# Design and Operational Principle of Recirculatory Aquaponic System in the Himalayas: Prospects and Challenges

# 23

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**Abstract**

In modern scientific soil-less cultivation, aquaponics/integrated agri-aquaculture farming (IAAF) is gaining wide popularity, especially in urban and hilly areas with water and space constraints. Following the concept "waste to wealth," this hi-tech natural/organic by-product utilization strategy produces fish and plants for human consumption and use without any external input. It requires only 10% of water as compared to the traditional farming. The recirculatory aquaponic system (RAS) has the benefit of solving problems like waste management headaches and unwanted weed infestation, including soil-borne pests and diseases, hence, providing optimum space for the growth of much healthier plants. In an optimized system, the fish, plant, and microbial (bio-filter) components technically co-exist in symbiotic equilibrium, where the ammonia- and nitrite-oxidizing bacteria convert the toxic ammonia to nitrate for utilization by plants. However, some proportions of nitrite and ammonia are also utilized by the plants, depending on their species and varieties. The varieties with hardy nature and giving better production are chosen. Selection of fish and plant species varies according to the type, locality, and aquaponics method for the grow-out cultivation. Based on the material compatibility and type of plants to be cultivated, several categories of organic and inorganic media bed substrates can be used to cater the needs. are a good number of aquaponic techniques such as nutrient film technique (NFT), media bed, deep water culture (DWC)/raft, drip and wick system, Verti Stack, Dutch bucket, Vertigrow, ebb and flow (flood and drain), aeroponics, etc. are practiced in small scale to commercial farming, each bearing its benefits. These systems can be installed in the form of mini, small, semi, hobby, open pond,

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domestic, backyard, demonstration, or commercial way as per their purpose, area confinement, and scale of operation. As a primary food source, aquaponics may not fully replace the long-established conventional farming. Still, it can suffice as a much-warranted solution for the area/country without possessing adequate space, water, and fertile soil for the fisheries and agriculture to promote further.

**Keywords**

Aquaponics · Integrated agri-aquaculture farming · Soil-less farming · Media bed · Organic produce

## 23.1 Introduction

In recent times, aquaponics has been one among the safer food production units that produce chemical-free food of good quality in a confined space. With the application of this kind of high-tech techniques, relatively nontoxic quality of food is produced by natural means with no or limited external inputs. This self-sustained integrated food production system has the potential to produce two diversified groups of crops such as fish and plants in a limited space or area for human consumption and/or use, hence also referred as "Integrated Agri-Aquaculture Farming" (IAAF). The term "aquaponics" is the amalgamation of two words, i.e., "*aqua*" (aquaculture- raising fish in a controlled environment) and "*ponics*" (growing in soil-less media). This is an integrated fish and plant production technology, which basically unites two sub-units like "aquaculture" and "hydroponics," but for fruitful operational functioning of the unit, it is scientifically comprised of three components such as fish, plant, and microbes. It is basically a futuristic production system, more preferably equipped for urban places including temperate Himalayan hills, where there is limitation for both space and water. According to Palm et al. (2018), aquaponics is a type of production system that produces both aquatic organisms and plants in an integrated manner where majority of the nutrients required by the plants for their optimal growth and survival were being obtained from the effluents generated by the aquatic organisms under cultivation. This technique is quite effective in growing wide varieties of crops and requires only 10% of water with no use of chemical fertilizers in contrast to traditional farming method in soil (Duarte et al. 2015). As the system produced good-quality chemical-free foods that are safe for human consumption, hence, it got organic certification in developed countries such as the USA. But to make the system viable, it should be scientifically designed, keeping eye on several intrinsic factors such as the types of fish and plant to be cultivated, their ratio, solid waste removal and biofiltration system, etc.

