (NH_3) and ammonium (NH_4^+): Ammonia is extremely toxic for fish**, values of under 1 mg/L compromise the survival of many species and increment stress in many others (depending on the exposure time). Even concentrations as low as 0.08 mg/L of unionized ammonia have been demonstrated to depress food consumption on tilapia fish, the same study on tilapia fish states that mortalities from prolonged exposure may begin at concentrations as low as 0.2 mg/L. [47]

The limit in the level of ammonia that should be allowed in the system is set by the fish, as plants can tolerate higher ammonia levels. Excess ammonia becomes fatal for fish quite quickly. [12]

Ammonia levels over 2 mg/L can be considered high and would be a sign of poor biofilter function. Ammonium is a product of the fish excretions and the decomposition of organic matter (degradation of the protein from unconsumed food). Non ionized ammonium (NH_3 gas) and the first excretion product from the fish are toxic for both fish and plants. [12]

Increase of ammonium concentrations in the water produces an increase of ammonium and pH levels in the fish´s blood, destabilizes the membrane, affects water permeability, and harms the fish´s gills.

The toxicity of non-ionized ammonium rises with a low dissolved oxygen concentration, a high pH level and high temperatures. Un-ionized ammonium (NH_3) has a higher toxicity than ionized ammonium (NH_4^+). Ammonium levels above 10 mg/L can prevent calcium and copper uptake in the plants, as well as it promotes a more significative shoot growth in the plant compared to its roots, resulting in an intense green coloration of leaves; excess of ammonia on the other hand, has toxic effects on plants. [16,38]

However, ammonia is necessary in the system for it to be converted into nitrates to nourish the plants, in fact, if plants in the aquaponic system are not growing it could be a sign that not enough ammonia is being produced and converted into nitrates. [38]

Low ammonia appears when the number of fishes in the system are not enough for the plants, or when there is too much water in the system for the number of plants being cultivated. Solving this problem comes with adding more fishes to the system, feeding them more (see section 1.5.-), or using a smaller tank. [38]

The ratio at which ammonia and ammonium are found is affected by pH and temperature. When these two parameters are high, the percentage of total ammonia nitrogen that is ammonia rises. When the pH is under 7.0, most of the ammonia (>95%) will be as the ionized form (NH_4^+), the portion of ammonia in its toxic form (NH_3) increases greatly with pH, the same happens with temperature. For example, at a pH of 7.0 and 20ºC, only 0.396% of the total ammonia nitrogen will be un-ionized ammonia (NH_3), at a pH of 8.0 and 26ºC this percentage rises to 5.75%, and if the water reaches pH 10.0 and a temperature of 32ºC, 90.6% of the total ammonia nitrogen is in its toxic form (NH_3). [38]

To determine the portion of total ammonia nitrogen that is in its toxic form (NH_3) and the portion of ammonium (NH_4^+), it is a simple as multiplying the total ammonia nitrogen by the percentage value given at the corresponding pH level and temperature. [38]

Table 1 shows a series of values for temperature and pH and the corresponding percentage of total ammonia nitrogen that would be ammonia (NH_3).

Table 1. Percentage of Total Ammonia Nitrogen (TAN) in freshwater that is in the toxic un-ionized ammonia form at different pH values and temperatures (ºC).

	Temperature (°C)										
pH	10	16	18	20	21	22	24.5	26	28	30	32
7.0	0.18	0.29	0.34	0.40	0.43	0.46	0.55	0.61	0.70	0.80	0.95
7.2	0.29	0.47	0.54	0.63	0.67	0.72	0.86	0.96	1.10	1.25	1.25
7.4	0.46	0.74	0.85	0.99	1.06	1.14	1.36	1.50	1.73	1.98	2.36
7.6	0.73	1.16	1.35	1.56	1.67	1.80	2.14	2.36	2.72	3.11	3.11
7.8	0.16	1.82	2.12	2.44	2.63	2.80	3.35	3.68	4.24	4.84	4.84
8.0	1.82	2.86	3.31	3.82	4.10	4.39	5.21	5.75	6.56	7.46	8.77
8.2	2.86	4.45	5.16	5.92	6.34	6.79	8.01	8.75	10.00	11.30	13.20
8.4	4.45	6.88	7.93	9.07	9.69	10.30	12.10	13.00	15.00	16.80	19.50
8.6	6.88	10.50	12.00	13.70	14.50	15.50	17.90	19.40	21.80	24.30	27.70
8.8	10.50	15.70	17.80	20.00	21.20	22.50	25.70	27.80	30.70	33.70	37.80
9.0	15.60	22.70	25.60	28.40	29.90	31.50	35.50	37.70	41.20	44.60	49.00
9.2	22.70	31.80	35.20	38.60	40.40	42.10	46.50	49.20	63.80	56.10	70.80
9.4	31.80	42.50	46.30	49.90	51.80	53.50	58.00	60.50	63.80	66.90	70.70
9.6	42.50	53.90	57.70	61.30	63.00	64.60	68.50	70.80	73.60	76.20	85.90
9.8	53.90	65.00	68.40	71.60	72.90	74.30	77.60	79.40	81.60	83.60	85.90
10.0	65.00	74.60	77.40	79.90	81.00	82.10	84.50	85.90	87.50	89.00	90.60

Note. Adapted from data presented in Francis-Floyd et al. [2009] and Florida Department of Environmental Protection Chemistry Laboratory Methods Manual [2001])

g. **Biological oxygen demand (BOD):** BOD represents the amount of oxygen necessary to biologically oxidize the organic matter by aerobic bacteria at a specified temperature. It is represented in mg O_2/L.

Organic matter consumes oxygen dissolved in the water for degradation, if the concentration of organic matter in the water is too high, it could lead to an excessive consumption of oxygen, inducing asphyxia of aquatic organisms.

The most common method for measuring BOD is to use a special BOD bottle with the water test. The test is left for 5 days at a constant temperature of 20°C in the dark, after the 5 days the oxygen content is measured in comparison to the original value, the oxygen consumption during this period indicates the oxygen demand of the water. This method is denoted BOD_5.

In aquaculture samples nitrification begins at the start of the BOD test that is because the water rich in organic matter already has a nitrifying bacterial colony. Nitrification can represent up to 40% of BOD_5 analysis. [48]

h. Chemical oxygen demand (COD): COD represents the amount of oxygen necessary to decontaminate water, therefore, this parameter is used to evaluate the efficiency of water depuration. [49]

Apart from causing a fall in oxygen levels in the water, high COD induces an enhancement of toxic elements, eutrophication and surfactants (part of the so-called precedent pollutants, which in spite of being biodegradable in many cases, are very damaging for the environment and living organisms because of their bioaccumulation and permanence. [38]

The optimal COD levels that should be found in water vary depending on the use that this water will be given. The environmental regulation in Spain requires 125 mg/L in water discharged into a river after having been processed in a sewage water plant (RD 509/1996). The standard value for fish culture is under 50 mg/L; however, fish culture is not the main objective of this study, and this limit does not define compatibility with life. The average COD of a clean river is 30 mg/L. [49–51]

i. Dissolved oxygen (DO): DO has vital importance for fish, plant roots and microflora and must be maintained in any aquaponic systems. [52]

Dissolved oxygen is a determinant parameter in the water´s quality, this is because the absence of this parameter has very quick and drastic effects, fish could die in a matter of hours, and low concentrations of this parameter affect the nitrification process, preventing it from being completed.

To keep the high levels required, it is advantageous to add aeration methods and alternatives inside the different components in the system, for this goal, instruments that inject air into the water are good enough as oxygen constitutes 21% of it. [16]

High amounts of dissolved oxygen are crucial for the fish, plants and bacteria in the system. While plant roots and microbes can survive DO levels under 3 mg/L, most fish need the concentration to surpass 5 mg/L. [27,53]

The requirements vary depending on the fish species. For example, warm water fish, such as tilapia, can generally tolerate lower concentrations than cold water fish, such as trout, can. Given the fact that DO requirements for fish will be higher than those of plant and microbes, whenever the necessary level for fish is achieved, so will be the target for these organisms be met. [28]

j. **Other nutrients:** In addition to the factors explained above, plants need a series of other nutrients for their nourishment:

- Potassium (K): Necessary for many fundamental processes of the plants, such as cell division and photosynthesis.
- Phosphorus (P): Stimulates root development, bud growth and flower quantity.
- Calcium (Ca): Necessary for cell development, calcium also gives plants a higher resistance to fungal attacks and bacterial infections.
- Magnesium (Mg): Involved in the constitution of chlorophyll molecules.
- Sulphur (S): Sulphur helps restore damages causes by iron deficiencies.
- Iron (Fe): Fundamental for many biological processes such as photosynthesis.

- Chlorine (Cl): Chlorine is involved in photosynthesis and other biological processes.
- Sodium (Na): Depending on the species, sodium can improve some characteristics of plants (e.g. taste in tomatoes) while it can be damaging for growth in others (e.g. beans).
- Manganese (Mn): Manganese is involved in root growth as well as their protection against pathogens.
- Boron (B): Fundamental for fruit maturation and seed development.
- Zinc (Zn): Participates in some enzymatic reactions.
- Copper (Cu): Takes part in respiratory processes as well as photosynthesis.
- Molybdenum (Mo): Fundamental for the synthesis of protein and absorption of nitrogen.

In case the plants show a deficiency in any of these nutrients, they should be introduced externally. [16,40]

Table 2 Optimal parameters for aquaponic systems summarizes the optimal values or ranges for the most significant parameters for the water measured in an aquaponic system.

Table 2 Optimal parameters for aquaponic systems.

Parameter	**Optimal range/value**
nitrate	<30 mg/L [36]
nitrite	<1mg/L [12]
pH	≈7.5 [39]
TDS	<250 [36]
Temperature	16-25ºC [16,46]
Ammonia (NH3)	< 1mg/L [47]
DO	>5mg/L [27]

1.5.- Fish-to-plant ratio

The number of plants that can be grown in the system is directly related to the amount of nutrients available. These nutrients come from the waste produced by the fish and is therefore directly related to the amount of food fish consume instead of how it is normally thought of as the ratio between the number of fish and plants. Hence the number of plants that can be grown in an aquaponic plant is directly related to the amount of food that is fed to the fish. The Figure 1.14 shows an approximate ratio where a 1000L tank with fish provides sufficient nutrients for a 1 m^2 of strawberries plants. [32]

Figure 1.14 Aquaponic System-Aquaponics – Invictus, (n.d.) [54]

The critical factor needed to design the dimensions in a system is the feeding rate ratio, which is the amount of food that it is needed to feed to the system to produce the fish waste concentrations needed for a given number of plants.

To calculate the dimensions needed in the design process of an aquaponic plant, the following steps are recommended:

- **i.** Determine the number of plants to be grown, as well as the species of these.
- **ii.** Determine the area these plants need to grow, depending on the maximum density (maximum number of plants per square meter) necessary for the desired plant.

iii. Determine the amount of food the fish would need to be fed to meet the nutrient requirements of the plants.

iv. Determine the weight of fish required to eat the calculated amount of food.

v. Determine the volume of water the calculated fish need to live in.

With these five factors, it is possible to correlate the amount of food needed for the desired amount or number of plants. [32,55]

While doing the research to develop the UVI aquaponic system method, Dr James Rakocy determined that fish feed contains several nutrients required by the fish for optimal health and growth, but the nutrition requirements of the fish differ from that of the plants. In his study, Dr Rakocy pointed out some key factors that differentiate the nutrition requirements for each species:

- Plants have important requirements on potassium and calcium which are very far from the amount required by the fish.
- Fish require to be fed with large amounts of protein, which is metabolized into energy, resulting in the production of waste that is predominantly composed of nitrogen and phosphorus.
- Plants have requirements for other key macronutrients that fish do not need at all, such as sulphur, magnesium, and iron among others. [32]

Rakocy encountered an important problematic as fish seem to not be able to produce the necessary amounts of potassium, iron, and calcium, essential for plants, at an initial feeding rate, and fish feed also does not contain other key nutrients necessary for the plants. The Figure 1.15 illustrates the tilapias and watermelons harvested by Dr. Rackoy and two colleagues in the UVI system in the Virgin Islands during a course.

Figure 1.15 Dr. James Rakocy (left) with colleagues- Rakocy (n.d.) [56]

When feeding the fish with the necessary amount of food to produce the macronutrients demanded by the plants (apart from calcium, iron and potassium) the nitrogen levels increased creating an excess of this element. To solve this problematic, Rakocy implemented controllable denitrification systems utilizing orchard netting, this method is shown in the Figure 1.16. This caused solids to build upon the netting until a small denitrification occurred, removing nitrogen from the system (the denitrification would turn nitrate to nitrogen gas which would escape the system via air). Dr Rakocy also implemented the removal of fish waste solids periodically with the help of sedimentation and exchanging the water. [32]

Figure 1.16 Orchard netting in a denitrifying tank [57]

The Rakocy/UVI feeding ratios are 60-100 grams of fish feed per square meter of plant growing area a day for Tilapia fish. Depending on the kind of plant, the ratio will be closer to the lower limit of 60 g or the higher of 100 g, light feeding plants such as lettuce or basil are closer to 60 g/m^2/day and heavy feeding plants such as tomatoes are closer to 100 g/m^2/day. This ratio developed by Rakocy and Hargreaves in 1993 is particular to the UVI System, does not utilize the solid fish waste fraction, is over-supplied with nitrogen and has the requirement of passive denitrification occurring in the system to control the nitrogen accumulation. [28]

Another important author in aquaponics is Wilson Lennard. On his thesis "Aquaponic integration of Murray Cod aquaculture and Lettuce hydroponics" from 2006, Lennard presents a mathematical modelling to calculate aquaponic feeding ratios working with Murray Cod (an Australian fish species) and lettuce. Dr Lennar found that the complete balancing of nitrogen in an aquaponic system results in the deficiency of other key nutrients for the plants, such as phosphorus, potassium, and calcium, hence making Rakocy´s method more optimal (as no extra supplementation of these nutrients is needed).

On his research, Dr Lennar states that the only predictable and scientifically verified way to size the components (fish and plants) in the system is basing the calculations on the ratio between fish feed that is entered and the number of plants or growing area of these. [28]

Lennar considers the nutrients available from solid fish waste, considering the aerobic remineralization of this waste, adding merely the nutrients required by the specific plant that will be grown that are missing from fish waste. This way, Lennar significatively lowers Rakocy´s ratio. [28]

For example, the ratio calculated by Lennar for some leafy greens stays under 11 g/m^2/day. The ratio stablished by Dr. Lennar is a lot more specific to that of Dr. Rakocy´s, as Lennar sought to directly pair individual fish waste nutrient production rates depending on the kind of fish feed implemented, its conversion and utilization, with the specific nutrient requirements of each plant. [28]

1.6.- Hydroponic subsystems

According on the scale of the system, the place, and the needs we find different hydroponic systems for growing vegetables used in aquaponics, mainly we will find these three: deep water culture (DWC), nutrient film technique (NFT) and media substrate.

