Case Study

Nitrogen recovery via aquaponics in Nepal: current status, prospects, and challenges

Rishav Adhikari¹ · Sriyanka Rauniyar¹ · Nishan Pokhrel² · Amrita Wagle³ · Takeshi Komai⁴ · Shukra Raj Paudel^{1,5}

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Abstract

Aquaponics is a bio-integrated system that couples recirculating aquaculture with hydroponics. Existing aquaculture has been a continuous source of environmental degradation; however, minimal concern has been documented toward its waste management. This paper aims to review the fundamental aspects of aquaponics, its components, types and influencing factors, and also to estimate potential nitrogen recovery from aquaponics. This review also explores the nitrogen transformation pathway and discusses potential challenges for aquaponics in Nepal. The estimated the nitrogen recovery potential of aquaponics in Nepal are 3509 tonnes (t) and 7157t, equivalent to 7628t and 15558t of urea fertilizer for the years 2020 and 2030, respectively. Globally, nitrogen loss from aquaculture was estimated to be 7.52×10^6 t for 2016. Developing countries like India, Bangladesh, Nigeria, etc. are also major source of existing nitrogen loss from aquaculture. For environmental and production sustainability, wastewater utilization via aquaponics is crucial, therefore, needs global attention and policy formulation. Identification of isotopic signature or abundance of stable isotopes in aquaponics helps find the exact pathway of nitrogen transformation in the system.

Keywords Aquaponics · Aquaculture wastewater · Nitrogen transformation · Nitrogen recovery

1 Introduction

Food and nutritional security has become one of the critical global issues in the modern society. Soaring urbanization and population demands has caused to increase resource supply from limited production area. Nepal as a developing country significantly relies on agriculture and the effects of climate change on such graniferous lands are detrimental to people's welfare and economic development [33]. In this county, aquaculture and farming (for fish and vegetables) are prevalent among farmers. Aquaculture has become a major source of global fish protein for the world population and globally fish food

is consumed at about 19.2 kg per capita per year [18]. In Nepal, aquaculture comprises 66.83% of its total fish production, and has become the fastest growing industry with average annual growth rate of 11.10% per annum [18, 40]. Vegetables are cultivated in minor section of cultivable lands in Nepal—insufficient to meet the national demand. Farming and aquaculture are one of the major sources of food supply and employment opportunities for which the country possesses substantially favorable environment. Traditional framing practices are required to replace with alternative production practices with respect to pollution control and potential nutrient recovery. Aquaculture is considered as one of the major fish food production

✉ Shukra Raj Paudel, srpaudel@ioe.edu.np | ¹Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Pulchowk, Lalitpur, Nepal. ²Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA. ³Department of Medical Microbiology, Nobel College, Pokhara University, Sinamangal, Kathmandu, Nepal. ⁴Department of Environmental Studies for Advanced Society, Graduate School of Environmental Studies, Tohoku University, Sendai 9808579, Japan. ⁵Department of Environmental Engineering, College of Science and Technology, Korea University, Sejong, Republic of Korea.

industries which consumes and release huge amount of nitrogen [22]. Higher nutrient concentration of aquaculture effluent stimulates algae growth that subsequently results in eutrophication and hypoxia in water bodies [39]. On the other side, antibiotic resistance used in aquaculture to lessen diseases dissemination causes chemical pollution [22]. And, aquaculture is also a considerable source of nitrous oxide: a potent greenhouse gas [39, 40]. Moreover, excessive use of chemical fertilizers causes heavy metal accumulation, water eutrophication, nitrate accumulation, soil degradation, and release of nitrous oxide and nitrogen into the atmosphere [40, 50]. Therefore, sustainable approaches for efficient aquaponic production (fish and plant biomass) and management of nitrogen (nitrogen, nitrous oxide) loss using new techniques have been realized for Nepalese context too. In parallel, nutrient recovery from aquaculture wastewater with sustainable organic farming can also provide clean water (less nitrate and ammonium concentration) for recirculating aquaculture tank.

Wastewater from aquaculture contains nutrients like nitrogen and phosphorus, which can be utilized for the growth of plant species. Past studies documented that aquaponics is a sustainable approach for nutrient utilization from aquaculture wastewater with ensuing organic production of vegetables [28, 51, 58, 63]. However, this technology is in emerging practice, and has many challenges. In aquaponics, there exist a symbiotic relationship

among fishes, microorganisms and plants. Aquaculture wastewater can supply most of the nutrients required for plants provided that the optimum ratio between daily feed input and plant growing area is to be maintained [42]. In fact, the waste produced by fish serves as manure for the plants which eventually becomes convenient for fish on recirculation [57]. Aquaculture wastewater has high amount of nitrogen content in the form of total ammonia nitrogen (TAN), which undergoes nitrification via nitrifying bacteria resulting nitrate (NO_3^-) (Fig. 1). Nitrate, a basic nutrient for plants, is assimilated by plants resulting in clear water essential for fish [41, 59]. Plants like tomato (*Solanum lycopersicum*) and lettuce (*Lactuca sativa*) have very good nutrient uptake from aquaponics system which also results in potential reduction of N_2O emission [22, 40, 41, 59]. Thus, aquaponics is not only considered a production alternative but also is considered as a promising means of wastewater treatment system.

