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REVIEW

The Review of Existing and In-Progress Technologies of the Different Subsystems Required for the Structural and Functional Elements of the Model of Multi-Purpose Aquaponic Production System

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Abstract

The integrated intensive rearing of fish with the hydroponic growing of plants, also known as aquaponics, has received a significant amount of attention from the scientific community, with an increasing number of studies offering new and sustainable ways to produce food. By integrating an aquaponic system within a RAS (recirculating aquaculture system), fish farms that practice an intensive aquaculture technology can increase their feasibility by supplementing their income with revenue from a secondary product – plants that are grown with nutrients resulted from the metabolic waste of the reared fish. The purpose of this review is to present a comprehensive research on the design and the technologies used in an aquaponic production system. It has been observed that for leafy greens vegetables a higher productivity was recorded in the case of the media grow bed hydroponic system (media grow beds > deep water culture >nutrient film technique). The economic advantage of this type of hydroponic module is an increased productivity of the vegetal biomass, from a quantitative aspect, although the actual economic value of the obtained plants can be lower, since the investment costs of the media grow beds aquaponic technique is higher than those of deep water culture (deep water culture < media grow beds <nutrient film technique). There are also other factors that need to be taken into account when implementing an aquaponic system, such as: choosing an appropriate fish – plant combination and ratio and other technical and technological aspects.

Keywords: *aquaponic technique, deep water culture, media grow beds, nutrient film technique, recirculating aquaculture system*

1. Introduction

Aquaponics is a combination of the words aquaculture (rearing fish) and hydroponics (growing plants in water without soil) and the eco-innovative technology behind the concept (35) is the integration of hydroponic plant production into recirculating aquaculture systems (RAS). Aquaponics is a man-made ecosystem of plants, fish, bacteria, sometimes worms and/or other organisms, growing together symbiotically. Aquaponics is also a biointegrated food production system that links recirculating aquaculture with hydroponic vegetable, flower, or herb production (8).

Research in aquaponics began in the 1970s, and the integration of aquaculture and the hydroponic cultivation of plants has been examined repeatedly over the past three decades with a wide variety of system designs, plant and aquatic animal species, and experimental protocols (27). The first aquaponic system (called an aqua-vegeculture system) it was created in 1986 that channeled tilapia effluent into sand-planted tomato beds (19, 20).

Recently, the incorporation of RAS with vegetable hydroponics production has become an interesting model to private sector, aquaculture and environmental scientists (4, 9, 30).

Classic RAS are designed to rear large quantities of fish in relatively small volumes of water (30), thus making water treatment a necessity in order to remove the toxic products that result from fish waste and unconsumed fish feed. Integrated aquaponic systems control the accumulation of waste nutrients from fish culture (27) which may lower overall consumption of water (20) and produce additional, saleable crops (27).

Production of multiple crops via the combination of aquaculture and hydroponic technologies synergizes he economic value of both enterprises (31).The hydroponic system drives potential profitability of the combined system with major annual returns deriving from plant production (1).Also, integrated systems use water more efficiently through the interacting activities of fish and plants (10). The addition of water to a fish tank to satisfy the oxygen requirements depends on the oxygen consumption of the fish, the oxygen concentration in the inlet water and the lowest acceptable concentration in the outlet water (14).

Aquaculture effluent provides most of the nutrients required by plants if the optimum ratio between daily feed input and plant growing area is maintained (29).

The rate of change in nutrient concentration can be influenced by varying the ratio of plants to fish (30). Since the soluble nutrients available to the plants in the hydroponic system do not correlate with the proportions of nutrients assimilated by normally growing plants, the rates of change in concentration for individual nutrients differ. Thus, suboptimal concentrations and ratios of nutrients result, reducing the nutritional adequacy of the solution for plants. The nutrient content of a diet can be manipulated to make the relative proportions of nutrients excreted by fish more similar to the relative proportions of nutrients assimilated by plants(9). With such a diet, there would be an optimal ratio of fish to plants and optimal nutrient supplementation (33). Several mass balance models have been proposed from previous studies (21; 22; 24; 32), from which the total nitrogen and phosphorus discharges into receiving waters can be estimated.