1.6.1.-Deep Water Culture (DWC)

Deep water culture, also known as floating rafts, doesn't require too much labour and maintenance and allows for large planting areas, so they are used in domestic and semi-commercial plants. However, this system is not suitable for commercial plants because the maintenance and labour costs are too high. In this system, nutrient rich water circulates trough canals, usually about 30 centimeters in depth, while a raft of polystyrene or foam floats above. The plants are cultivated in holes made on the floating rafts with net baskets, so that their roots are hanging directly in the oxygenated nutrient rich water, getting nourished and oxygenated for quick growth. This subsystem is represented in the Figure 1.17. [58]

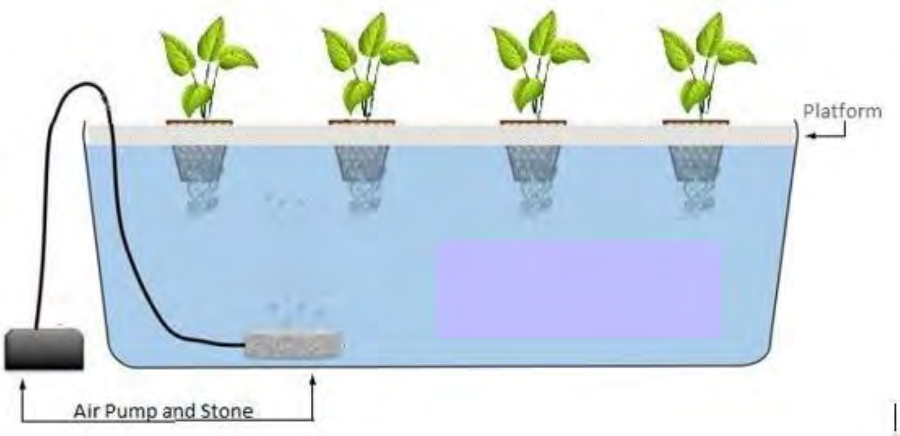

Figure 1.17 Representation of Deep Water Culture - *Planteli* [59]

The DWC is usually separated from the fish tank as two different components. Many commercial aquaponic plants implement this system developed by Dr. Rakocy at the university of the Virgin Islands since it allows plants to grow faster and therefore produce more crops. [58]

The recommended depth of the water in the DWC canals is 30 cm, and retention time should be one to four hours long, regardless of the size, to allow the adequate nutrient reposition in the channel. The faster the flow, the faster plants will grow since these would receive a larger number of ions. [12]

Aeration of the roots is essential for plant health and growth; it is important to implement a system of aeration to add oxygen into the water. Aeration can be accomplished using air pumps, diffusers, air rocks or other mechanisms.

The principal advantages of DWC systems are:

- High crops productivity with cheap workforce.
- Roots are more exposed to the nutrients in the water.
- The surface of the roots, allows its colonization by nitrifying bacteria, acts as a biological filter avoiding the need to have this tank.
- Very simple and can be the easiest aquaponic culture system to build.
- Plants are very easy to harvest as these are submerged in water and not into media.
- The high-water volume secures more stability in the water´s quality and temperature than other systems.
- Easy maintenance as rafts are easy to clean.
- It allows rafts to be put directly on the fish tank’s water, making it very space efficient.
- It is adequate for domestic as well as semi-commercial production. [12,60]

The principal disadvantages of this system are:

- Somewhat restricted to smaller leafy greens such as lettuce or basil.
- Cannot be used for fruity plants and some other plants.
- High costs of labour and maintenance for commercial plants.
- Can create a mosquito culture if not correctly designed. [12]

1.6.2.-Media bed substrate

Media beds consist of a grow bed filled with grow media in which crops are planted. The media used can be expanded clay, tuff, pea gravel or perlite. The plants receive nutrients with the constant flood and drain of the media in which they are, by the action of a siphon, while the surface stays dry. The fact that the upper surface of the media stays dry makes it a barrier, which separates the wet media from the environment, and most importantly, from light, hence preventing the growth of algae on the media. The flood and drain can be made with the help of a siphon which expels water of the bed once this reaches a certain level. How the siphon is placed in the media bed is shown in the Figure 1.18 and in the Figure 1.19 is observed the media bed with the representation of the plants and the level up to where the water reaches.

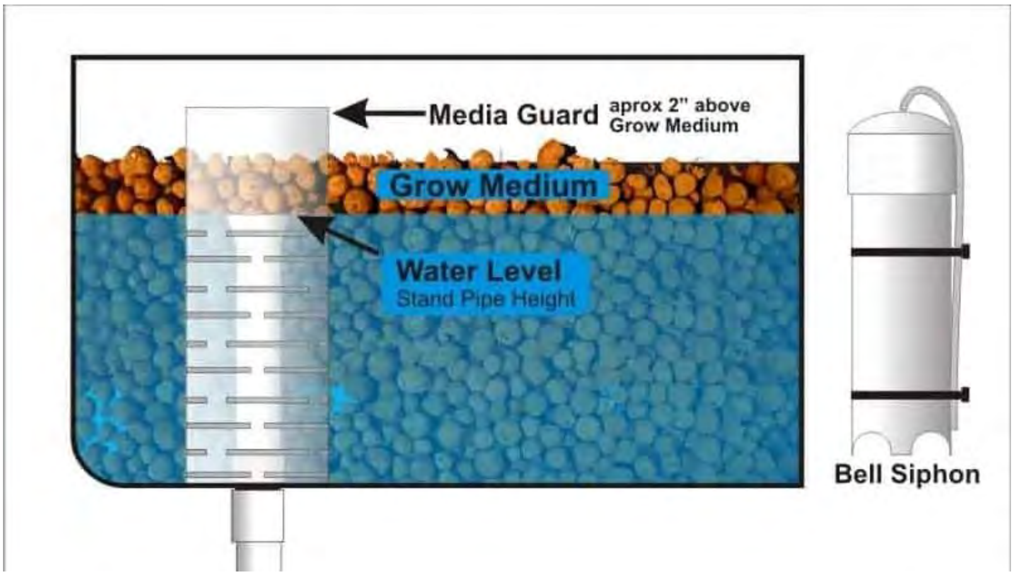

Figure 1.18 Representation of Media Bed siphon mechanism - Agroarbol [61]

Media beds can retain solids found in the water that drains through them, if enough solids are accumulated in the media bed, zones with low or zero oxygen concentrations may appear, causing anaerobic activity to rise in some areas of the media bed from which said solids cannot be easily extracted, resulting in a possible denitrification process occurring in the media bed. Therefore, this system requires high maintenance to avoid a clog of solids in the substrate, which makes it suitable for domestic installations but not for commercial systems.

Since denitrification rises pH levels, if a region of the media bed is working under anaerobic conditions, the nitrification process occurring in other areas may not overcome the effects of denitrification, causing the pH level to rise above desired levels. In this case, it could be necessary to add acid agents to the system (such as lemon). [62]

The principal advantages of media beds are:

- **These systems can provide biofiltration**, as the substrate used to hold the plants can also host nitrifying bacteria, providing nitrification and mineralization. [58]
- They are suitable for most types of plants.
- The various media options allow the construction of lighter beds (using lighter media) which can be used in places like rooftops. [58]

The principal disadvantages of this system are:

- The media entails an additional cost as does its transportation.
- Using gravel makes very heavy beds, hindering installation and limiting the locations at which they can be placed.
- Most labour-intensive system.
- This system is not suitable for large scale plants.
- The possibility of waste clogging the media and denitrification appearing.

- The colocation and removal of plants is slightly more laborious compared to other systems. [58]

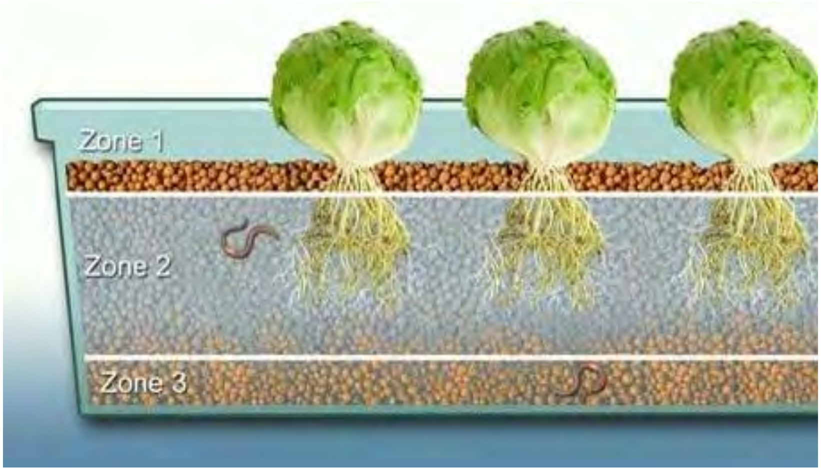

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Figure 1.19 Representation of a Media Bed -Hallam, M. (n.d.) [63]

1.6.3.-Nutrient Film Technique (NFT)

NFT, nutrient film technique, consists on the use of pipes or canals to run a shallow stream of water through the plant´s roots, which develop inside the pipes. The pipes or canals have holes made into them where net baskets can be placed housing the plants. It is important to avoid light exposure of the roots as this would promote algae growth. In Figure 1.20 we can observe the representation of an NFT systems while Figure 1.21 shows an actual NFT production system of strawberries. [64]

The water flow is very slow, typically about 1 or 2 liters per minute, and it usually is continuous. In the present NFT technique is the most efficient hydroponic system combining little labour with a large cultivation area and a good ratio of water use, energy and investment costs. [65]

[1] The zone division in the picture represents an upper level (zone 1) which always stays dry, thanks to the siphon; an intermediate level (zone 2) which is the broader area and is continuously flooded and drained; and a lower level (zone 3), which always stays wet.

The principal advantages of NFT are:

- It is very light weighted, making it suitable for roof-top agriculture.
- High productivity.
- Doesn't need any media.
- Introducing and removing plants is very simple as it is only necessary to place and remove baskets from the respective holes.
- Pipes can be stacked at different levels, making it very space efficient.
- The shallow stream of water allows the roots of the plants to be very aerated, meaning these will be very well oxygenated.[66]

The principal disadvantages of this system are:

- The supporting structures and pipes can present a high set up cost.
- The roots could clog the canals, impeding water to reach the rest of the plants.
- The water temperature can quickly be modified when running through the canals.
- Limited to smaller, leafy plants. Not suitable for plants with bigger roots. [58]

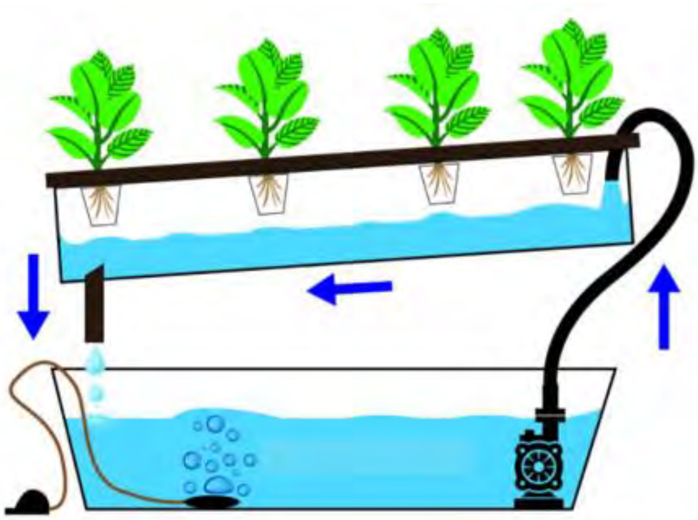

Figure 1.20 Nutrient Film Technique representation- The hydroponics guru (n.d.) [67]

A recent survey made on commercial scale producers indicated that most owners used DWC (77%) and media beds (76%), most of them combine different systems. [66]

Figure 1.21 Growing of strawberries in NFT vertical farming - Christine Aubry [68]

1.7.- Fish selection

Species selection will depend on the type of system, climatic factors and market demand among other factors.

Many species are suitable for aquaponic cultivation, such as tilapia, common carp, silver carp, grass carp, barramundi, jade perch, catfish, trout, salmon, Murray cod and largemouth bass, among them we can highlight the following three:

- Trout are highly sought after for their culinary value but their high water quality requirements as well as high oxygen saturation in the water make them unsuitable for some systems such as a community in Peru at a high altitude where the amount of oxygen is not sufficient.

- Tilapia, the most used fish in aquaponics because of its fast growth and ease of care, is limited to systems where a temperature higher than 20ºC can be maintained

- Goldfish, although not suitable for human consumption, are also used thanks to their resistance to low temperatures and low water quality, as well as their sale as ornamental fish in aquariums. [69]

1.7.1.-Fish density

Fish stocking density in aquaculture and fish breeding in general, refers to the relation between the fish mass in the system and the water volume that houses the fish (kg/m^3). It is recommended that the density stays under 20 kg of fish per 1000 L. Higher stocking densities would require more sophisticated aeration mechanisms to achieve optimal dissolved oxygen levels for the fish, and stronger filtration mechanisms to treat waste.

However, in aquaponics, it is more significant to talk of fish density as the relation between fish mass in the system and plant growing surface (kg/m^2). For leafy greens, the suggested density would be 20 to 25 grams of fish per square meter. [70]

However, knowing the fish mass in the system can be complicated as weighting the fish can be quite problematic and because the fish will grow, and their mass will vary. Although this growth can be estimated, it is more optimal to apply the fish-to-plant ratio, which, as it is explained in section 1.5.-, relates fish feed to planting surface.

2.- AQUAPONIC SYSTEMS SCALES

There are several ways to categorize the aquaponic systems as depending on the stocking density (low or high density systems), subsystems (deep water culture, nutrient film technique or media bed substrate) or size. Depending on the size aquaponic systems can be classified as mini, hobby, backyard, semi-commercial and commercial aquaponic systems. [16,21]

2.1.- Mini aquaponic systems

Mini aquaponic systems are the way in which aquarium hobbyists are usually introduced to aquaponics as this type of systems consist of an aquarium, a few plants in a small hydroponic bed that will be in charge of filtering the water for the fish, an aquarium filter and an aerator, as it is represented in Figure 2.1. The size of these systems is lower than 2 m^2.

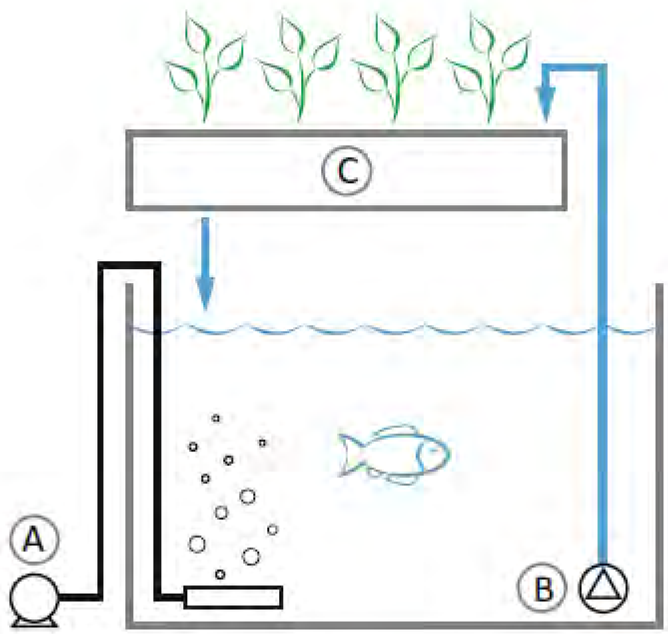

Figure 2.1 Principle of a mini aquaponic system with aeration (a), a pump (b) and the hydroponics (c) act like a biofilter [21]

2.2.- Hobby aquaponic systems

These systems have a higher stocking density so it is necessary to add a settler or clarifier, to avoid the clogging of the media beds, which will collect the sludge composed of feces and uneaten food. The size of these systems is up to 10 m^2.

The water flows from the fish tank through the settler to the hydroponic tanks and to the sump where a pump returns the water back to the fish tank. As seen in Figure 2.2.