The system can be based on the stocking of single fish species or polyponics with the mixture diversified aquatic organisms or following the concept of freshwater Integrated Multi-trophic Aquaculture (IMTA), where the plants are being grown in the fish culture pond itself with the help of some floating rafts. In a basic recirculation aquaponic system (RAS), the feed loss and fish waste can be reused within the system to convert these into valuable plant biomass, and also the water is replaced only to compensate the plant-mediated evapo-transpiration loss (Lennard and Leonard 2006). The effluents, generated from fish farming units, are difficult to treat because of large volume, carrying fairly dilute nutrients (Adler et al. 1996c; Heinen et al. 1996). There are a number of methods to lessen nutrient discharge of aquaculture effluents such as reduction of excess phosphorus in fish diet (Heinen et al. 1996; Jacobsen and Børresen 1995; Ketola and Harland 1993), decrease of uneaten feed (Asgard et al. 1991; Summerfelt et al. 1995), aggressive separation of uneaten feed and feces from the system (Summerfelt 1996), and application of various biological, chemical, physical (Adler et al. 2000; Metcalf and Eddy Inc. 1991), and plant-based mechanisms for the removal of nutrients (Adler et al. 1996b, c; Adler 1998; Rakocy and Hargreaves 1993). Of these solutions, plant-based removal of nutrients not only has the potential to offset the treatment costs but also fetch additional revenues (Adler et al. 2000) to the growers. This system is capable enough as relief from waste management headache and follows the concept "waste to wealth" as by-product utilization is an important strategy to uphold both the economic and environmental sustainability of aquaculture (Adler et al. 1996a). In general, status of aquaponics as a food production mean in temperate climates of the country is in infant state, but this integrated food production system will definitely be a step forward for the production of safe chemical-free food for the livelihood and income generation of hill communities with limited land holdings and water source, residing at difficult upland terrains of Indian Himalayan Region (IHR).

## 23.2 Principles

For the success of any kind of aquaponic system, the microbial communities play a vital role in the maintenance of optimal water quality, including the transformation and bioavailability of nutrients for the wellbeing of both animal and plants. The fundamental underneath principle for the operational functioning of the system is the efficient management of both waste and water to produce two crops rather than one, along with the partition and share nutrient resources between cultivated animals and plants. The waste produced from one biological system acts as nutrients for another biological system, and the fresh nutrient-rich water can also be re-used through recirculation process with the intervention of microbes (biological filtration). The maximum proportion of the aquatic animal waste contains ammonia, which is utilized basically by a group of ammonia-oxidizing bacteria to produce nitrite, which is again acted by another group of bacteria, i.e., nitrite-oxidizing bacteria so that finally nitrate is produced (Fig. 23.1). In lower thermal climates like the Himalayas, the major representatives of ammonia-oxidizing genera in the recirculatory system are *Nitrosomonas*, *Nitrososphaera*, and *Nitrosospira* (Moschos et al. 2022), including some ammonia-oxidizing archaea and *Nitrotoga* species (Bagchi et al. 2014; Hüpeden et al. 2016). However, among various nitrifying bacteria genera, the *Nitrobacter* group is generally more sensitive to lower water temperature than the *Nitrosomonas* group; hence, harmful accumulation of nitrites may be taken care of judiciously especially during colder seasons.