No pesticides or antibiotics are used at any stage; therefore, the aquaponic production system can be regarded as a part of the organic agriculture (28).

The aim of this review is to create a comprehensive image on the design and the technical aspects of an integrated aquaponic system.

2. Materials and Methods

2.1. Recirculating Aquaculture Systems (RAS)

Recirculating aquaculture systems are indoor, tank-based systems in which fish are reared at high density under controlled environmental conditions.

The proper functioning of a RAS depends on some key factors, such as: mechanical filtration (solid removal), biofiltration and dissolved gas control.

To maintain good water quality the water has to be filtered to remove solids, ammonia and CO2. Likewise the dissolved oxygen level, pH and temperature have to be kept at secure levels at all times (35). The RAS technology has been developed in recent years, especially in relation to sludge handling and biofiltration. The RAS technology development, together with more stringent environmental requirements and the need to increase profitability, have led to increased interest in integrated multitrophic production methods such as aquaponics (6).

Generally, recirculating aquaculture systems require continuous wastewater treatment using a variety of techniques that have traditionally been relatively expensive and require very skillful personnel to operate (17). The design of the water reuse system, needs to be efficient, cost effective, and simple to operate (3).

2.2. Mechanical filtration

In order to maintain a good water quality and a good functioning of the system, the removal of solid waste (fish feces and unconsumed fish feed) is an essential process that must not be neglected. Not only does waste increases the risk of fish disease and gill damage, but also increase the ammonia in the water, decrease the oxygen concentration due to higher biochemical oxygen demand (BOD), reduces the biofilter efficiency by fouling the media with heterotrophic bacteria, and favors clogging that leads to the formation of anaerobic spots that release hydrogen sulphide, an extremely toxic gas for both fish and nitrifying bacteria (35).

It is important to remove the solids from the water fast, to decrease the retention time of the solids in the system; in this way reducing the risk that the solids will break into smaller particles which are more difficult to treat and which consume oxygen. This is why mechanical filtration units are placed immediately after the rearing tanks and before the bio filtration unit. The solids removed from the system, in the form of sludge rich in nutrients can be used in agriculture as a natural fertilizer.

Mechanical filtration can be accomplished in many ways. Normally filtration methods rely on gravity (sedimentation, swirl separators/radial flow separators), screening (microscreen (drum) filter, sand filter and bead filter), oxidation (ozone treatment) or foam fractionation (35).

When choosing a solids filtration method (either passive sedimentation or mechanical) a good criteria can be the fish rearing intensity of the farm. For a small farm with a low rearing intensity and low water volume a sedimentation filtration is best suited. As the farm size increases, stocking densities and feed rates get higher, water volume is higher as well and a mechanical drum filter is best suited in this case. Some types of mechanical filters include: sedimentation basins, drum-filters, sand filters, bead filters, foam fractionator.

Table 1. Comparison of different mechanical filter systems (35)

Type	Op. water volume (m^3/h)	Op. pressure (PSI)	Cost (€)	Pros	Cons
Clarifier	5	Atmosph.	1000	Maintenance-free. No electricity, requires only purging the system from sludge.	Low water volume compared to alternatives. Water retention time depends on the particle size to be removed.
Foam fractionator	17-34	Atmosph.	1200	Maintenance-free. No electricity, requires only purging the system from sludge.	Low water volume compared to alternatives. Water retention time depends on the particle size to be removed.
Bead filter	1) 10 2) 23 3) 45 4) 68	10 20	1) 3000 2) 8050 3) 12000 4) 20000	Simple operations, limited space for water treatment. Suitable for small or medium farms.	Requires electricity, some maintenance needed, beads may need to be replaced. Water needed for backflush with relative disposal. Number of flushes depend on the solid load.
Sand filter	1) 10 2) 22	30-50	1) 700 2) 1200	Simple operations, limited space for water treatment. Suitable for small or medium farms.	Requires electricity for pumping, not practical with organic wastes, as particles foul on sand making clogs. More frequent backflush.
Drum filter	1) 30 2) 90 3) 140	Atmosph.	1) 5200 2) 7000 3) 9000	Effective for big farms. Water movement is by gravity.	Requires electricity, some maintenance needed, screens need to be periodically replaced. Water needed for backflush with relative disposal.