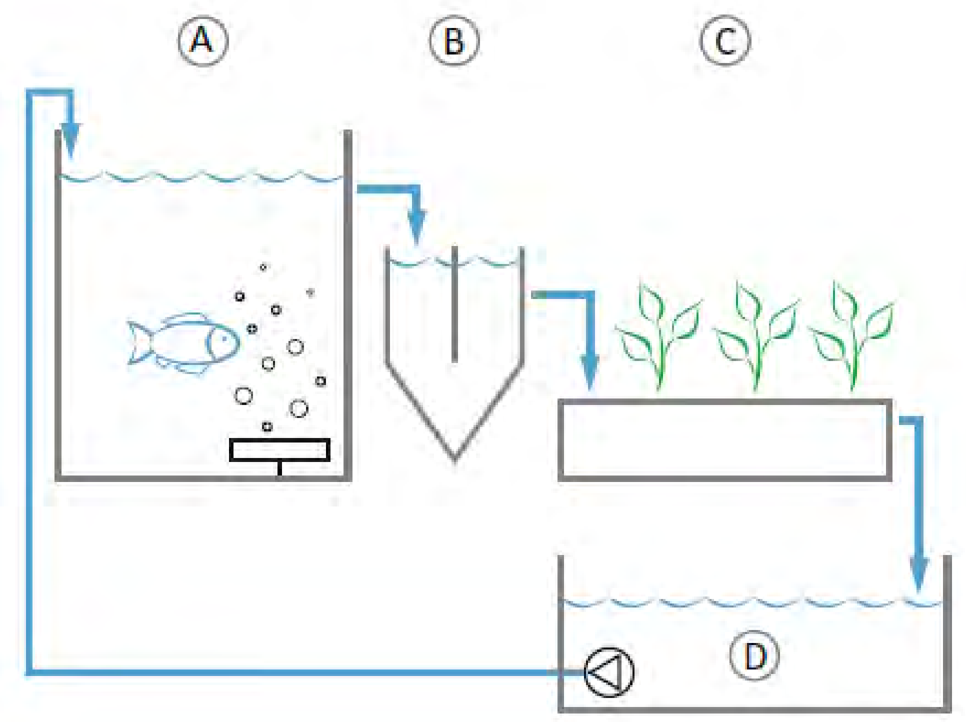

Figure 2.2 Principle of a hobby aquaponic system with (a) fish tank and aeration, (b) a clarifier, (c) hydroponics bed which acts like a biofilter and (d) a sump with the pump. [21]

These systems are installed by hobbyists who beyond getting food production are interested in growing a variety of aquatic organisms and plants for their own use and for fun.

2.3.- Backyard aquaponic systems

In this type of systems, it is necessary to add a biofilter due to the increased stocking density in order to accommodate a colony of nitrifying bacteria large enough to avoid ammonium levels in the water that could be harmful to the fish. The size of these systems is going to be between 10 and 50 m^2.

The water flows from the fish tank through the settler and biofilter to the hydroponic tanks and to the sump where a pump returns the water back to the fish tank. As seen in Figure 2.3

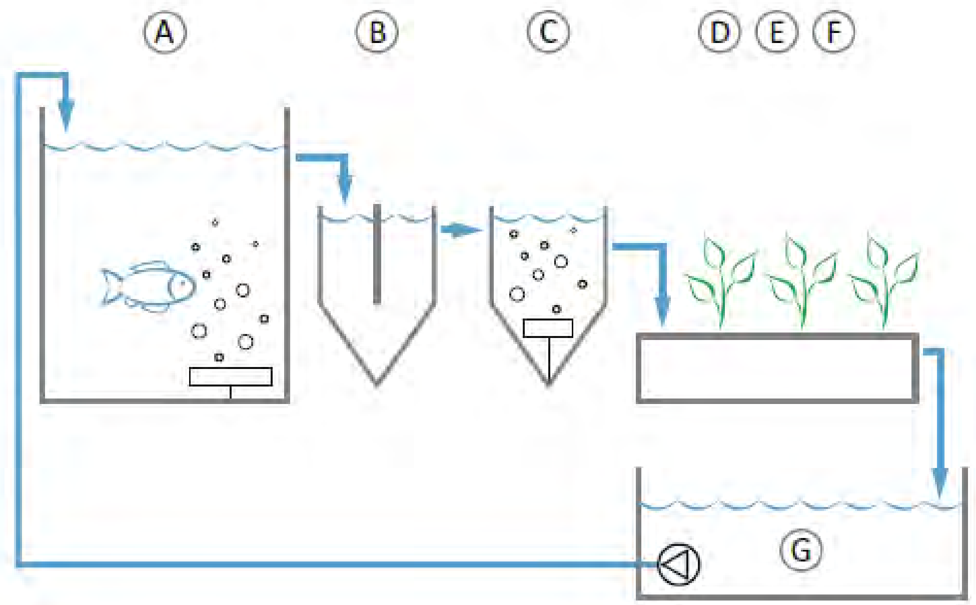

Figure 2.3 Principle of a domestic backyard aquaponic system with (a) fish tank and aeration, (b) clarifier, (c) biofilter with substrates and aeration, (d) (e) (f) hydroponic units (DWC channels, media beds and NFT channels) and (g) a sump with one pump. [21]

2.4.- Semi-commercial and commercial aquaponic systems

This type of systems is focused on the commercialization of the production. It has tanks with a higher stocking density, additional filters, water quality control devices and a larger hydroponic area where the vegetables are grown. It is shown in the Figure 2.4.

The design and control of these systems must be done in a very precise way since failures can lead to the loss of a large economic amount due to factors such as breakage of components, appearance of pests (loss of crops) or contamination of the water (death of fish) among other factors are critical.

Semi-commercial aquaponic systems can reach 100m^2 while a commercial aquaponic farm is above that size, in Brussels is located the biggest aquaponic farm of Europe, it occupies an area of 4000 m2 where trout, herbs, eggplants, peppers, tomatoes and other vegetables are grown. [71]

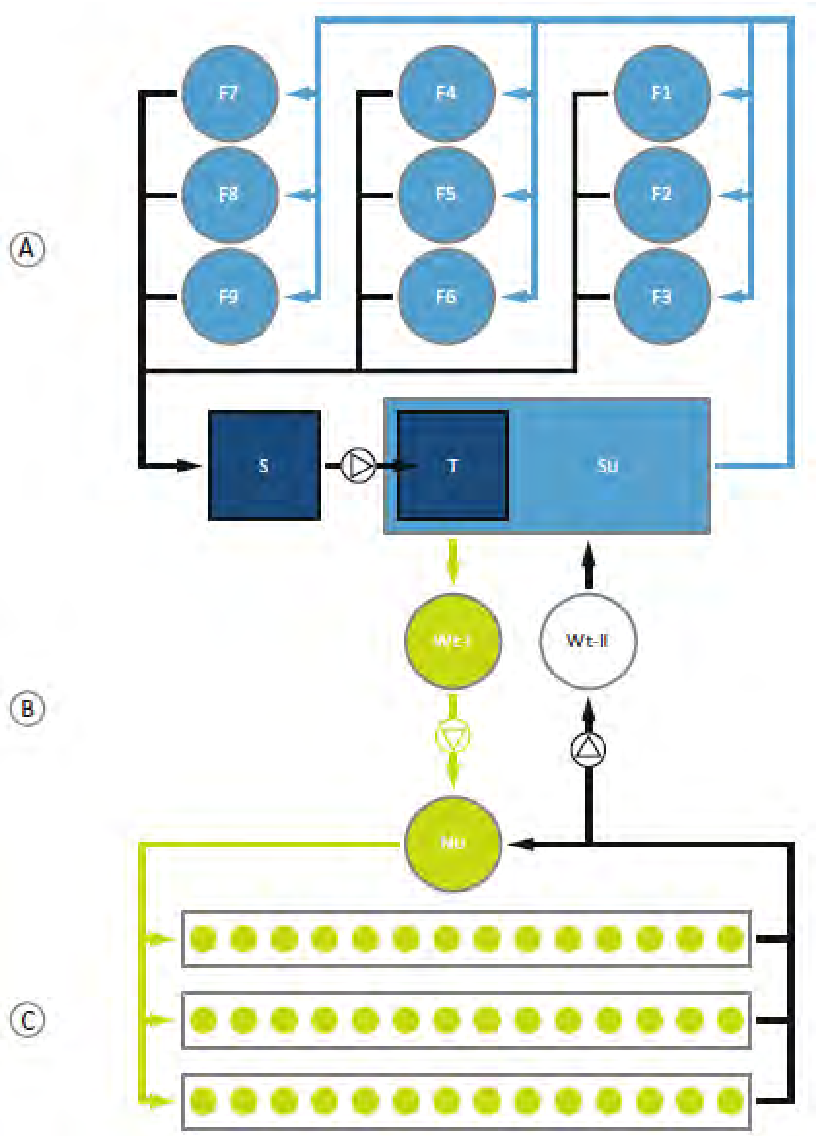

Figure 2.4 Schema of a commercial aquaponic system with (a) aquaculture unit, (b) the water transfer system and (c) the hydroponic unit. [21]

3.- AIM AND SCOPE

The present study documents the construction of a backyard plant consisting in a fish tank with a capacity of 1000 liters and three cultivating systems with a capacity for up to around 45 plants.

The system was designed to self-supply two four members families on the harvested vegetables. It was designed, built, and maintained by two 23-year-old final year students of Industrial Engineering bachelor.

The system has been actively running for eight months. It was monitored periodically, testing parameters weekly the first weeks. After the first weeks, the water continued being tested periodically, but less frequently also after these 8 months, a study on the growth rate of the fish was carried out, as described in section 7.2.-

4.- MATERIALS AND METHODS

For the construction of the aquaponics system, three 1000-liter IBC tanks were used, these served as the fish tank, radial flow filter and the last was cut so part would serve as a deposit and the other would be the recipient for the media bed. For the NFT, three PVC channels were placed in parallel with an adequate inclination for the water to flow; and lastly the DWC was placed on a bathtub, with a cut styrofoam board to serve as a floating raft. To pump the water, one 270-Watt pump is submerged in the sump, pumping the water through a hose into the fish tank. Another 25-Watt pump is also submerged in the sump to pump water to the NTF channels.

The 270-Watt pump can provide a water flow of up to 6800 L/h. This flow is exceptionally higher than what is needed for the system, hence the flow had to be regulated using a valve at the end of the hose that connects the sump and fish tank. The faucets at the beginning of the NFT channels regulate the flow for the second (25-Watt) pump.

The fish tank is located on the highest part of the terrain, a pipe allows the water to continuously flow onto the radial flow filter, which is slightly lower than the fish tank so that the water flows by the action gravity. After passing through the filter, the water flows to the media bed culture (slightly lowered) where a bell siphon is allocated, continually flooding, and draining this recipient, the siphon ejects the water directly into the sump, which is the lowest component in the terrain. In the sump, two pumps are submerged, the first (270-Watt) pumps the water into the fish tank, closing the first circuit; the other pump (25-Watt), directs the water into the NFT channels through a pipe that ends in three valves, one directing the water into each of the channels. The channels are inclined to allow a continuous and shallow stream of water to run through the plants' roots. At the end of the NFT channels, the water directed to the DWC bathtub, which is lowered, and then connected to the sump, closing the second circuit. Figure 4.1 shows a schematization of the systems functioning and placement of each of the main components. The system has been built in a location almost at sea level, that way environmental oxygen concentration levels found are high, this allows the system to be viable without the need of external sources of additional oxygen to oxygenate the water (other than aeration mechanisms that use environmental air).

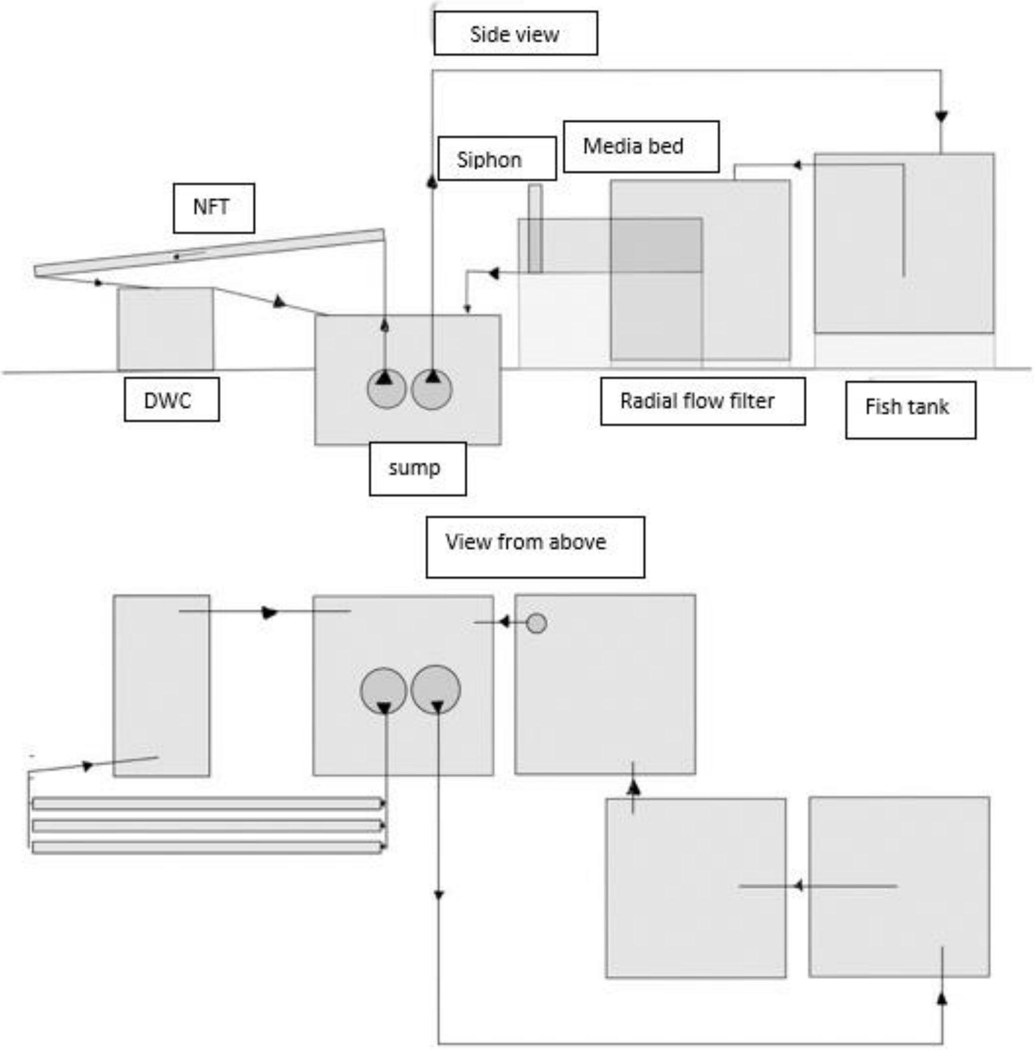

Figure 4.1- Schematization of the system. Own elaboration

The construction of the plant began January 27th, 2021. The first circuit (fish tank, filter, media bed and sump) was filled and water started circulation on March 21st. The NFT system was added on May 1st and finally, the DWC was added on May 29th, 2021. The construction of the system was done during the weekends, as it was combined with the finalization of studies of the two student who developed it.

4.1.- Material selection

To calculate the size of the different components of the system, the steps followed were similar to those explained in section 1.5.-

First, the plant growing area was estimated according to the space available. Since this study searched to implement the three basic aquaponic cultivating systems (DWC, NFT and media beds) the dimensioning pursued to implement a similar area for each of the three systems.

After designing the growing area of 2 m^2 (at maximum capacity) it was calculated that the number of fish to be introduced in the system should round 50 fish. This was an estimation based on the amount of feed the fish might need. However, it was expected that the process would require a period of trial and error until an equilibrium in the fish-to-plant ratio was reached.

A common rule to estimate the water volume needed for any given number of fish, is to offer a liter of water per centimeter of fish. With the aim of having 50 fish that will approximately have 10-15 cm of length, at least 500 to 750 L would be needed. [72]

For these 50 fish, a tank of 1000 L would be big enough. The 1000 L IBC tanks were chosen based on the volume needed but also on their availability and the practicality that these tanks offered to be cut, transported, and installed.

The previous specifications were considered to choose the components for the system:

- ***Fish tank***

  The fish tank is located on the highest part of the terrain. It is made with a 1000 L IBC tank which has been cut on the upper side to create an access to the fish. The hose coming from the sump continuously pours water directly into the tank. This water flow is regulated with a valve, so the water level stays constant in the tank. Submerged in the tank is an L-shaped 40 mm pipe which allows water to flow to the radial flow filter while avoiding any fish from going into this pipe and into the filter. This pipe serves as a bottom inlet and must be slightly pressed down to avoid the water entry hole to be big enough to suck any fish in. The Figure 4.2 shows the tank and the radial flow filter.