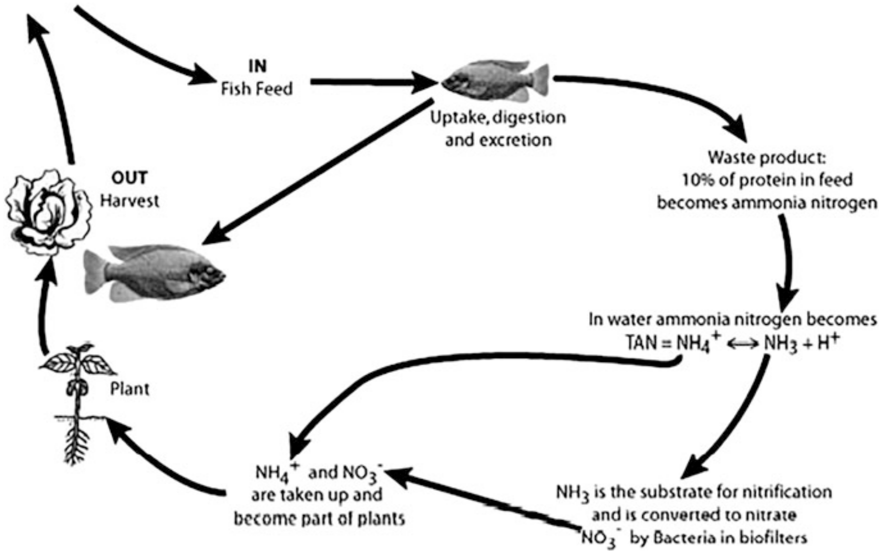


**Fig. 23.1** Nitrogen cycle in aquaponics. (Source: Tyson et al. 2011)

Nitrates, including other nutrient elements produced as a final output by the nitrifying bacteria, are utilized by growing vegetables and plants to meet the nutrient make-up for their better growth and production, although some percentage of nitrite and ammonia are also utilized by the plants depending on the species and varieties. In an aquaponic system, the proper functioning of nitrogen cycle and efficient conversion of nutrients are mainly dependent on the composition and performance of beneficial microbial communities of the system, which are again regulated by several intrinsic water parameters like temperature, pH, dissolved oxygen (DO), alkalinity, and so on (Junge et al. 2017). Most of the biofilter bacteria perform optimally at 17–34 °C water temperature, and their growth rate becomes double at every 10 °C increase in water temperature within the biokinetic zone (BKZ). The DO, particularly for low thermal Himalayan uplands, also need to be maintained at least 60–70% of the saturation level as the beneficial bacteria become literally unproductive below the dissolved oxygen concentration of 2 mg/L (Masser et al. 1999). Similarly, fish and the microbial population require slightly alkaline pH, whereas plants need slightly acidic pH; hence, a pH range of 6.8–7.2 may be maintained in the system to benefit all the partners optimally (Tyson et al. 2004).

Aquatic animals and plants grown in the aquaponic system are generally safe as they are devoid of external fertilizer inputs. For cold-water climates of the Himalayan region, a wide varieties of fish and plants like trout, Murray cod, tilapia, koi, gold fish, crappie, red ear sunfish, bluegill, yabbies, silver/golden perch, salmon, jade perch, salmon, yellow perch, largemouth bass, arctic char, pike perch, sturgeon, walleye, catfish, and pacu along with leafy greens such as kale, Swiss chard, celery, parsley, dill, lettuce, pak choi, and sage, including a number of medicinal and culinary herbs may be advocated to the aquaponic growers that can perform optimally within the thermal regime range of 10–22 °C. For long-term sustainability with optimal output of the system, golden ratio among aquatic animal, plant, and microbial components has to be maintained and balanced with each other in a symbiotic equilibrium. In the context of cold-water Himalayan aquaponic system, in particular, there is dearth of information regarding the specific system design and principle of operation, rather similar strains of nitrifying bacteria are generally colonized in cold-water biofilter as that of tropical system but may not comparably with parallel kind of proficiency. For improved biofilter performance and efficient nutrient conversion in cold-water aquaponics, several kinds of biofilters such as bead filter, sand filter, trickling filter, and moving bed bioreactors (MBBR) may also be used in addition to swirl separator. In order to further strengthen the waste conversion process in low thermal regimes, the ebb-and-flow/flood-and-drain media bed method with bell siphon (among several aquaponic techniques) may be advocated to the growers, as it not only provides cushion for additional biofiltration but also makes the system more resilient to lethal accumulations due to further oxygenation. The prime aim of setting up of an aquaponic system in cold climatic hilly areas of Himalayan region is to strengthen the local economy with the production of high-valued chemical-free healthy foods in locality with the use of pricey imported crop and fish varieties.

## 23.3 Design of Aquaponic Systems

Basically, the aquaponic system is the hybrid of RAS for fish culture and hydroponic for plant cultivation (Goddek et al. 2015). The basic components of the system are fish-rearing tanks, solid removals (mechanical filters such as clarifier and microscreen), biofilter, hydroponic component, and sump (Rakocy 2012; Somerville et al. 2014). For aquaponics in cold-water Himalayas, the standardization of filtration units, especially the quality and volume of biofilter media, may be optimized well as the beneficial nitrifying bacteria may not perform efficiently at lower water temperature. The system can be grouped into mini, small, semi, hobby, open pond, domestic, backyard, demonstration, and commercial system (Fig. 23.2) based on their purpose, nature, function, installation, area confinement, and scale of production (Rakocy et al. 2010; Somerville et al. 2014). As the functionality of each kind of system is based on their adaptations to the geo-climatic variations of that particular site, therefore, the cold-water aquaponics in Himalayan uplands may not render that much impressive result as compared to tropical models.