2.3. Biofiltration

A key feature of recirculating aquaculture and of integrated aquaponic systems is the biofiltration component. By recirculating the same water, dangerous toxins accumulate that need to be removed. This is achieved by biotreating the water, converting the dissolved ammonia, which is a toxic metabolic product excreted by the fish, into the much less harmless nitrate. Due to the biofiltration process, realized by beneficial bacteria, RAS are able to avoid the discharge and/or replenishment of the most part of the technological water, thus huge water savings are obtained. A healthy and matured biofiltration unit is crucial for a stable and well working RAS (36).

In the bio filtration process, three nitrifying bacteria species are responsible for maintaining optimal water quality parameters. The *Nitrosomonas* converts ammonium into nitrite and the *Nitrobacter* and *Nitrospira* are converting nitrite into nitrate. It must be mentioned that these bacteria species are naturally occurring in the environment.

The biofilter is a cylindrical or polyhedral shaped canister or tank that holds the porous filtration media, the bacteria and the water, which must be well aerated since the nitrification process is oxygen consuming. The design of a biofilter can be a rudimentary one or a complex industrial one. Since you can't actually see the bacteria on the filtration media, the only way to determine its presence and effectiveness is by constantly monitoring the ammonia, nitrite and nitrate levels of the technological water.

There are other environmental factors that influence the proper working of a biofilter, such as: water temperature, pH, dissolved oxygen and salinity.

When first starting a RAS, there is an acclimation period (as long as six weeks), during which the biofilter becomes effective. The nitrifying bacteria needs time to multiply and colonize the filtration media in order to be able to efficiently treat the entire volume of water within the system. If fish are introduced into the system and fed, they will provide the ammonia needed to start the nitrification process. However the existing bacteria won't be able to properly treat the water and lethal toxicity levels can be achieved. That is why it is recommended that the system need to run without fish for a period, and to speed up the bacteria developing process, another ammonia source must be added to the system. Also, inoculating the system with technological water and/or filtration media from an already established system is another way to speed up the acclimation time of the system.

At the startup of the new system, ammonia levels will increase until the *Nitrosomonas* bacteria colonizes the system and starts converting ammonia into nitrite. As the ammonia levels start to decrease, the nitrite levels increase until the *Nitrobacter/Nitrospira* bacteria colonizes the system, converting nitrite into nitrate, and thus decreasing the nitrite levels. The nitrate in the technological water is relatively harmless to the fish, and when integrating a hydroponic module with a RAS, the nitrate constitutes the main nitrogen source for the plants, thus removing it from the system.

The size of the biofiltration unit depends on several factors (5), such as: the temperature; the dissolved oxygen concentration in the water; the biofilter's water exchange; the salinity of the water; the fish stocking density and the feeding regime; the surface area of filtration media; the protein content of the fish feed.

There are several options when choosing a biofilter, its performance depending on the technology being used and the characteristics of the filtration media being used. Of which the most common are:

– The trickling filter – this is usually a tower-like tank or canister filled with different specific surface media (plastic beads or balls, gravel, pumice, LECA, polyurethane foam). Water is sprinkled in the upper part of the filter, and, as the name says, trickles down through the filtration media. This filter type provides a passive aeration and carbon dioxide removal.