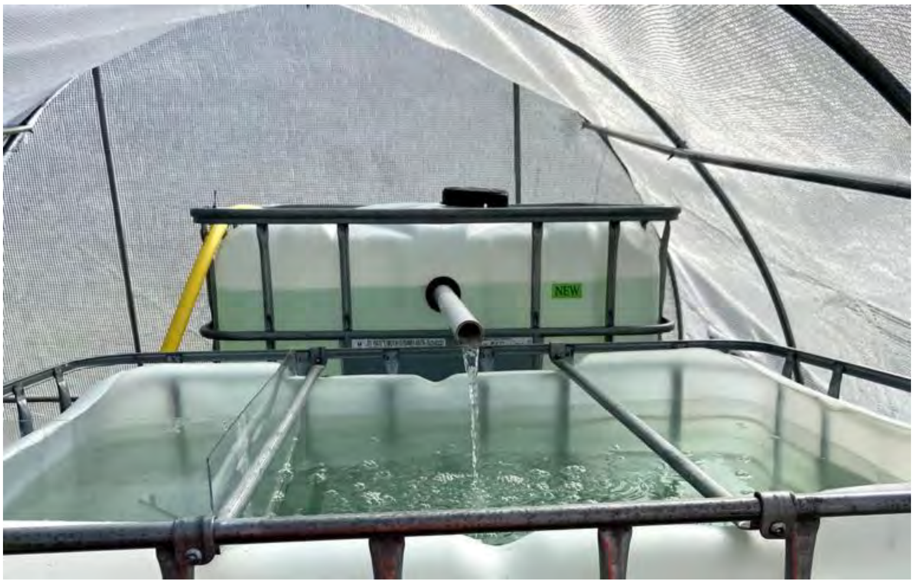

Figure 4.2 Fish tank (upper) and connection into radial flow filter (lower)-*Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

- ***Radial flow filter***

The radial flow filter is the second highest located component and consist of a 1000 L IBC tank with the upper side having been cut to allow access. The water comes directly from the fish tank into the filter through a pipe and the slow flow allows waste precedent from the fish to settle into the bottom of the tank and can be evacuated thanks to the valve located at the bottom of the IBC tank. The tank has been divided using polypropylene sheets that were cut and attached with silicon. These divisions allow the filter to have a zone that holds a group of bio balls, which constitute the biofilter. The Figure 4.3 shows the front of the radial flow filter.

Figure 4.3 Radial Flow Filter- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

- ***Sump***

  A third IBC tank was transversally cut at three quarters of its height to obtain two separate containers. The first half is used as the sump with a capacity of approximately 650 L. This component has been placed under ground and is located between the media bed and the DWC. Water pours into the sump from the syphon of the media bed intermittently and from the DWC continuously. The sump is shown in the Figure 4.4.

Figure 4.4 Sump (270-Watt pump in picture)- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

The main function of the sump is to have a deposit that can absorb the continuous change of water level due to the nature of the media bed bell siphon system and to have a secure amount of water to supply the system compensating the evaporation of water and any possible leaks. The two pumps are submerged into the water in the sump, the first one (270 W) pumps the water through a hose back into the fish tank, this is the highest energy that must be introduced into de system due to the difference in height between the two components (sump and fish tank) which is approximately 1.5 meters, and the 25 mm diameter hose is about 3 meters long. The second pump (25W) must overcome a slower head loss since it pumps the water from the sump into the NFT channels, which are located about 50 cm above the intake.

- ***Media bed***

The second part of the IBC tank that has been cut serves as container for the media bed culture. The 250 L of capacity are filled with a ground of rocks (approximately 50 L) and above these, expanded clay (approximately 200 L). The container is continuously flooded and drained with water which is poured continuously from the filter. In the Figure 4.5 is shown the media bed.

A syphon system installed at the opposite side of the water inlet expels the water once it reaches the top of the container, draining it and allowing it to be filled up to the top again. Since water level cannot reach the expanded clay at the surface, it stays dry, creating a covering layer which retains humidity and prevents algae from developing.

Figure 4.5 Media Bed- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

- ***Nutrient Film Technique***

  The NFT culture consist of three 60x80 mm PVC channels placed parallelly. The water from the sump comes into each of the channels through a pipe with three valves which are regulated for the water stream to be shallow, continuous, and equal in the three channels. The two meters long channels have and inclination of 30 cm from beginning to end to facilitate the water flow. At the end, a 12 cm channel collects the water which is poured into the DWC bathtub through a 4 cm diameter pipe. The upper side of the channels has been perforated with 10 cm holes to place the plants, separated 20 cm from each other. In the Figure 4.6 is observed the NFT channels.

Figure 4.6 Nutrient Film Technique- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

- ***Deep Water Culture***

  The DWC is placed on a bathtub, located between the ending side of the NFT and the sump, and is slightly lower than the NFT and higher than the sump to allow the water to flow. At the opposite side of the water entry, the bathtub's own sink is used as an outlet, with a 2 cm diameter flexible pipe, the water is conducted back into the sump. A polystyrene raft has been cut in shape to fit the bathtub and float on the water, it has also been perforated with nine 10 cm holes, eight of them to fit the plants and one to let the water intake in. The DWC is seen in the Figure 4.7.

Figure 4.7 Deep Water Culture- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

The species of fish used were comet goldfish (Carassius auratus), an image this fish is shown in Figure 4.8. A single tailed goldfish commonly bred in the United States. These fish have a varied feeding, their body´s color intensity and size will depend on the on the quality of their nutrition. Traditionally they are orange/yellow colored, but thanks to selective reproduction, nowadays they can be found in a variety of colors. [72,73]

Figure 4.8 comet goldfish (n.d.). [72]

This is a cold-water species, but do not require much care in this aspect since they easily adapt to their environment and climatization, this way they can live in warmer tanks. Comet goldfish are better living in company and in larger tanks since they are very active. The temperature of the water should stay between 16 and 25 degrees centigrade. Temperatures under 10 ºC can cause digestive problems. Most packed dry food contains all the nutrients these fish need. [46]

Goldfish grow throughout their lives around 2.5 cm per year this means than on their early stage they grow more rapidly, the growth rate will depend on different factors as temperature, density stocking, amount of food and water quality. [74]

These fish have a life expectancy of 5 to 19 years, and they can grow up to 20 cm (without measuring the tail). They grow quite quickly. These fish produce a high amount of bioburden. They should be fed 2-3 times a day and only be given an amount they can consume in under two minutes. [72,73,75]

The plants planted in the system consisted in lettuce and aromatic herbs (basil, cilantro, peppermint, and mint), the first plants introduced in the system are shown in the Figure 4.9. A total of 12 lettuce plants were planted among the NFT and DWC, four aromatic plants were also planted in the NFT (basil, coriander, and peppermint), and four mint plants were planted in the media bed as well as a lemongrass plant. Lettuce is a very good plant for aquaponic since the conditions this plant needs are very similar to the fish's needs (pH, temperature, etc). [76]

Figure 4.9 Close look of lettuce planted in NFT- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

To insert the fish into the system, these were first acclimated by slowly exchanging the water they were in and gradually replacing it with water from the system. Meaning during an approximately a six-hour period, a portion of the water containing the fish is taken out and water from the system is put in their container every 30 minutes approximately, until most of the water the fish are in comes from the system, and at this point they are directly poured out inside the fish tank.

To place the plants shown in the Figure 4.10, in the system their roots first must be cleaned. Each plant is cleaned and separated. Each plant is then planted in its appropriate place using expanded clay to hold it (as soil would hold it).

Figure 4.10 Clean plants ready to be planted- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

4.2.- Plant construction

Firstly, three 1000 L IBC tanks were obtained and proceeded to be cut according to design, as shown in Figure 4.11 and Figure 4.12.

Figure 4.11 Radial flow filter (left) and fish tank (right)- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

Figure 4.12 Media bed container (left) and sump (right)- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

The NFT channels had to be highly modified to fit the design. The upper cover was perforated with 10 cm circular holes to fit the plants, as shown in Figure 4.13. Two of the three channels were perforated with each hole having a 20 cm distance from one another and the other with a separation of 15 cm, resulting in two channels that fit eight plants and one that can fit ten plants. The rails inside the channels had to be sanded to allow the stream of water to reach the bottom of the nests that house the plants.

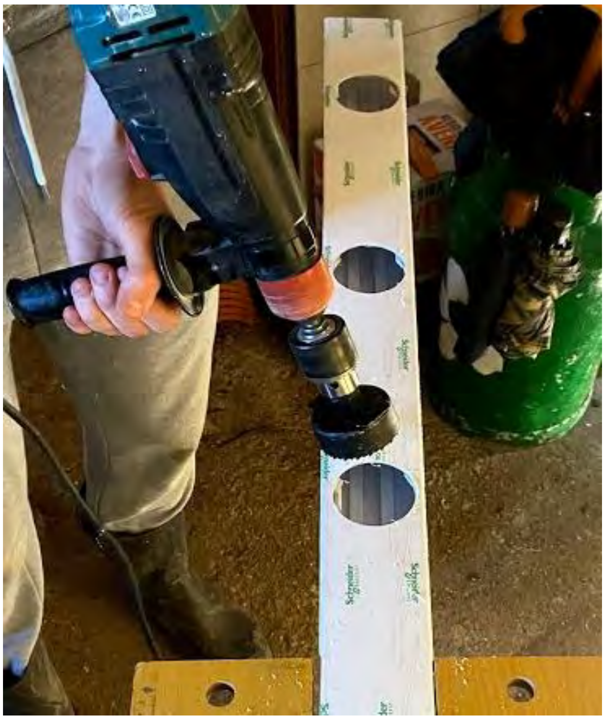

Figure 4.13 NFT hole perforation- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

For the siphon, a 3 cm diameter pipe was cut at a height of 40 cm and placed inside a 5-diameter pipe cut at a height of 50 cm. The first was perforated at the bottom to let water in, and the top was covered by gluing a 5 cm methacrylate diameter circle, to allow vacuum to appear inside. A small hole was made at the top to connect a 0.5 cm plastic hose that connects the top and bottom. Figure 4.14 shows the result of the inside pipe.

Figure 4.14 Inside pipe of the siphon- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

The external pipe is similarly perforated at the bottom and a lid was made off a 5 cm cap to cover the superior entry, avoiding unwanted solids to enter. When placed in the system, rocks are placed on top of the internal pipe to secure that it stays attached to the bottom of the media bed container for optimal functioning.

Figure 4.15 shows the siphon in place in the system, only the external pipe can be seen.

Figure 4.15 Siphon in place- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

The land in which the system is located has a slight natural incline. To allocate all components leveled and at necessary height, the terrain had to be worked. All components needed some amount of soil to be moved underneath to have a flat base to be placed upon. To allocate each component at the necessary height, several pallets were placed underneath as seen in Figure 4.16.

Figure 4.16 Pallets placement. -*Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

A hole was dug in the ground to fit the sump allowing it to be lowered as it is needed as seen in Figure 4.17 and Figure 4.18.

Figure 4.17 Digging a hole for the sump- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

Figure 4.18 Sump placement- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

A 3x8 meter greenhouse was built to house the complete system which can be seen in Figure 4.19.

Figure 4.19 Greenhouse construction and IBC components placement- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

Figure 10.1 represents the timeline in which the terrain preparation for the plant took place. After building the green house, the rest of the components were brought inside. The distribution was that shown on Figure 4.1.

The sump, previously positioned in place, such as the filter, media bed and fish tank, was filled with water. The first pump was put in place (inside the sump) and the 25 mm diameter hose is connected to the outlet, directing the water into the fish tank as shown on Figure 4.2. The inlet was placed in the middle of the fish tank allowing water flow onto the radial flow filter. The pipe that connects the filter and media bed was also put in place.

The media bed was filled with the clean rocks and expanded clay, simultaneously placing the siphon in place to secure the lower surface of the siphon to be affixed to the media bed´s ground for its optimal functioning.

For the addition of the NFT and DWC, the second pump (25 W) connects the sump to the NFT inlet, the three NFT channels were placed on three easels, previously leveled with the necessary inclination, channels were secured to the easels. Another channel was placed perpendicularly at the end of the NFT (as shown in Figure 4.20) to collect the water and direct it to the DWC, which was connected to the sump through its own sink.

To help running water to uniformly reach all the lower surface of the plant baskets and therefore optimally reaching the roots of the plants, a sponge was cut into 1-inch-thick rectangles, each placed inside the channel before each basket.

Figure 4.20 NFT outlet detail (water collection channel)- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

The DWC was built using a bathtub filled with water and a polystyrene board was accommodated with holes in it for plant nests, this board floats on the water in the bathtub. To help oxygenate the water in the system, an aerating pump was introduced. The pump has three outlets, one was placed in the fish tank, another one in the DWC bathtub, and the last one was placed in the sump, close to the bio-balls net. The outlets flow air into diffuser rocks which help distribute air.

4.3.- System´s maintenance and filtration

To get rid of excess waste, the sludge settled at the bottom of the radial flow filter must be expelled. For this, a hose is connected to the outlet of this tank, collecting liquid from the bottom, and thus expelling an important fraction of the sludge. This procedure was performed weekly.

The water was poured onto an adjacent fruit tree[2], this way the water that was taken out of the system served a purpose and was not wasted. Simultaneously, a low flow of water was poured into the sump, to replace the water taken out though the filter´s outlet as well as any water that might have evaporated the system throughout the week or any leaks if there were.

The most significative parameters of the water (pH, temperature, TDS, DO, NH_4^+, COD, NO_2^- and NO_3^-) were measured to both document the process and revise the evolution towards optimal levels to consider any necessary actions to be taken.

Figure 10.1 represents the timeline for which the system´s operation took place, starting with the moment water started circulating and considering each time water parameters were measured.

[2] Water was poured close to an avocado tree. The tree is about five years old and had not yielded any usable fruit in the past. This year five avocados appeared in the tree, but their size is small as of the end of this study. It is possible that the nutrient rich water that was poured onto the tree from the aquaponic system had a positive effect on it.

To dispose and/or extinguish unwanted waste or harmful chemicals from the system, both mechanical and biological filtration mechanisms take place. For this purpose, three systems are implemented, these are the mechanical filters and the biofilter.

4.3.1.-Mechanical filters

The mechanical filtration would occur in three stages, a settling tank or clarifier, a foam filter of different particle sizes to collect the smallest wastes and even if some waste gets through these two filtration systems there is a third one, the media bed, which expanded clay will help to retain the possible solids that reach this stage.

As the first stage of the water filtration process, the radial flow filter allows the expelling of the greater solid particles, which not only are harmful for the fish and plants (blocking roots and precluding the absorption of water and nutrients), but could also damage the pumps, pipes, and other components.

Fish waste has a density very close to the water one, making it harder for it to settle and allowing its expulsion from the system. One way to accomplish this is by implementing a radial flow filter system. this type of system has three big advantages:

- They are much more compact than a standard settling basin.
- They are much more effective than other settling devices that are smaller than a basin.
- Even though there are other settling devices that can remove a greater percentage of the total solid material in the flow, these have a much higher material budget to keep them working.

The radial flow filter used is based on a typical model of radial flow system, which was modified to a square container for economic and logistical reasons. A typical radial flow system, as shown in Figure 4.21, consist of a cylindrical container with the water coming in from bottom to top so it pours radially, hence the name.

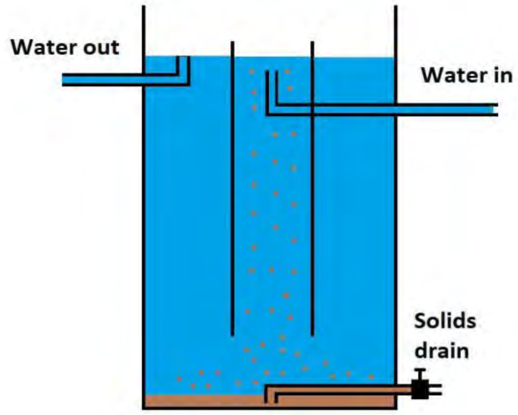

Figure 4.21-Typical radial Flow filter [77]

The filter implemented in the system studied, serves the same function, with the exception that the container is cubic instead of cylindrical and the water intake is poured from above the surface of the system.

The water that comes into the filter proceeds from the bottom of the fish tank, this water carries the highest amount of solid waste of the system and must be drained out of it as efficiently as possible. The water that enters the filter reduces its velocity and very slowly flows down the filter, as it gets to the bottom area of the filter, the settling appears, and the particles settle down to the bottom of the tank. As the water begins to rise again towards the top, the velocity has decreased even more, and the lateral walls of the filter help to continue decreasing it. The valve placed at the bottom of the IBC tank, allows the drainage of the settled particles out of the system.