The open pond aquaponics is a very cost-effective model and was developed long back primarily for catfish and tilapia. Now, this kind of system is being practiced for different types of carps, tench, pike, catfish, etc. and plants like water spinach, okra, tomato, and brinjal. The total pond area may be covered by 4–10% with plant grow-out raft for sustainable production without affecting fish growth. The carnivorous fish varieties could be more suitable for this kind of system as these will not temper the root of the plants unlike some of the herbivorous fish species.

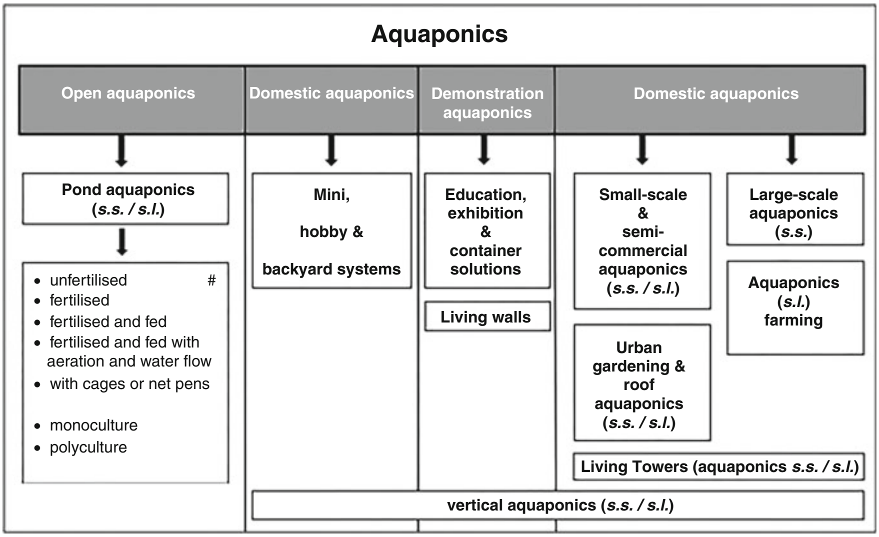


**Fig. 23.2** Four main categories of aquaponic system: open, domestic, demonstration, and commercial (s.s. sensu stricto, s.l. sensu lato). (#Adapted from Stickney (1994) and Horváth et al. (2002) (Source: Palm et al. 2018))

The domestic aquaponics is a kind of coupled classical system where the fish and the plants are generally grown in close vicinity. There are different categories of domestic aquaponic systems (Fig. 23.3) such as mini (<2 $m^2$), hobby (2–10 $m^2$), and backyard system (<50 $m^2$), based on the area coverage, design, and component use. The type of fish, plant, and filtration systems vary according to the kind of domestic system being installed. The mini and hobby kind of systems are basically characterized by less hydroponic area and single small fish tank or aquarium with lower fish stocking density (preferably ornamental fish), where the growing plants float directly on the fish culture water. While the improved models may have separate aquaculture and hydroponic components with internal filters, sedimentation unit, and sump, the nutrient-enriched water is being supplied to the plant bed through the provision of internal or external pump. The gravity-driven fish tank water flows in the direction of filtration units-plant system-sump and then pumped to the fish tank. This kind of indoor systems is generally meant for fish keeping round the year rather than targeting production, but additional aeration facilities may be provided for better growth and well-being of the cultivated animals.