- The moving bed bioreactors (MBBR) – this filtration unit contains neutrally buoyant filtration media that are constantly stirred by the aeration process. The aeration also assures the water is oxygenated and removes the carbon dioxide from the water. The media used in this type of biofilter is usually composed of plastic balls or other type of plastic product with high specific area.
- The bead filter – this filter it usually is a pressurized cylindrical canister. The media beads inside are periodically stirred and cleaned to prevent any accumulating waste which is removed through backwash.
- The sand filter – this type of filter, just like the bead filter it usually is a pressurized cylindrical canister with sand as filtration media. The very high specific area of the sand ensures a very high nitrification rate.

As it has been stated before, the nitrification process is an oxygen consuming one, beside the passive aeration occurring in the biofilter, the water needs to be adequately and constantly aerated (35), in order to supply sufficient oxygen to the microbial community, to the reared fish and even to the plants in the case of an integrated aquaponic system.

2.4. Hydroponics

The hydroponic technique is the cultivation of plant crops in a soil-less environment. For the growing of plants, the aquaponic systems use the design of the hydroponic systems.

The main design of aquaponic systems closely mirrors that of recirculating systems in general, with the addition of a hydroponic component (30).

The main components of an integrated aquaponic system are: the rearing tank, the solid removal units (sump and mechanical filter), the biofiltration unit, the aeration unit, the degassing unit, the pumps and the hydroponic culture module (Figure 1).

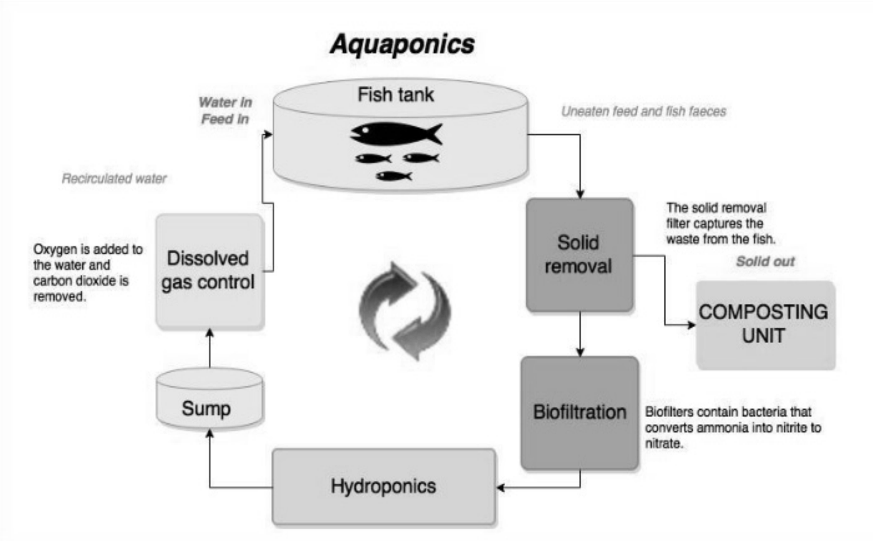

Figure 1. Schematic overview of an integrated aquaponic system (35)

An optimum arrangement of these components, as can be seen in Figure 2, thus the solid removal unit and the bio filtration unit must precede the hydroponic culture module (30).

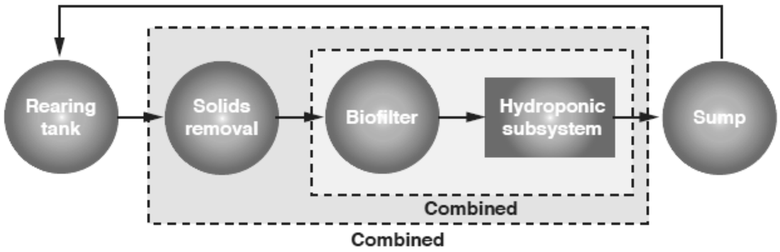

Figure 2. Optimum arrangement of aquaponic system components (not to scale) (30)

In this way, the effluent from the rearing unit is treated first by removing its suspended and settable solids, then it is biofiltered by removing as much ammonia and nitrite as possible, finally reaching the hydroponic culture module, where nutrients (nitrate and other micro and macro elements) are absorbed by the plants and additional ammonia and nitrite are removed by the bacteria growing on the surfaces of the hydroponic module and/or the grow media. After passing through the hydroponic culture module, the water is collected into a sump from where it is returned to the rearing unit.