A 4 cm diameter pipe is placed just below water level, at a lateral of the tank, allowing (filtered) water to run to the next stage. This pipe has been perforated to allow a higher water flow.

The minimum retention time recommended for a radial flow filter is 20 minutes, meaning at least 20 minutes should pass from the moment a particle of water comes into the filter until the moment it is expelled from it, but in any case, a higher time is always more beneficial. [58]

The filter used in this study has a capacity of 1000 L and the water flow is about 30 liters per hour, meaning the retention time is approximately 33 minutes, which is an improvement of the recommended 20 minutes.

The foam mechanical filter is placed under the radial flow filter´s outlet, it is implemented to improve the results of the radial flow filter and filters water pouring it directly into the media bed.

The water runs through a 20x40x25 cm box filled with four different filtrating materials, firstly two types of foam, the first one having thicker holes than the second. Underneath the foam lays a layer of perlon and finally, a 2x2 m of fabric (mosquito net) folded into a rectangle to fit the box; this way, each step of the materials in the box has smaller holes to let water trough than the last, preventing them from getting clogged and catching more of the waste found in the water.

The rocks and expanded clay found in the media bed also serve as a mechanical filter for the water, catching even more particles that could still be found in the water.

4.3.2.-Biofilter

The water proceeding from the syphon is very clean after having been through the radial flow filter and the mechanical filter. This water is poured into a net filled with approximately 60 liters of wheel shaped bio balls floating on the sump. These bio balls, as shown on Figure 4.22, are porous, allowing bacteria to host on their surface. The rocks and expanded clay in the media bed also serve as a biofilter, as the darkness found inside is very suitable for bacteria growth.

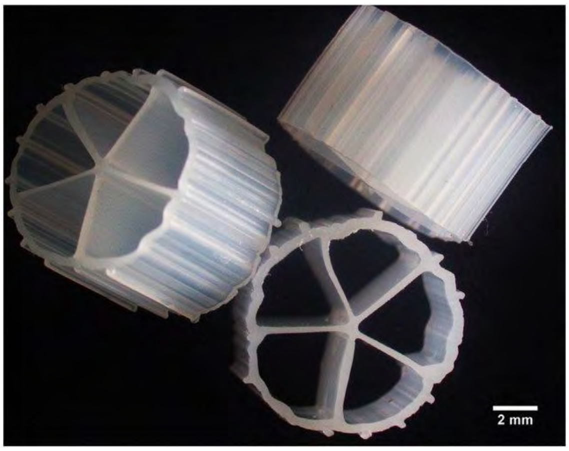

Figure 4.22- Wheel shaped bio-balls

There are bio-balls in the radial flow filter (about 40 L) that can also hold bacteria. These balls are contained in ¼ of the tank, separated by a polypropylene sheet. This can be observed in the Figure 4.23.

Figure 4.23 View from above of the radial Flow Filter-Bio balls can be observed in the lower left corner- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

Nitrifying bacteria require dissolved oxygen to be between 4 and 8 mg/L. To reach these conditions, the biofilter was placed directly under the media bed outlet allowing water to oxygen it, and an oxygenator was placed inside the biofilter. [16]

5.- MEASURING PROCEDURES

To perform the analysis of the system´s water quality and the evolution of parameters, two samples were taken weekly for a period of two and a half months. The measurements were made during the first 50 days of the system´s functioning with fish. A month after the first 50 days, another two measurements (made within a week of separation from each other) were made to observe the evolution of the system. After these measurements it was observed that the system had reached the stage of maturity since there weren't any significant changes in the water parameters, so we waited about 3 months to perform again the measurements and a last one was completed 2 months later.

The two samples were taken in two different locations in the system, which were always the same: the radial filter, and the sump. Dissolved oxygen (DO), pH and total dissolved solids (TDS) where always measured in site. Dissolved oxygen and pH are unstable and cannot be measured using refrigerated samples. The other parameters were measured at the laboratory of the Chemical and Environmental Engineering Department of the University of Oviedo, at the Gijón campus. To do so, a 500 mL bottle was filled with water from each location to be analyzed and these samples were refrigerated and brought to the laboratory. The analyses made at the laboratory were done using a photometer. This device is based on the measurement of the absorbance of electromagnetic radiation at a characteristic wavelength of the element to be measured. [78]

5.1.- Nitrates

Nitrates were measured at the laboratory by colorimetric determination as nitrite after reduction. A reducing agent was used to convert nitrate to nitrite in a weakly acidic medium. They form with a suitable aromatic amine an orange-yellow azo dye. [78]

The procedure was done using a nitrate measuring kit with the necessary reagents (nitrate-1 and nitrate-2). First, 10 mL of sample water were added to each test tube, the 10 drops of nitrate-1 were added, and the tube was shaken to mix. Afterwards, a small spoon of nitrate-2 was added, and the solution was mixed once again. The solution was left for five minutes after which each tube was placed in the photometer, previously tared with a tube filled with clear water, and it gave a result as extinction.

The value given by the photometer had to be converted using a calibration table to obtain the actual value. Said calibration table contained a range of 27 extinction values from 0.04 to 0.89 and their respective true values of nitrates in mg/L from 1 mg/L to 40 mg/L. This calibration table represented a variety of points of a curve. To convert the extinction value to the true value, the interpolation method was used between the two closest values in the calibration table to the one read by the photometer.

5.2.- Nitrites

Nitrites were determined by colorimetric determination of nitrite ions with sulphanilic acid and 1-naphthylamine. Nitrite ions form a diazonium salt in an acidic environment with sulfanilamide. This, coupled with naphthylamine, produces a purplish-red azo dye. [78]

The measuring procedure for nitrites was equivalent to that of nitrates, except for the reagents kit used being specific for nitrites and the reaction time being ten minutes instead of five.

The value read by the photometer also represented an extinction value and had to be converted using the corresponding calibration table. The conversion method was the same used for nitrates.

5.3.- Dissolved Oxygen

As stated before, Dissolved Oxygen was measured in-site. The measurement was obtained with a dissolved oxygen meter. The probe was directly introduced into the water at the two specific locations to be measured and the meter directly indicated the DO value.

The Dissolved Oxygen meter used was the model “VWR DO210”. This tool uses a polarographic electrode to measure DO and comes with a built-in temperature probe to measure temperature. Both parameters are measured simultaneously and displayed on its LCD. [79]

5.4.- Temperature

Temperature was also measured in-site. The value was given by the dissolved oxygen meter.

5.5.- pH

The pH value was measured in site. A pH meter was introduced directly into the water at the two specific locations in the system (filter and sump). The pH value was obtained in a matter of seconds.

5.6.- Total Dissolved Solids

TDS were measured in site using a TDS meter which was directly introduced into the water. The value was obtained in under two minutes. The TDS meter measures the conductivity of the water. Pure H_2O or distilled water does not conduct electricity, so if the TDS meter is submerged in it, the result would be zero. Electricity is conducted by the charge of the electrons that compose the minerals present in the water. TDS are composed of inorganic salts, commonly calcium, magnesium, potassium, sodium, among others. [80]

5.7.- Chemical Oxygen Demand

The COD was measured by photometric determination of decrease in chromate concentration after two hours oxidation at 150ºC. [78]

In the laboratory, 2,5 mL of water sample were introduced in a test tube. The tubes with the sample were brought to the safety cabinet where the reagents were added. The reagents were sulfuric acid and potassium dichromate, 1,5 mL of the oxidant solution were added to each sample, followed by 3,5 mL of the acid solution. The reaction took a time of 2 hours at 150ºC, the resulting substance is very stable, they were measured a week after.

When the sample was ready to be measured, the photometer was tared using a tube with clear water. To determine the COD, the tube was placed in the photometer which directly gave the COD in mg/L.

5.8.- Ammonium

Ammonium was determined in the laboratory. The reagent powder contained dichloroiscyanuric acid, which formed hypochlorite, and this reacted with the ammonium present in the sample forming monochloramine. This then formed a quinone imine along with phenol from the reagents and this last reaction created an intensely blue colored indophenol, which was then evaluated photometrically. [78]

6.- ORIGINAL DESIGN MODIFICATIONS

Once the design of the facility was made, there were approaches that could not be carried out in practice and others that were not optimal. These issues could only be taken into consideration once the installation process began or seeing the progress of the system.

6.1.- Bacteria development

A used aquarium filter was implemented to accelerate the maturation of the biofilter and introduce the nitrifying bacteria into the system from the beginning.

Introducing a filter which had been used in an aquarium for over a year, introduces nitrifying bacteria directly into the system, meaning these bacteria would be developed and inside the system from the beginning, instead of them having to enter the system from the environment and slowly reproduce.

6.2.- Design modifications

Some deviations were made from the original design, as well as modifications on typical designs, whether for logistical or economic reasons. The most significant are the following:

- ***Additional Mechanical filter***
  The set of foam, perlon and fabric placed at the outlet of the radial flow filter was an addition made to the filter to maximize the elimination of waste particles that could be found in the water after the first filtration stage.

- ***Bio-filter location***
  Originally, the totality of the bio-balls were designed to be inside the radial flow filter. The filter would have inside division that would allow the bio-balls to float only at the outermost stage of the water´s flow in it.

6.3.- Lower number of fish

The number of fish that were introduced into the system was clearly lower than the number of the original design. As it is said in section 4.-, it was first aimed to introduce 50 fish, however the actual number of fish was around 30.

The difference between original design and the actual number was due to economic and logistic reasons. Each fish has a cost at least of 2-3 euros. The system had already had a high cost as almost all components had to be bought (all except from the DWC bathtub).

After some reflection, it was decided to keep a lower fish density and balance it out by removing plants as necessary.

7.- RESULTS AND DISCUSSION

7.1.- Plant growth

Plants were introduced into the system between May 1st and May 15th of the current year. Two weeks after all the plants were introduced an important development was appreciated, especially in lettuce, which acquired significant coloration, passing from a pale green color (see Figure 7.1) to a very intense violet color (see Figure 7.2).

Figure 7.1 Lettuce after plantation- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

Figure 7.2 Lettuce two weeks after plantation- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

Important development was also appreciated in the roots of all plants, as these grew substantially in the first two weeks (see Figure 7.3 and Figure 7.4).

Figure 7.3 Detail of lettuce roots at the moment of plantation- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

Figure 7.4 Detail of lettuce roots two weeks after plantation- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

All plants had very good aspect after the first two weeks of having been introduced into the system, coloration was intense, stems looked strong, and some growth could be appreciated. The good and healthy appearance lasted for the following month. plants appeared to continue growing and developing. (See Figure 7.5).

Figure 7.5 system appearance by June 4th - *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

On June 12th, it was observed that coriander, located and the top of the NFT system, had started to look dry and weak. By June 17th, the peppermint located in the NFT system also appeared dry and weak, showing that it was perishing; Figure 7.6 shows how the lower leaves of the peppermint plant looked dry and the plant had a negative aspect in general.

Figure 7.6 Peppermint on June 17th - *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

The system continued functioning normally as the plants all kept worsening in aspect and growth rates kept slowing down until completely stopping. The bad plant situation was closely monitored, and it seemed that they were not receiving enough nutrients, as their aspect kept worsening (see Figure 7.7). This way it was decided to lower the plant density to allow more nutrients to be available for the remaining plants. On July 1st the peppermint plants were removed from the media bed, after which it could be appreciated that the roots of these plants had grown considerably, as can be seen on Figure 7.8.

Figure 7.7 Coriander on July 24th - *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

Figure 7.8 Peppermint after removal- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

Plant density kept being lowered to benefit remaining plants. Basil, coriander, and some lettuces were removed in the following weeks. By August 26th the remaining lettuce gleaned, demonstrating the end of their life cycle after very little growth (see Figure 7.9). Overall, plants started showing signs of malnourishment after the first 50 days of plant operation.

Figure 7.9 Gleaned lettuce- *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

7.2.- Fish growth rate

On April 24th of the current year, 26 fish were introduced into the system, shown in the Figure 7.10, starting the system´s operation. Another ten fish were added on June 4th. The fish were fed four times a day, the amount of feed they were given added up to approximately 8 grams per day; this much feed was determined by the amount the fish could eat in under two minutes each time they were fed, which is the general rule to estimate the how much feed they should be given.

Figure 7.10 First group of fish at insertion-April24th - *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

The fish showed progressive growth and overall, a good appearance, thus indicating that they were well nourished and healthy. The good aspect and growth rates fish showed throughout the entirety of the system´s functioning was an indicator that they were being fed enough for their necessities, and that their environment was adequate, meaning the water quality wasn't harmful for their health in any apparent way. This good aspect and growth were observed in the fish continuously until the last time the system was analyzed for the present study; the difference in size and anatomy is visually notorious when comparing Figure 7.10 and Figure 7.11.

Figure 7.11 Fish appearance-July 17th - *Note*. Photograph of the pilot plant of the present study (2021). Own elaboration

After one month in the system, we proceeded to weigh the fish, 7 fish were caught obtaining a weight of 30 grams, in other words an average weight of 4.29 grams, 245 days later a second weighing was carried out, this time 9 fish were captured getting a weight of 414 grams, an average weight of 46 grams indicating that after this time they grew 973% compared to the first weighing. In the Figure 7.12 is seen the weighing procedure.

Figure 7.12 Weighting of the fish.

As a reference to compare the data obtained from our project, it was used the research work: [81]

Looking at the **Table 3**, we can see that the growth rate of the goldfish in our system is slightly lower than the rate of the reference research work, this is due to several factors:

- The growth was assumed to be linear which is not the case because at the beginning the fish double their size in a very short period and as they become adults this rate slows down.
- The initial size of the fish in the research work was smaller and they had a greater margin for growth.

- The stocking density was lower in the research work 10 juniors per 450 liters (23 fish/m^3) versus 36 juniors per 1000 liters (36 fish/m^3) on our system.

- The temperature exposed by the fish of the research work was 27ºC while the temperature in our system oscillated between 24.4ºC and 12.7ºC.

These factors indicate that both feeding and water quality have been satisfactory to allow normal growth of the fish. [81]

Table 3 Growth rate comparative between our system and the reference research work.

Pilot	05/06/2021	05/02/2022		**Research**	**Pilot**
Weight of 7 fish (g)	30		Initial Weight (g)	3.32	4.29
Weight of 9 fish (g)		414	Final Weight (g)	9.18	46
Unit weight (g)	4.29	46	Weight gain per day (%)	4.89	3.97
Days		245	Weight gain after 36 days (%)	176	143
			Weight gain after 245 days (%)		973

7.3.- Water quality parameters

The parameters were analyzed after several number of testing with the data obtained both numeric tables and graphs were included in the results. These parameters are the nitrates, nitrites, DO, temperature, pH, TDS, COD, ammonium, TAN and total nitrogen.

7.3.1.-Nitrates

As it is explained in section 1.4.4.-a, nitrate is necessary for plant nourishment. Figure 7.13 shows how nitrates were at its highest at the beginning, two weeks after introducing the first group of fish.

As seen in section 1.4.4.-, nitrates over 30 mg/L can be harmful for fish, however, nitrate is a necessary nutrient for plant nourishment, and so if this nutrient is not found in the water, plants will not grow and/or will perish.

Nitrate levels never reached a point that would make it harmful for fish, as the highest value measured was under 13 mg/L. This is corroborated by the fact that fish showed good health throughout the whole study.