On the other hand, the backyard kind of domestic aquaponic system generally comprised of large fish tanks with more water holding capacity (Malcolm 2007) and improved filtration mechanisms (sedimentation and biofiltration units) with different types of hydroponic units spread over larger area. The airlift pumps may be used, if necessary, in order to target higher yield for human consumption. The backward systems can be installed in urban or cold climatic hilly areas, but a water heating system may be used to maximize the production in low thermal areas of northern

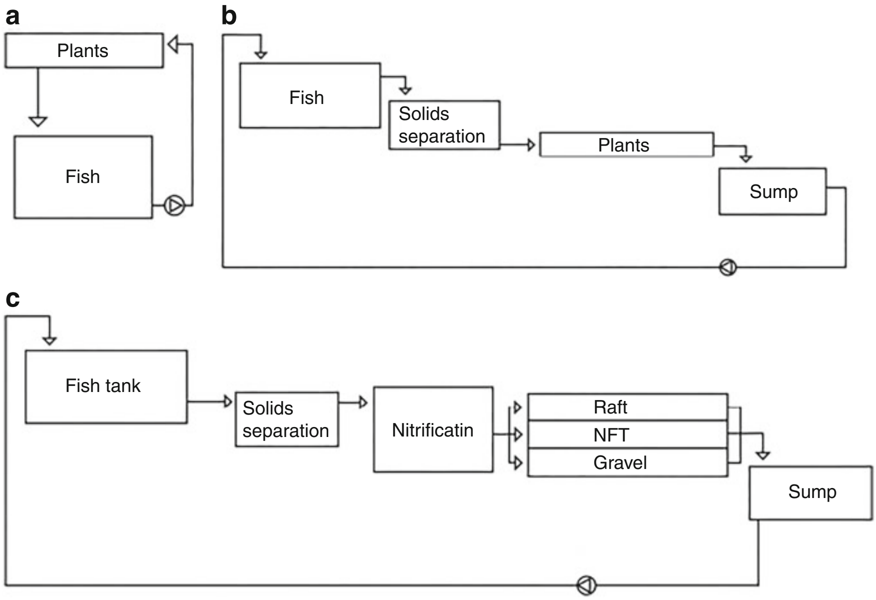


**Fig. 23.3** Design of domestic aquaponic systems. (**a**) Mini-system. (**b**) Hobby system. (**c**) Backyard system. (Source: Palm et al. 2018)

hemisphere. For sustainability and enhanced productivity of the system, it can be integrated with vermiponics using tiger worms, i.e., *Eisenia fetida* in flood-and-drain mechanism, which not only encourage added fertilization for plants but also can act as food for the direct consumption by fish. But during cultivation process, the model requires higher degree of management (Somerville et al. 2014) due to the formation of anaerobic zones, hence limited in commercial application.

The design and operating principle of demonstration aquaponics are more or less similar to domestic form but generally installed in schools, colleges, universities, and industries for education and exhibition purposes. The basic motto is to educate the learners regarding the principles of food chain use with sustainable yield in higher scale. Models like vertical aquaponics and living walls (Wilson 2015) may be categorized under demonstration aquaponics and can be exhibited in organizations/industries to educate the people about waste-to-wealth principle.

On the basis of area and scale of production, commercial aquaponic systems are basically categorized (Fig. 23.4) into various groups such as small-scale (50–100 $m^2$), semi-commercial (100–500 $m^2$), and large-scale (<500 $m^2$) systems. Small-scale aquaponics can use one or more fish and plant units based on the demand of the produce as are generally meant for retail market. The mechanical and biological filters with different hydroponic subsystems such as DWC (raft), NFT, or ebb-and-flow techniques can be used to optimize fish and plant production. A minimum of one pump with backup option (in case of any failure) is needed for better sustainability of the system. For media bed substrates, a wide variety of