The hydroponic units are populated with seedling grown outside the system in soil or in other types of media (e.g. Rockwool, peat moss and coconut coir). The efficiency of hydroponically grown plant can be found in the physiological adaptation in young plants called "luxury consumption". This mechanism, first described in 1974 (37), states that luxury consumption is "...the increase in tissue nutrient concentration above the maximum yield, which does not result in further yield increase." In other words, when there are excess nutrients available to seedlings, they can uptake and store them, then mobilize the nutrients to tissues in the future when needed (11).

More than 30 types of vegetables have been raised in integrated systems on an experimental basis (26). Lettuce, herbs, and specialty greens (spinach, chives, basil, and watercress) have low to medium nutritional requirements and are well adapted to aquaponic systems, whereas fruiting plants (tomatoes, bell peppers, and cucumbers) have a higher nutritional demand and perform better in a heavily stocked, well-established aquaponic system (7).

Various fish species are presently used in aquaponic systems including Nile tilapia (*Oreochromisniloticus*), hybrid tilapia (*Oreochromis urolepishornorum* X *Oreochromis mosambicus*), koi carp (*Cyprinus carpio*), hybrid carp (*Ctenopharyngodon idella* X *Aristichthys nobilis*), hybrid striped bass (*Morone chrysops* X *Morone saxatilis*), and goldfish (*Carassius sp.*) (34). Rainbow trout (*Oncorhynchus mykiss)* (1), Australian barramundi (*Lates calcarifer*) and Murray cod (*Maccullochella peelii peelii*), as well as various crustaceans such as red claw crayfish, (*Cherax quadricarinatus*) have also been grown in aquaponic systems (8).

Different types of hydroponic media have been used for growing crops in aquaponic systems, including gravel bed ebb and flow systems, aeroponics, nutrient film technique (NFT), rock wool culture, and sand beds (13). As a medium for growing vegetables using aquaculture, was used sand (18) and floating rafts (25).

There are three main aquaponic techniques in use worldwide: media grow beds, deep water culture (DWC) or floating rafts and the nutrient film technique (NFT) (35).All three of these techniques work well, but a proper mechanical filtration is still needed.

2.4.1. Media grow beds

This system is mostly used in backyard aquaponic systems and in small scale systems. It is a solid media-filled bed system (35) filled with light expanded clay aggregate (LECA) (Figure 3A), pumice (Figure 3B), Growstone (Figure 3C), gravel (Figure 3D), zeolite (Figure 3E) or expanded shale (Figure 3F).

Figure 3. Different types of growing media (35)

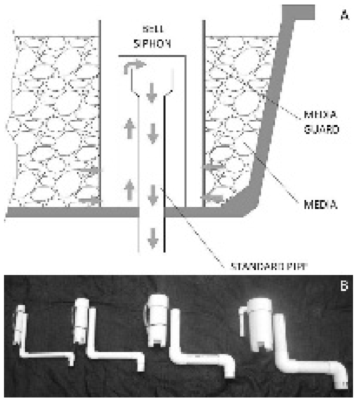

Figure 4. Bell siphon schematic (A) and examples of bell siphon (B) (12)

These media provide the plants with a good root fixation substrate, also because of the porosity (high specific surface area) and a good water and air retention rate, the media provides extra biofiltration/nitrification and mineralization.