Table 4 Evolution of the concentration of Nitrates in the water in mg/L according to the location of the sampling point and analysis performed using colorimetric determination as nitrite after reduction

	Days							
	14	**21**	**28**	**35**	**49**	**92**	**181**	**229**
Filter	12.1	0.4	1	0.3	0	0.4	0.45	0.4
Sump	11.8	3.1	1	0.4	0.3	0.3	0.3	0.3

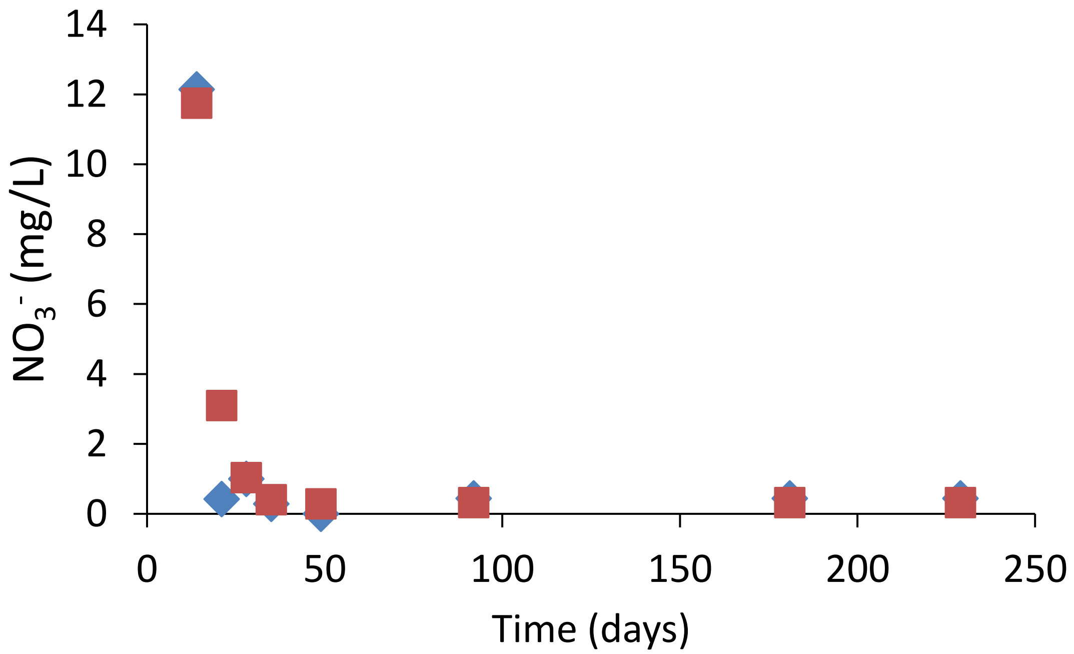

Figure 7.13 Nitrates evolution. Data corresponding to the sump (red) and filter (blue)

7.3.2.-Nitrites

Nitrites, as nitrates, were at the highest at the beginning of operation. Nevertheless, the highest nitrate levels measured in the system were still very low, keeping under 0.5 mg/L. As seen in Figure 7.14.

The level at which this parameter becomes dangerous is 1 mg/L, as it is said in section 1.4.4.-b. Nitrites never got close to a concentration that could be harmful for the fish.

Table 5 Evolution of the concentration of nitrites in the water in mg/L according to the location of the sampling point.

	Days							
	14	**21**	**28**	**35**	**49**	**92**	**181**	**229**
Filter	0.5	0.3	0.1	0.1	0.04	0.05	0.05	0.05
Sump	0.4	0.2	0.1	0.04	0.03	0.05	0.05	0.05

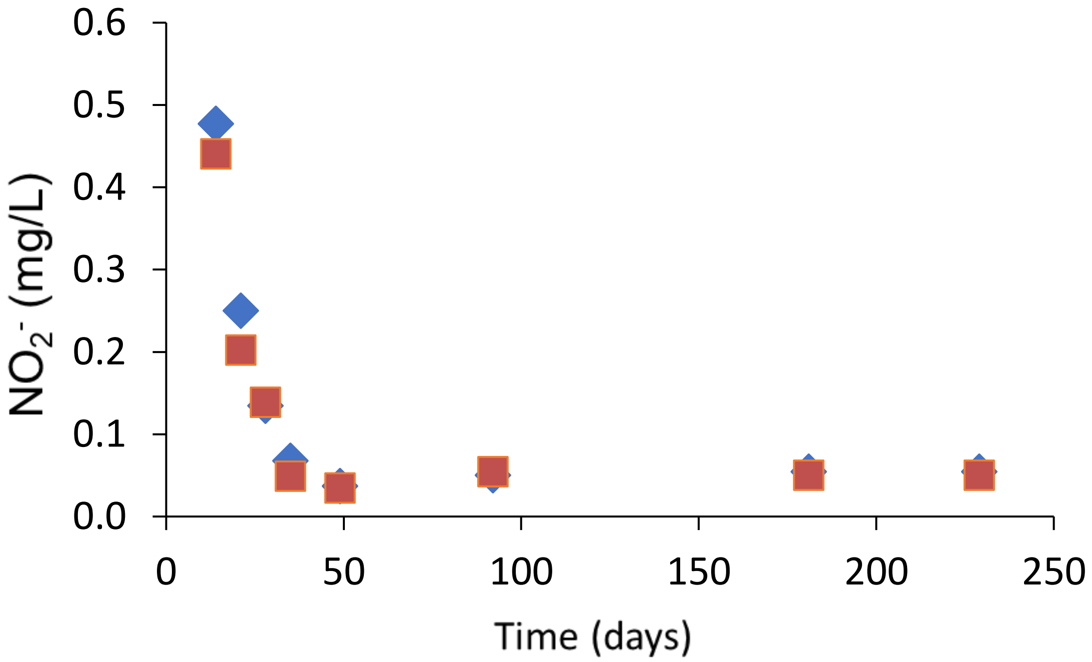

Figure 7.14 Nitrites evolution. Data corresponding to the sump (red) and filter (blue)

7.3.3.-Dissolved oxygen

The minimum requirements of DO is set by fishes' needs, which require at least 5 mg/L (see section 1.4.4.-i). It can be seen, in the **Table 6**, these levels were surpassed in the system the whole time.

Aeration mechanisms were introduced into the system after the first week. Figure 7.15 shows how this action made DO levels rise from an average of 6.17 mg/L to 8.62 mg/L. After this, DO levels stayed very stable the whole time.

Table 6 Evolution of the concentration of DO in the water in mg/L according to the location of the sampling.

	Days							
	0	**7**	**21**	**28**	**35**	**49**	**85**	**92**
Filter	5.6	8.66	9.2	9.3	9.4	8.9	7.6	7.6
Sump	6.8	8.6	8.4	8.7	8.2	8.2	8.3	7.8

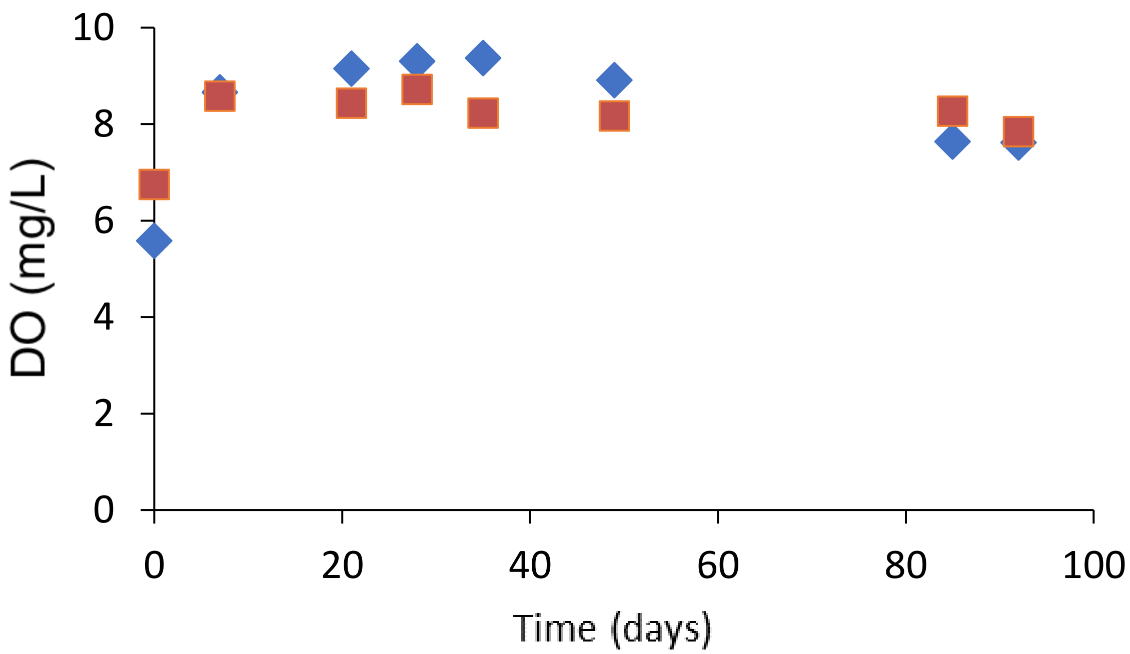

Figure 7.15 Dissolved Oxygen evolution. Data corresponding to the sump (red) and filter (blue)

7.3.4.-Temperature

Temperature in the system stayed at a range between 12.6ºC and 24.4ºC, as seen in the Figure 7.16. This temperature range is perfectly adequate for bacteria and plants (see section 1.4.4.-e). Temperature was also in the correct range for the fish, which need 10 to 25ºC (see section 4.-)

Table 7 Evolution of the Temperature in the water in ºC according to the location of the sampling.

	Days									
	0	**7**	**21**	**28**	**35**	**49**	**85**	**92**	**181**	**229**
Filter	23.2	18.5	20.0	21.1	24.0	23.0	24.1	24.4	14.8	12.7
Sump	23.1	18.3	20.0	20.8	23.4	23.1	23.9	24.2	14.5	12.6

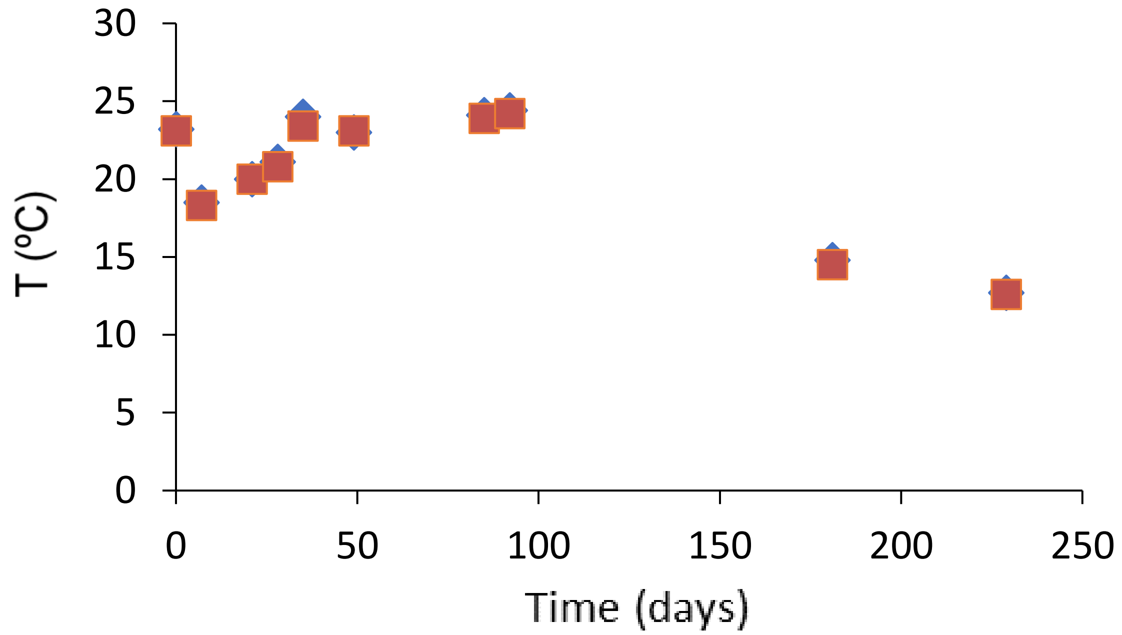

Figure 7.16 Temperature evolution. Data corresponding to the sump (red) and filter (blue)

7.3.5.-pH

pH levels were particularly high at the beginning of operation. As stated in section 1.4.4.-c, this parameter can stand up to 8.0 while still keeping optimal conditions for bacteria, fish and plants, hence it was observed after the first measurements that actions had to be taken in order to stabilize pH and bring it to the optimal range of 6.5-8.0 for aquaponic systems.

Figure 7.17 shows how these levels were lowered after the first month, which matches the period in which peat and oak tree leaves were added into the system to lower pH.

The pH level appeared to rise again after 92 days. This should be fixed by repeating the procedure of adding agents such as peat and/or oak tree leaves, until the system reaches an equilibrium and it is no longer needed to alter the pH.

Table 8 evolution of pH in the water according to the location of the sampling.

	Days									
	7	**14**	**21**	**28**	**35**	**49**	**85**	**92**	**85**	**92**
Filter	8.4	9.1	8.6	8.6	7.8	6.9	7.2	8.5	8.1	7.6
Sump	8.6	8.9	8.7	8.7	8.2	7.3	6.9	8.0	7.9	7.7

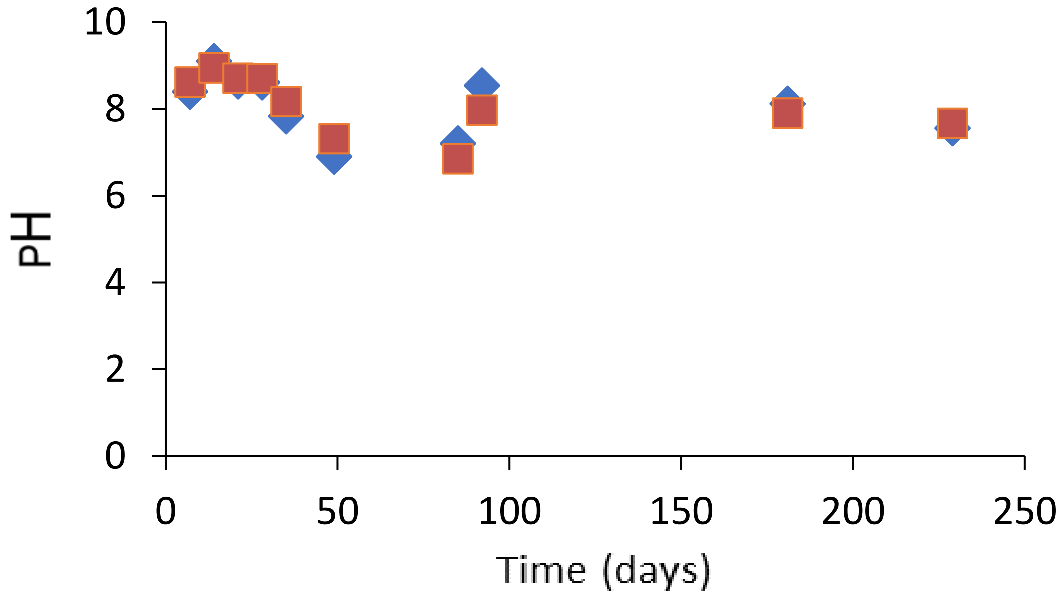

Figure 7.17 pH level evolution. Data corresponding to the sump (red) and filter (blue)

7.3.6.-Total dissolved solids

Total Dissolved Solids (TDS) never surpassed 78 mg/L, as seen in the Figure 7.18. These levels are safe for all species (see section 1.4.4.-d). Low TDS concentration is an indicator of low fish density as it is fish who produce waste, and this waste increases TDS.

This parameter allows us to control the organic and inorganic materials in the water, even so it is important to notice that it doesn't state the source of the solids, that's the reason why nitrates, nitrites or ammonium must be measured separately.

Table 9 Evolution of Total Dissolved Solids in mg/L according to the location of the sampling.