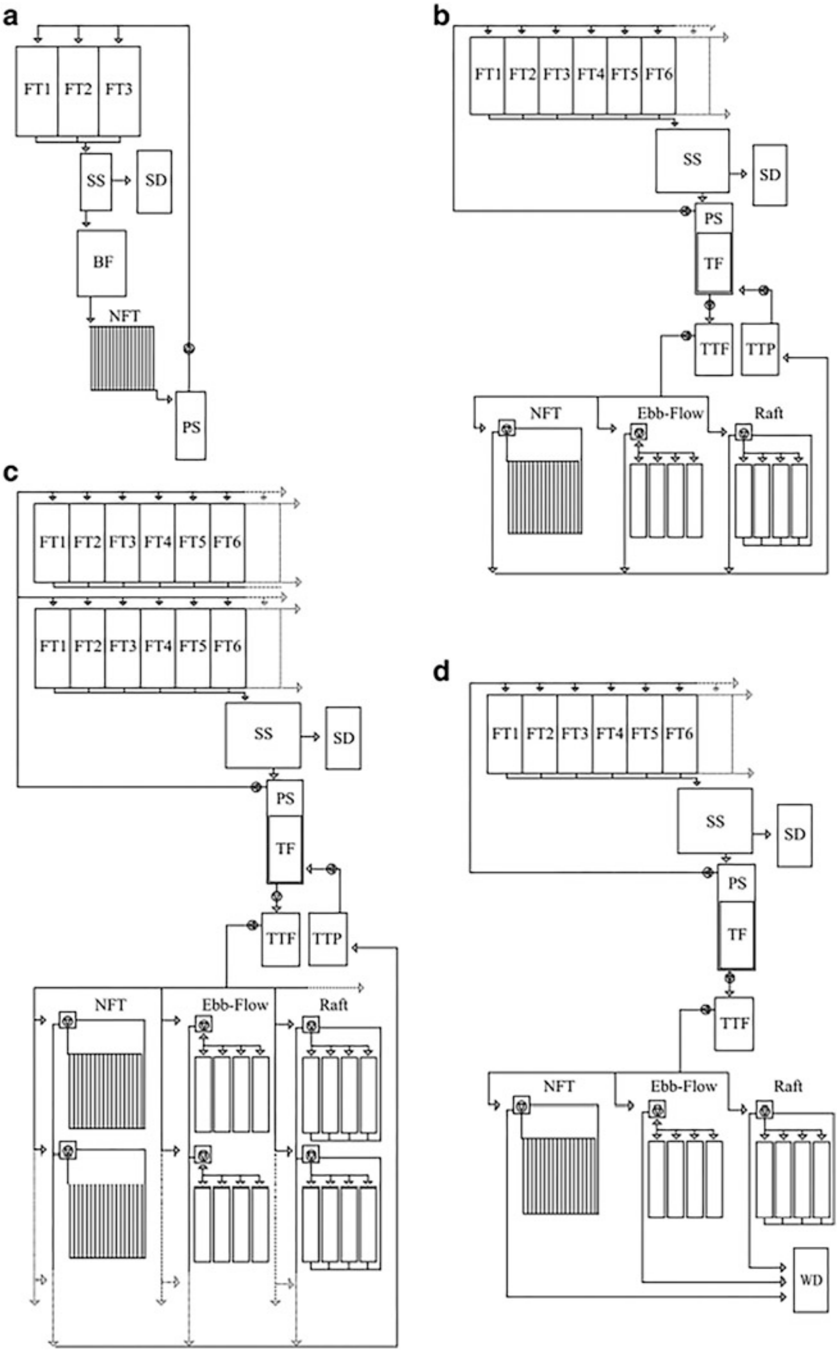


**Fig. 23.4** Scale of aquaponic systems. (**a**) Small scale. (**b**) Semi-commercial. (**c**) Large scale. (**d**) Decoupled. *FT* fish tank, *SS* solids separation, *SD* solids disposal, *PS* pump sump, *BF* biofiltration, *TF* trickling filter, *NFT* nutrient film technique, *TTF* transfer tank fish process water, *TTP* transfer tank plant process water, *WD* water discard. (Source: Palm et al. 2018)

materials such as coarse sand, perlite (Rakocy et al. 2006), LECA (light expanded clay aggregate) (Graber and Junge 2009), volcanic gravel/pumice, limestone gravel, river and crushed stone, and recycled plastics (e.g., plastic bottle caps) can be used, but the prospects of biodegradable organic materials like coconut fiber, cocopeat, sawdust, peat moss, rice hulls, etc. (Somerville et al. 2014) could not be overlooked. Among different kinds of hydroponic media beds, gravel is more effective in the accumulation of nutrients, e.g., phosphorus (Palm et al. 2015). Some of the benefits of the small-scale system are of gravity-driven water flow, low energy consumption (single pump), and very low rate of water exchange unlike large-scale commercial system with higher degree of mechanization. These kinds of systems are quite used for the development of roof gardens in urban areas (Somerville et al. 2014), adding value to the rooftops and urban areas as well. With further customization, according to the specific geographical locations particularly for cold climatic Himalayan stretches, this model can cater the needs of hill populations in terms of livelihood security and socioeconomic upliftment.