In small scale aquaponic systems that practice a low fish stocking density, the biofilter can be completely excluded, the nitrification process being realized by the grow bed media.

Also red earthworms (*Eisenia fetida*) can be added in the grow bed.

These annelids help break down solid waste and excess roots, they supress plant diseases and provide extra nutrients to the plants through their excrements – vermicompost. Vermicompost has been shown to enhance plant growth, crop yield, and improve root structure and development (23).

The media grow bed system can be implemented by choosing one of the two flood regimes: constant (continuous) flow or reciprocating flow (“ebb and flow”).

The constant flow process is simple, just as the name suggests, water flows continuously and constant into the grow bed through an inlet at one end and fills it until it reaches a certain desired level, then flows out through an outlet or overflow, usually located at the other end of the grow bed.

The reciprocating flow process can be achieved by either rigging the influent pump to turn on and off at specific intervals, or more conveniently, by using a bell siphon (Figure 4) over the outlet.

Water flows into the grow bed and it fills it up to a specific level, then it drains out almost completely only to start the process once more. This effect is achieved by narrowing the outlet pipe, thus creating a suction effect once the water reaches a certain (desired) level.

In the reciprocating flow variant the media and the plant roots get better aeration (30), unlike the constant flow variant in which the same media and the roots are always under the water level. When cultivating a plant with high nutritional requirements, a constant flow system is recommended, but the reciprocating flow system has a better biofiltration and solid removal.

It was demonstrated that lettuce has a greater yield in the constant flow variant and also that it has a better water treatment capability (15, 16). Even so the scientific community is divided regarding this matter.

The design of a media grow bed system is quite simple; it is comprised of a rectangular shaped trough made of plastic or of wood or concrete covered with impermeable lining, plastic pipes (with valves) and optionally a bell siphon. The media grow bed is better suited for plants that bear fruit since the media provides better fixation for the roots and support for the plant.

The crop yield of the media grow bed system is better than that of the DWC system, which in turn is better than the NFT system (16).

2.4.2. Deep water culture (DWC)

Also known as the floating raft system, the deep water culture system is optimal for both small and large scale production systems.

The design is simple, the hydroponic tanks are large, not too deep, and usually a minimum of 30cm water depth level is maintained.

The plants grow on polystyrene or plastic sheets that float on the surface of the water, usually fixed in small plastic net pots.

Just like the media grow bed troughs, the deep water culture tanks, in this case, have a simple design; rectangular shape, made of plastic, metal, wood or concrete covered with impermeable lining, etc. Water flows in the hydroponic module through an inlet at one end and it flows out through an overflow outlet at the other end of the unit. This way a constant water level is always maintained and in case of a pump malfunction or power failure, the plants do not die.

The roots of the plant grow directly into the oxygenated water flowing from the fish tanks with a volumetric exchange rate of approximately 30% per hour (35). If the solids filtration and removal is not done properly, sludge accumulating at the bottom of the hydroponic tank and on the roots of the plant blocking oxygen and nutrients uptake.

Crop management involves transplanting the seedlings into the system and harvesting the plants once they achieve marketable size. This process can be improved by applying a conveyor movement of the rafts similar to the conveyor production system (CPS) used in the NFT systems. The seedlings are introduced on floating trays into the system at inlet end of the hydroponic module and moved along the length of the tank as it grows, reaching the outlet end of the tank when it's ready to be harvested.

The DWC system is easiest to build and the least expensive of the three types of aquaponic systems.

2.4.3. Nutrient film technique (NFT)

The nutrient film technique system uses long and narrow plastic tubes with a thin layer (film) of water continuously flowing through them.

An absolute requirement in the case of the NFT systems is a good preliminary mechanical filtering (35). Solids accumulating on the roots must be avoided, not only because it can inhibit plant growth, but also because it can lead to clogging of the system.