	Days									
	7	**14**	**21**	**8**	**35**	**49**	**85**	**92**	**181**	**229**
Filter	67	75	69	59	70	77	72	78	70	75
Sump	68	76	69	61	68	78	66	75	69	73

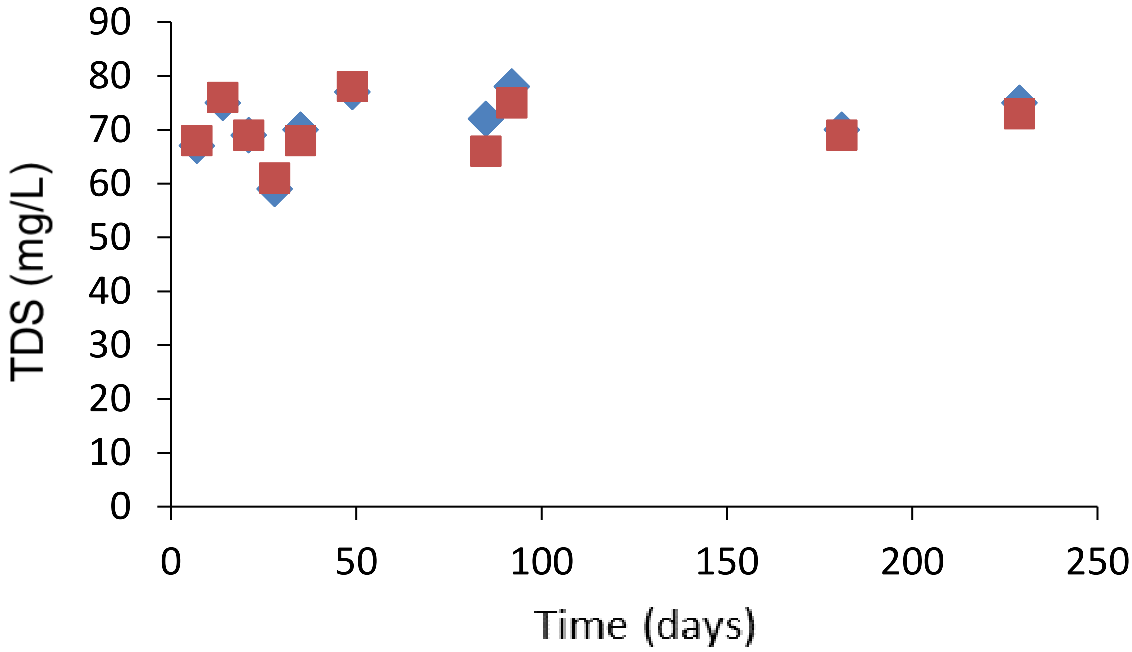

Figure 7.18 Total Dissolved Solids evolution. Data corresponding to the sump (red) and filter (blue)

7.3.7.-Chemical Oxygen Demand

Chemical Oxygen Demand levels stayed very stable during most of the duration of this study. As it is stated in section 1.4.4.-g, if COD levels are too high, it would cause an insufficiency in oxygen levels in the water, which would be incompatible with life. This is not the case for this study according to the results observed in the fish and adequate DO levels.

The fact that fish kept good health and showed growth throughout the study demonstrates that the levels of COD found in the water are perfectly compatible with their life. Also, Dissolved Oxygen found in the water was always inside the right parameters, and higher COD levels reduce DO. It is possible that the use of aeration mechanisms has counteracted the negative effects of a high COD.

The decrease in COD levels found in the sump in the measurement on day 49th is an indicator that the system might have reached a stabilization as the nitrification process has appeared. This is shown in the Figure 7.19. Once this stabilization was reached it was procced to do another measure to confirm this state after several months, indicating the system is fully mature.

Table 10 Evolution of the Chemical Oxygen Demand in mg/L according to the location of the sampling point.

	Days				
	7	**14**	**21**	**28**	**49**
Filter	262	221	217	253	250
Sump	259	256	243	250	91

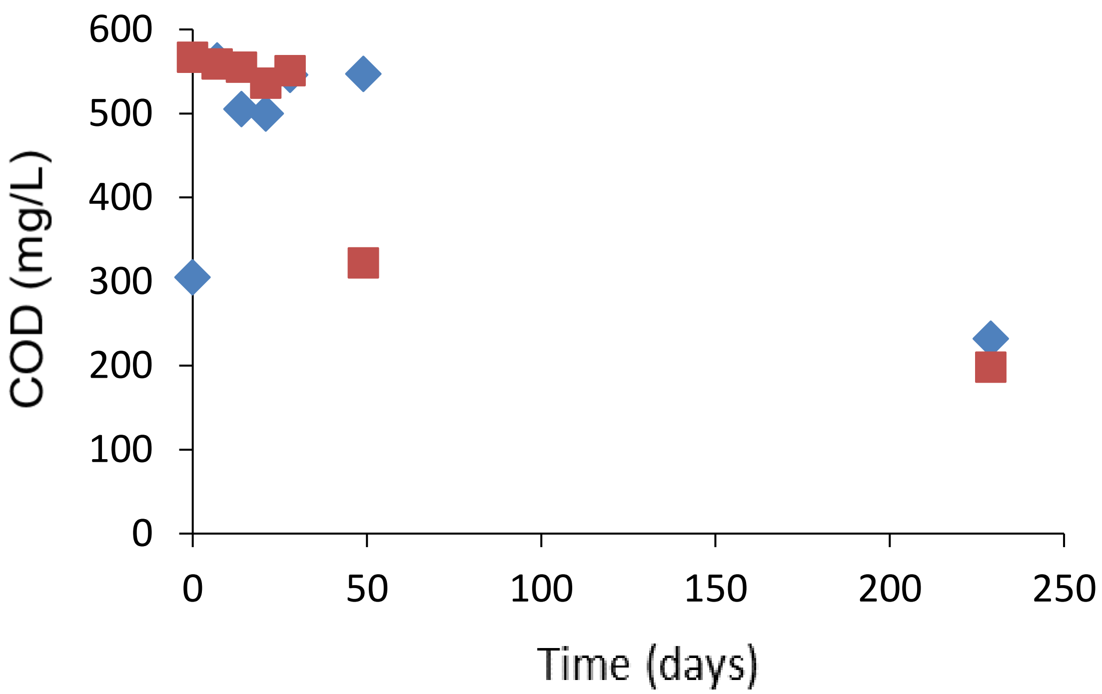

Figure 7.19 Chemical Oxygen Demand evolution. Data corresponding to the sump (red) and filter (blue)

7.3.8.-Ammonium

Ammonium, like other forms of nitrogen (NO_2^- and NO_3^-) experienced a high point at the beginning followed by a downfall after the first two weeks. This parameter also showed a possible trend to rise again after the plants were removed.

To evaluate this parameter, it results more interesting to analyze all forms of ammonia (NH_3 and NH_4^+).

Table 11 Evolution of the concentration of Ammonium in the water in mg/L according to the location of the sampling point.

	Days						
	14	**21**	**35**	**49**	**92**	**181**	**229**
Filter	1.4	0.5	0	0	1	0	0
Sump	1.5	0.9	0	0	1	0	0

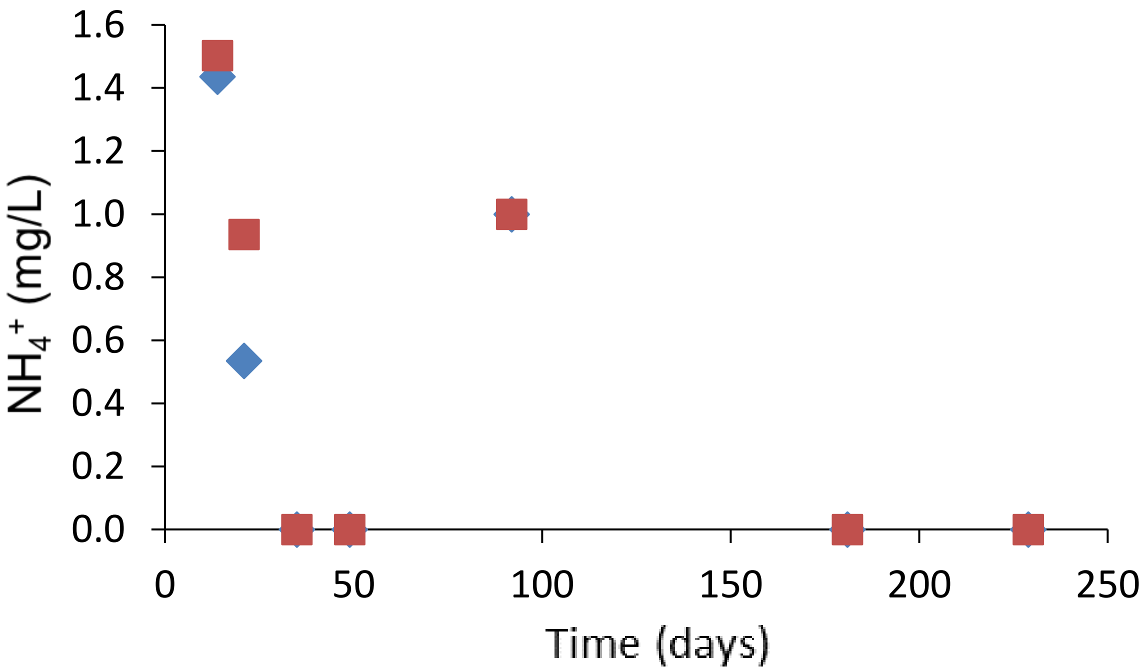

Figure 7.20 Ammonium evolution. Data corresponding to the sump (red) and filter (blue)

7.3.9.-Total Ammonia Nitrogen

Using **Table 1**, total ammonia nitrogen was calculated from the measured ammonium values, using the average Ammonium, pH and temperature in the system each day of measurement. **Table 12** calculated using the ammonium, pH and temperature measured at the sample point and **Table 1** in Freshwater that is in the Toxic Un-ionized Ammonia Form at different pH values and temperatures. Average data from sump and filter, shows the corresponding ammonium and ammonia values.

As it can be seen in Figure 7.21, the temperature and pH levels found in the system throughout the entirety of the study allowed the Total Ammonia Nitrogen composition to be in majority the non-toxic form of ammonia (NH_4^+).

Table 12 Total Ammonia Nitrogen composition. Average data from sump and filter.

	Days						
	14	**21**	**35**	**49**	**92**	**181**	**229**
Temperature (ºC)	19.2	20	23.7	23.1	24.3	14.65	12.65
pH	9.1	8.7	8	7.1	8.3	8	7.6
NH_4^+ (mg/L)	1.5	0.7	0	0	1	0	0
NH_4^+ (%)	65.8%	77.8%	82.9%	99.1%	91%	97,37%	99,08%
NH_3 (mg/L)	0.8	0.2	0	0	0.1	0	0
NH_3 (%)	34.3%	22.2%	17.1%	0.9%	9%	2.63%	0.92%
TAN (mg/L)	2.2	0.9	0	0	1.1	0	0

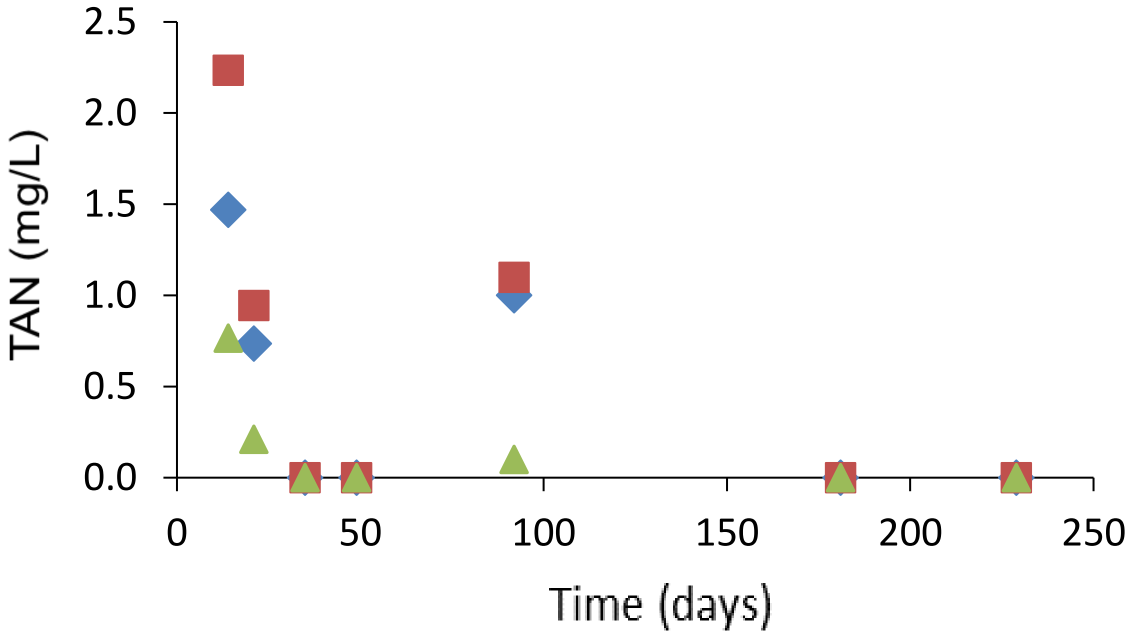

Figure 7.21 Total Ammonia Nitrogen composition evolution. Data from TAN (red), NH_4^+ (blue) and NH_3 (green)

The results found in toxic ammonia in the system suggest that this parameter was not responsible for the plants' downfall. As stated in section 1.4.4.-f, un-ionized ammonia (NH_3) is toxic for fish from 1 mg/L, and plants can tolerate higher levels. As it can be seen on **Table 12**, ammonia levels were an estimate of 0.8 mg/L at its highest.

Apart from the fact that ammonia never reached levels that were potentially dangerous for plants, the downfall in plants came after ammonia levels dropped.

If ammonia had been too high in the system (assuming measurements were not accurate) it would have provoked the death of fish before it had caused the plants to die as they did.

7.3.10.-Total Nitrogen

Analyzing the evolution of the nitrogen concentration in the water throughout the first 92 days of operation (see Figure 7.22), considering nitrites (NO_2^-), nitrates (NO_3^-) and ammonium (NH_4^+), it is visible that at the beginning of the system's operation nitrates levels started a level of 12 mg/L and quickly fell in the consequent weeks, while the other forms of nitrogen stayed at low levels the whole time.

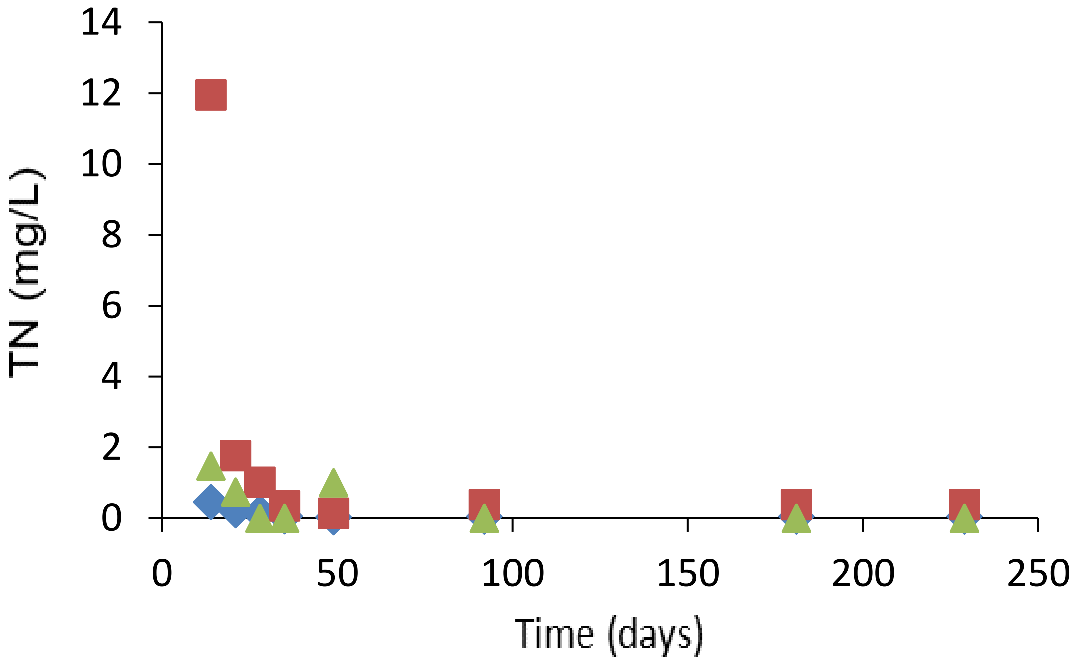

Figure 7.22 Total nitrogen evolution. Data corresponding to average concentrations of NO_3^- (red), NO_2^- (blue) and NH_4^+ (green) from filter and sump

As it is said in section 1.4.3.-, nitrate levels are usually very low at the beginning and progressively rise as the system matures and the bacteria colonies grow and perform nitrification. This process is illustrated in Figure 1.13.