The yield of semi-commercial aquaponics is higher than the small-scale system, and the produce may be supplied to both retail and wholesale markets. This system requires more than one pump with additional gravity flow to circulate the water, but there will be higher investment costs if the system includes multi-loop (bypass systems). The numbers of fish tanks and the stocking rate of fish may be increased in this semi-commercial model, but the wastewater containing higher nitrate concentrations needs to be oxygenated inside the biofilter. The treated nutrient-enriched water is then channelized through hydroponic units, which may be of DWC, NFT, ebb-flow, aeroponics, or combination of various subsystems. This semi-commercial system may be of coupled or decoupled with additional drip irrigation (Raviv and Lieth 2008) facility, and the design can be modified as per the specificity of the location and site. For smart farming with higher plant output, technologies such as $CO_2$ greenhouse enrichment (environmental control), potent water monitoring tools, power backup systems, efficient solids removal and biofiltration devices, biosecurity, and pest management including waste and sludge management systems are needed with alternative energy supplies.

In large-scale aquaponics, utmost yield of fish and plants can be obtained with effective management, using fully mechanized appliances and even computer-based facilities for the monitoring of water quality parameters. The fish and plants are chosen judiciously for better productivity within a confined area. In addition to the fish and plant selection, the stocking rate of fish and planting interval including the type of hydroponic system to be used are well taken care of. The system requires high investment cost with high degree of power consumption and, hence, generally operated with alternate energy sources. For better control of the climatic conditions, especially when cold thermal Himalayan belts are in target, these units are generally installed within the polyhouses or greenhouses with water heating appliances and the produce mainly targeted for indirect markets such as grocery stores, hotels, and wholesalers including private and government organizations like colleges, universities, etc. (Love et al. 2015). The system is generally equipped with multiple rearing units, rearing fish of different age or size groups, and staggered harvesting principles for both fish and plants are followed not only to maximize the production but also to get better price as per the market demand (Rakocy et al. 2006; Rakocy 2012). For a highly engineered system, special units such as cold traps, biogas, and photovoltaic systems may be arranged for better sustainability, particularly for temperate climates (Kloas et al. 2012). To maximize the plant output in large-scale aquaponics, intercropping method may be adopted with short-cycle plants like herbs, leafy vegetables, salad greens, etc. in addition to year-round producers like mint, basil, or other woody herbs with the latter bearing the advantage to be regrown by cutting at regular period of time (Rakocy 2012). The addition of biodigester unit or anaerobic nutrient remineralization component (ANRC) with an upflow anaerobic sludge blanket (UASB) reactor following the removal of sludge improves the water quality of the system (Goddek et al. 2016; Junge et al. 2017). The system generally does not encourage the cultivation of plants with media bed due to the need for higher degree of management, but the disease of both fish and plants can be managed better by adopting decoupling principle in large-scale systems.

In decoupled system, the fish culture and hydroponic components are physically disconnected from each other (Thorarinsdottir et al. 2015) for better control on nutrient supplementation, disease management, and water quality parameters. As the main focus of these kinds of systems is horticulture with higher rate of production (Delaide et al. 2016), hence, proper nutrient management can be achieved by not circulating the fish tank wastewater to all the components, rather may be channelized through plant production units after optimal supplementation with hydroponic fertilizing solutions specific to the plants under cultivation. Large-scale decoupled models are generally highly mechanized setups with multi-loop operation using a number of water pumps. In addition, as the system literally comprised of two subunits, hence, maintenance of optimal water quality in two subsystems definitely needs higher rate of investments.