The NFT tubes are placed at a 1% angle, the water entering at the raised end, flowing through the tube and being gravitationally evacuated at the lowered end. Water is introduced into the NFT hydroponic modules with a low flow pump, aiming for a 1-2 L/min flow regime (35). Also these pumps require less energy to recirculate the water into the hydroponic units, reducing the operational cost.

An absolute advantage of the NFT system over the other two systems is the possibility to design and build the system vertically, making excellent use of the available growing area.

In order to avoid the oxygen depletion be the plant roots due to the small volume of water flowing through, the tube must not be longer than 10 m.

NFT systems also have some drawbacks, like the risk of root clogging and the decrease of the water's nutrients towards the end of the channel. The first issue can be resolved with a good solid waste control, whereas the second one can be overcome by implementing a conveyor production system (CPS) (Figure 5) within the hydroponic modules.

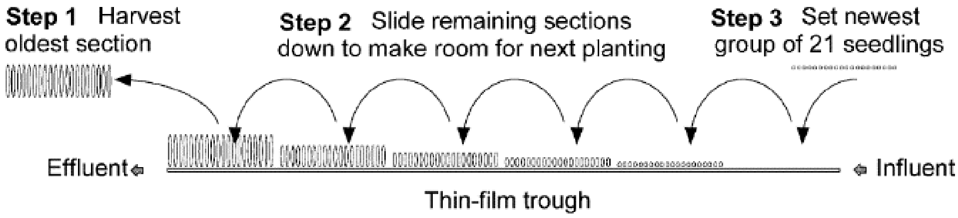

Figure 5. Schematic of a conveyor production system (CPS) (2)

The CPS works by introducing the seedlings into the system at the start of the channel, and as it grows, periodically moving it towards the end, where it is harvested. The CPS not only efficiently removes the nutrients from the water, and also reduces the sensitivity of plants to imbalances of mobile nutrients in the wastewater (2).

NFT is suitable for a small size plants, such as herbs and salads, but it can also be used to grow larger plants, such as tomatoes and okra. A great risk of this system is the possibility of a crop loss in case of a system malfunction or power failure – the roots drying up and the plants dying if the water input is compromised. That's why backup solution for power and water flow must be implements.

The NFT system is very suitable for large scale production systems because of its ease of use and simple maintenance. The design and building of this type of system requires more work and it is the most expensive of the three aquaponic systems.

5. Lighting

One important component of the aquaponic system is the lighting equipment needed for assuring a fast and proper plant development.

There are several options to choose from, such as: fluorescent bulbs, metal halide bulbs. The lights come in various wave lengths, they cover a certain area and need to be mounted at a certain height above the plants, depending on plant species. When choosing the lighting solution for an aquaponic system, a very important aspect also needs to be the acquisition to operating cost ratio. Basically the more expensive the lighting system acquisition is the less expensive the operation cost over a longer period of time is.

The lighting operation period during a day can vary depending on the crop that is grown and the time of year, but usually around 10 hours of light: 14 hours of dark (15).

Conclusions

An integrated aquaponic production system is a very good way to increase the income of a fish farm, growing a secondary sustainable marketable product.

All three aquaponic systems have their advantages and disadvantages from multiple point of views; choosing which one to integrate with a RAS is up to the farmer, depending on the necessities, maintenance and management capabilities and not the least on the available investment costs.

As general conclusions of this review, the following can be stated:

- The media grow bed system has a better plant biomass yield than the deep water culture (DWC) system, respectively than the nutrient film technique (NFT) system.
- The DWCsystem has better water treatment capabilities than the media grow bed system respectively, than the NFT system.
- The DWC system has lower investment costs than the media grow bed system, respectively than the NFT system.
- The DWC system is easier to build than the media grow bed system, respectively than the NFT system.
- The NFT system is easier to maintain than the DWC system, respectively than the media grow bed system.

Keeping in mind all of the above, a DWC system is recommended for a starting aquaponic system.

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