In this system it was possible to reach the conditions that a regular aquaponic plant would have after 50 days in only two weeks. As it is said in section 6.1.-, the bacteria development was accelerated using an old filter that contained necessary bacteria.

The fact that the nitrogen distribution is that seen in Figure 7.22, is a good indicator that by the first two weeks, nitrification was occurring in the system. For nitrates to exist in the system, ammonia needs to be converted into nitrites and these into nitrates, and this is achieved in the nitrification process, which occurs when the biofilter has matured.

However, nitrogen levels fell after the first weeks. All forms of nitrogen reached very low levels, making the water lack necessary nutrients for plants.

There are two main possible reasons why the total nitrogen levels could have dropped to almost zero after the first month of operation. Either anaerobic conditions have appeared, and denitrification is occurring in the system, or the fish-to-plant ratio is incorrect and there are not enough nutrients in the system available for the plants. Both possibilities are evaluated:

- **Development of anaerobic conditions and denitrification**: Anaerobic conditions can develop in the media bed, causing a denitrification process to appear in areas of said component and thus transforming nitrates into nitrogen gas which is expelled into the atmosphere.

  This first theory is rather unlikely given the Dissolved Oxygen levels found in the water throughout the whole study. Anaerobic conditions surge when oxygen levels are very low, close to zero (see section 1.4.2.-). DO levels in this study show oxygen concentrations in the water were not close to zero at any point.

  Apart from that, anaerobic conditions require both zones with no oxygen access and an accumulation of solid waste; the media bed has effectively been working since the beginning with water flooding and draining it constantly, so there is little reason to believe there are zones in this deposit that oxygen cannot reach. Also, the position of the bed after the radial flow filter and additional mechanical filter has allowed water flowing into the media bed to be very clean, so there is no solid waste accumulation in the media bed.

- **Incorrect Fish-to-plant ratio and lack of nutrient availability for plants**: The plant growing surface is approximately 2 square meters at maximum capacity. According to Rakocy´s methodology, this amount of plant would require 120 to 200 grams of food per day.

$$\frac{(60-100)grams}{m^2 * day} * 2\,m^2 = 120-200\frac{grams}{day}$$

The initial planted surface was approximately 1 m^2, as the planting surface was only occupied to its 50% capacity; for this surface the fish feed needed would be the following:

$$\frac{(60-100)grams}{m^2 * day} * 1\,m^2 = 60-100\frac{grams}{day}$$

Since the number of fish implemented are consuming under 10 grams per day, thus are only being fed that much, the plant requirements are higher than those reached, meaning there are too many plants for the number of fish.

Original calculations estimated that the number of fish introduced in the system would be able to consume enough feed for the total plant growing surface, but these calculations were significantly distant from reality. For the amount of feed the fish were consuming daily, and according to Rakocy´s formula, a surface of only 0.1 m^2 could be exploited.

As stated in section 1.5.-, Racoky´s formula is more generous with the amount of feed than that given by Lenard, which by considering the portion of solid waste lowers the amount of feed needed considerably. Dr Lennar calculated a ratio of 11 g/m^2/day for leafy greens, since the fish were consuming close to 10 grams of feed a day, according to Lennar it would be possible to exploit an area of almost 1 m^2.

$$\frac{10\,\frac{grams}{day}}{\frac{11\,grams}{m^2 * day}} = 0.91\,m^2$$

Even though according to Lennard´s ratio, the amount of feed entering the system wasn't enough to nourish almost 1m^2 of plants, the fact that these were perishing while the fish continued to appear healthy showed that the ratio was not correct and had to be altered to achieve enough nutrients to be available for the plants.

To reach an equilibrium in the fish to plant ratio, plants were progressively removed from the system to lower the growing surface, and the fish feed was gradually increased.

As it is shown in Figure 7.21, ammonia began rising back up after the plant density was significatively lowered, indicating that it is possible that the system will evolve to a point at which the nutrients in the water can be enough to nourish plants correctly. Plants feed from nitrates, but as it is explained in section 1.4.1.-, the system needs higher ammonia levels for the nitrifying bacteria to convert ammonia into nitrites and these into nitrates for the plants.

About half of the plants were withdrawn from the system after 70 days. It can be seen in Figure 7.22 that the nitrogen concentration in the system had risen by the time the sixth measurement was taken.

The elimination of plants was successful in getting the system to a point where there is a good balance between nutrient requirements of the plants and nutrient availability from the fish waste and fish feed. Even so, the nitrogen levels dropped again to very low levels but this time 1 m^2 of plants (basil, peppermint, and mint herbs) was successfully grown.

8.- CONCLUSIONS

The developed pilot plant that, according to AQUAPONIC SYSTEMS SCALES classification, would fit into the Backyard aquaponic systems type due to its size. It proved the possibility of developing this type of systems to complement the feeding of family nucleus and to support the family economy as it was said in the section 3.-AIM AND SCOPE.

Analyzed the results of the system we can say that it fulfilled the purpose although the capacity of the fish to offer enough nutrients to the plants was overestimated while the economic cost of the system was underestimated.

The nitrification process was correctly found in the system in a shorter time that it would take a new system thanks to the use of an old pump that contained bacteria. Although nitrification was properly stablished in the system at the first few weeks of operation, the number of fish in the system was too low for the number of plants that were introduced, causing the plants to eventually consume all the nutrients in the water and hence making all forms of nitrogen lower to zero.

The amount of feed the fish would consume was over estimated. The extraction of plants should take the system back to a point in which nutrients are optimally available for plants in the form of nitrates. The rise of nitrogen in the sixth measurement, especially ammonium, suggest the cycle might begin again, with all forms of nitrogen becoming higher and later getting nitrates to be the most significant form.

Finally, due to the increase in the size of the fish, the increase in the food intake, the reduction of the planted area to 1m^2 and the cultivation of oregano, peppermint, mint and basil, which are herbs with low nutrient requirements, we were able to achieve the growth of the plants without deficiencies and the correct health of the fish.

The initial designs and calculations are essential when building an aquaponic system. Once this process is completed, the construction of the system is very attainable.

Although there were issues that could not be predicted and appeared once construction was well underway, none of these were too problematic and could be fixed with minor modifications of the original design.

The construction of the system was effectively carried out. The two students were able to build the entirety of the system in a period of three months (working solely on weekends). Some processes required various attempts to achieve correctness, which slightly extended the time it was initially estimated that the construction period would take. Design modifications also caused delay in the construction.

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10.- ANNEX

10.1.- List of figures

10.2.- List of tables

10.3.- Budget

	Amount	Unit	Unit price	Total
MATERIALS				
IBC tanks (1000 L)	3	u	79.00 €	237.00 €
Polypropilene sheets	3	u	17.17 €	51.51 €
NFT channels (60*80mm*2m)	3	u	18.03 €	54.09 €
Fine expanded clay (50 L)	3	u	5.25 €	15.75 €
Expanded clay	120	L	0.28 €	34.09 €
Pipe T (20 mm)	2	u	1.10 €	2.20 €
Pipe T (40 mm)	1	u	1.55 €	1.55 €
Pipe elbows (20 mm)	2	u	0.75 €	1.50 €
Pipe elbows (40 mm)	2	u	0.89 €	1.78 €
NFT faucets	3	u	4.99 €	14.97 €
Shut off valve (fish tank and filter)	2	u	11.25 €	22.50 €
25 mm hose	4	m	1.50 €	6.00 €
40 mm PVC pipes (3 m)	2	u	3.95 €	7.90 €
25 mm PVC pipes (2.5 m)	2	u	2.30 €	4.60 €
Uniseals	4	u	7.50 €	30.00 €
Greenhouse (8x3x2)	1	u	209.99 €	209.99 €
IBC lid	1	u	5.39 €	5.39 €
Silicon (280 mL)	4	u	6.50 €	26.00 €
Bio-Balls (100 L)	1	bag	68.18 €	68.18 €
25 mm PVC lid	1	u	0.78 €	0.78 €
DWC discharge hose and faucet	1	u	22.90 €	22.90 €
Plant Nets	30	u	0.50 €	15.00 €
20 mm PVC pipes (2.4 m)	2	u	1.89 €	3.78 €
Faucet adapter (20mm)	3	u	1.50 €	4.50 €
NFT channels collector (1m)	1	u	1.99 €	1.99 €
NFT channels collector conecction with hole	1	u	2.15 €	2.15 €

NFT channels collector lid	2	u	0.95 €	1.90 €
NFT channels collector connection	2	u	1.05 €	2.10 €
NFT channels collector support	3	u	0.80 €	2.40 €
Net	1	u	18.79 €	18.79 €
IBC tank discharge Faucet	1	u	15.39 €	15.39 €
Mechanical Filter Sponge (50cmx50cmx4cm)	2	u	9.90 €	19.80 €
Perlon (250 gr)	2	u	9.90 €	9.80 €
			MATERIALS TOTAL	**926.27 €**
		FISH AND PLANTS		
Fish	30	u	1.81 €	54.23 €
Fish feed (30 L)	2	u	26.25 €	52.49 €
Lettuce Plants	12	u	0.10 €	1.20 €
Basil Plants	2	u	1.50 €	3.00 €
Corianter plants	1	u	1.25 €	1.25 €
Peppermint plants	1	u	1.20 €	1.20 €
Lemongrass plant	1	u	3.00 €	3.00 €
Mint plants	4	u	1.50 €	6.00 €
			FISH AND PLANTS TOTAL	**122.37 €**
		EQUIPMENT		
270 W pump	1	u	60.91 €	60.91 €
25 W Pump	1	u	19.99 €	19.99 €
Difuser rocks	3	u	6.50 €	19.50 €
Aeretor tubes (6m)	1	u	14.00 €	14.00 €
PH meter	1	u	10.00 €	10.00 €
TDS meter	1	u	10.00 €	10.00 €
Photometer	1	u	139.00 €	139.00 €
Automatic Feeder	2	u	14.00 €	28.00 €
8W Aerator	1	u	30.00 €	30.00 €
DO meter	1	u	180.00 €	180.00 €
NO_2^- measuring kit	1	u	10.89 €	10.89 €

NO_3^- measuring kit	1	u	10.89 €	10.89 €
NH_4^+ measuring kit	1	u	15.00 €	15.00 €
			EQUIPMENT TOTAL	**548.18 €**
TOOLS				
Teflon	4	u	0.75 €	3.00 €
Grinder	1	u	56.00 €	56.00 €
Crown Saw Kit	1	u	16.14 €	16.14 €
Tool Kit	1	u	26.99 €	26.99 €
Shovel	2	u	22.00 €	44.00 €
			TOOLS TOTAL	**146.13 €**
TRANSPORTATION				
Van rent	1	u	99.85 €	99.85 €
Gas Refuel	1	u	24.22 €	24.22 €
			TRANSPORTATION TOTAL	**124.07 €**
WORK				
Industrial Engineering Students	2			
Design and planification	24	hours	48.00 €	2304.00 €
Plant construction	256	hours	15.00 €	7680.00 €
Plant maintainance and water testing	16	hours	48.00 €	1536.00 €
			WORK TOTAL	**11,520.00 €**
			TOTAL OF CONSTRUCTION (WITHOUT WORKTIME PRICE)	**1867.02€**
			TOTAL (WITHOUT GENERAL EXPENSES AND INDUSTRIAL PROFIT)	**13,387.02€**
			13% GENERAL EXPENSES	**1740.31€**
			6% INDUSTRIAL PROFIT	**803.22€**
			TOTAL	**15,930.55€**

10.4.- Time planning

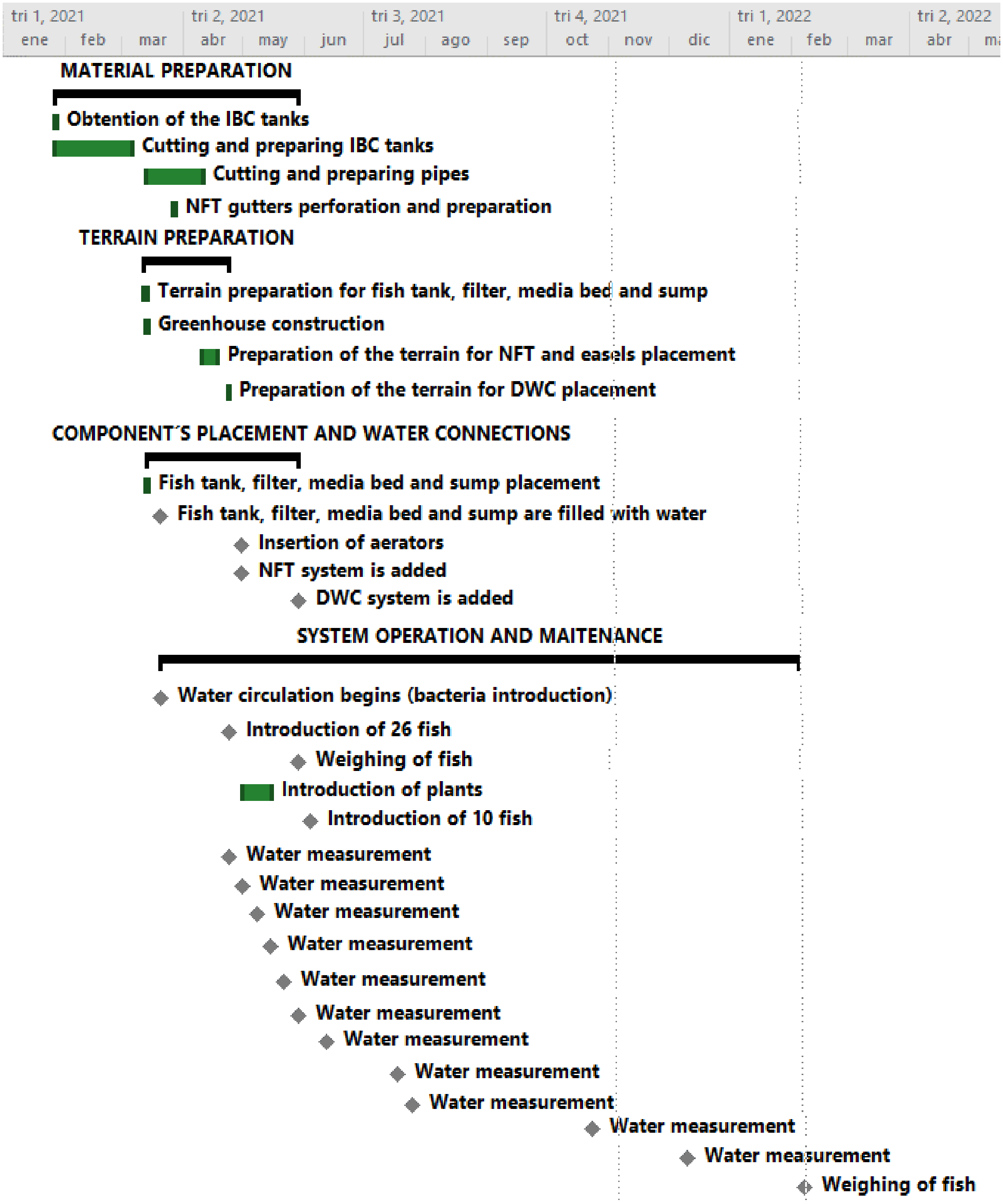

Figure 10.1 Time planning of the system

10.5.- Terms and abbreviations used

DWC	Deep Water Culture
NFT	Nutrient Film Technique
UVI	University of the Virgin Islands
NO	Nitric Oxide
N_2O	Nitrous Oxide
NH_3	Ammonia
NH_4^+	Ammonium
NO_2^-	Nitrites
NO_3^-	Nitrates
mg/L	milligrams per liter
TDS	Total Dissolved Solids
TAN	Total Ammonia Nitrogen
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
g	grams
m^2	square meters
L	liters
kg	kilograms
W	Watts
L/h	liters per hour
mm	millimeters
m	meters
cm	centimeters
ºC	degrees Celsius