## 23.4 Prospects and Challenges

The type and stocking rate of fish are the prime decisive factors for the growth and well-being of cultivated plants in any kind of aquaponics. Among the wide varieties of fish and plants sorted out for aquaponic farming, a fruitful combination of cold tolerant compatible farming materials may be selected for optimal output in low thermal Himalayan expanses. The better plant performance will be achieved when the selected fish have better dietary consumption rate, and also their waste is enriched with fair amount of plant growth nutrients. For example, low and high nutrient demand plants with less or more planting density may be chosen accordingly for respective carp and trout aquaponics. The nutrient requirement by the plants or in other words the effluent/nutrient removal from the system will depend on the type of plants under cultivation and its growth stages, i.e., the better the plant growth, the better will be the nutrient removal. Among some of the leafy greens advocated for cold-water Himalayan aquaponics, lettuce claims better efficiency in maintaining optimal water quality as it bears the capacity of utilizing ammonia nitrogen directly from the system. The cold-water aquaponic system with trout as a fish component can promote the farming of wide varieties of salad vegetables and medicinal plants. However, among various types and designs of aquaponic systems, the performance of DWC/raft system is quite impressive in cold thermal areas as it keeps the total suspended solids (TSS) in acceptable level by removing soluble nitrogen even at low concentrations.

On the other hand, the intensive production of fish and plants, particularly in cold climatic areas, will certainly attract some of the disease or deficiency symptoms in cultivated species, which should be addressed with organic agents (rather than chemical means) so as to avoid any harmful impact on the system environment. For small-scale production, indigenous solid separator with multifunctional biofilter-cum-media bed unit may be installed to cut short the space including investment cost for a DIY domestic cold-water aquaponics in particular. As one among the active farming techniques, the aquaponic system to be installed in remote terrains of temperate uplands needs continuous energy supply and, hence, may be operated with minimal mechanical equipment with power backup to avoid system collapse. Plant-based waste utilization/removal systems are principally based on the principle of "waste to wealth," i.e., compensate treatment expenditure, along with the provision of extra income for the marginal hill growers as well. Unlike soil farming, the health and growth of the plants are better in aquaponics because of the efficient water flow across plant roots for mass transfer of nutrients along with the omission of unwanted weeds and soil-borne diseases. These kinds of modern scientific natural farming systems are best suitable for small land holding hill farmers of Himalayas, including vertical and urban rooftop farming, but need proper technical know-how for its design, fabrication, and operation.

In order to extract optimal benefit from a cold-water aquaponic system, it may be designed and fabricated scientifically using efficient substrate media with better surface area for effective nutrient transformation to keep away from any kind of plant diseases/symptoms like chlorosis, rotting, leaf burn, drying, etc. The parameters, especially the macro- and micronutrients may be checked regularly and supplied with organic supplements, if needed. Among several water quality parameters, dissolved oxygen is one of the most critical parameters that determine the output of the system in terms of fish and plant biomass, and hence, its supplementation into water may be done through venture and airlift means besides the main aeration/oxygenation system. In DWC or raft aquaponics, most of the plants (transplanted plantlets/saplings) show drying symptoms during their early growth stages as shorter plant root fails to assess the underlying water, and hence, wick/cotton thread may be provided in each plant net pot for their better survival and growth. The NFT (nutrient film technique) is one of the most successful methods for soil-less plant cultivation, but plant selection including the height and diameter of NFT channel is vital for its success. For aquaponic farming in cold-water Himalayas, the NFT is one of the most suitable methods as the temperature of the channel water can be controlled in a better way with customized adjustments and is much efficient for the cultivation of leafy greens, but the system may not be as competent in growing root vegetables, including larger fruiting plants.

## 23.5 Conclusion

In order to get better yield from any of the aquaponic systems, the staggered/partial/multiple harvesting principle may be opted both for fish and plants, while periodic harvesting with restocking strategy shall be practiced for fish, especially in cold thermal Himalayan region. Climate control indoor setups like greenhouse or polyhouse with the provision for lighting and heating may be installed in temperate areas (northern hemisphere) for year-round production of diverse crop varieties (Knaus and Palm 2017a, b). The recirculation aquaponic system could be a fruitful model for better productivity within a limited space, especially in the upland terrains of Indian Himalayas, rooftops, and urban area farming, but the fish-plant combination, their cultivation area proportion, and the quality and sizing of the biofilter are needed to be standardized. New form of technologies may be researched and adopted in this line with efficient effluent removal, nutrient availability, and disease or pest control potential for better growth and well-being of cultivated varieties.

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