Aquaculture wastewater, however, contains nutrients like nitrogen (N), phosphorus (P) and Carbon (C) [12, [35]; this paper focuses only on nitrogen transformation and its potential recovery. Despite of its several production and environmental benefits, aquaponics practice is in emerging phase in Nepal. Therefore, this paper has placed the emphasis potentially to promote the application of aquaponics as an alternate production system for fish and vegetables in Nepal. The overarching goal of this paper is to estimate potential nitrogen recovery from aquaponic

Fig. 1 Symbiotic relationship among fish, microbes and plants in aquaponics

system in Nepal and in major continents of the world, and also to illustrate nitrogen transformation with fundamental science and aspects of aquaponics. This study also briefly discusses potential reduction of N_2O emission, status, and possibilities and challenges of aquaponics in Nepal.

2 Principle of aquaponics

Aquaponics is a freshwater ecosystem which is made up of interactions between its biotic (living) components which include fish, plants and bacteria, and abiotic (non-living) components that comprise of water, air, and growing media (Fig. 1). Humans nurture fishes in a fish tank by supplying the required amount of feed. Fishes excrete waste into water which contains high amount of ammonia after consuming supplied feed. Bacteria and other microorganisms transform those wastes into nutrient rich and water-soluble fertilizer containing nitrate and ammonium which are commonly used by the plants for their growth. Plants uptake nitrogen and it results in producing relatively clean wastewater. Finally, thus produced clean water is recirculated in the fish tank. The scientific idea of aquaponics remains same in all types of aquaponic system.

In aquaponic system, the excreted TAN from fish is oxidized to nitrite (NO_2^-) and nitrate (NO_3^-) by ammonia-oxidizing bacteria (AOB) and nitrite-oxidizing bacteria (NOB), respectively (Fig. 1), which consequently lowers ammonia and nitrite toxicity in the fish tank. Nitrate is assimilated by the plants that enhances the nitrogen use efficiency (NUE), and thus ultimately creates better environment for fish in the aquaculture tank [58, 60]. The nitrous oxide (N_2O), a potent greenhouse gas, can be minimized or managed to reduce through aquaponic system by altering plant species and their density thereby helping lower nitrogen species concentration for nitrification and denitrification process [22, 40, 41].

3 Components of an Aquaponic system

3.1 Biological components

3.1.1 Plants

Plants, hydroponic component in aquaponics, are cultured in a grow bed with nitrate rich water. Plants are important in maintaining aquaponics cycle since, they lower nitrate and ammonia concentration by utilizing for their own growth. Optimum utilization of excess nutrients present in the fish tank is the main goal of culturing plants in aquaponics. In point of commercial view, the plants should

generate highest level of income per unit area of culture. Therefore, selection of plant species is key to achieve water quality for recirculation; however, it also depends upon nutrient concentration and stocking density of fish [5]. Both leafy vegetables and fruits can be harvested in aquaponic systems [2]. Past studies have reported that culinary vegetables are economically suitable because of their growth performance, high demand and market values and availability [43].

Common vegetables harvested in aquaponic system are listed in Table 1. Leafy vegetables and herbs like cilantro, mint, parsley okra, etc. can also be grown in an aquaponic system. Fruiting crops like tomato, eggplant, pepper, strawberries are preferred for high nutrient concentration, and are only suitable for well-established and large-scale aquaponics [2, 38, 43]. In aquaponic systems, flowers like marigold and zinnia have been successfully harvested, and have potential to grow medicinal herbs too [43]. Hydroponic performance of anaquaponic system is remarkably affected by the plant species. Higher root surface area of plants is crucial to abundance of nitrifying bacteria and higher nitrogen transformation and utilization efficiencies (NUE) of the aquaponic system. Nitrogen uptake capacity of plants also plays a vital role in avoiding the accumulation of NO_3^- in aquaponics [21, 41].

3.1.2 Fishes

Fishes, a major source of nutrient in aquaculture wastewater, supply nutrients to plants on the grow bed. And, they are reared and nurtured in the fish tank with required amount of water. Protein and nitrogen content in the fish biomass varies among the fish species resulting in variation in aqueous nitrogen after assimilation in the fish tank [18, 22]. This eventually results in variation of nutrient; especially nitrate (NO_3^-) in the hydroponic component. Diverse fish species (both warm and cold water) depending on their performance have been adopted/studied in aquaponic systems [8], some of which includes: Tilapia (*Oreochromis niloticus*), Nile tilapia (*Oreochromis niloticus*), Red tilapia (*Oreochromis aureus* × *Oreochromis mossambicus*), Catfish (*Siluriformes*), Trout (*Oncorhynchus mykiss*), Perch (*Perca*), Common carp (*Cyprinus carpio*), Koi carp, Largemouth bass (*Micropterus salmoides*), Murray cod (*Maccullochella peelii*), Mullet (*Mugilidae*), Pacu (*Colossoma macropomum*) [2, 8, 38, 43]. Fish species that can resist high stocking density are expected to do well in aquaponic farming [43]. Among several fish species, Tilapia (*Oreochromis niloticus*) is most commonly reared fish species in aquaponics because of their high tolerance to wide range of temperature, salinity, low dissolved oxygen levels, and high ammonia concentration [8].

Table 1 List of common vegetables harvested in aquaponic systems

Plant species	Scientific name	pH	Temperature range (°C)	Recommended aquaponic method	References
Basil	<i>Ocimum basilicum</i>	5.5–6.5	18–30 (20–25)	MB, NFT, FRT	Somerville et al. [53]
Cauliflower	<i>Brassica oleracea</i> var. <i>botrytis</i>	6.0–6.5	20–25	MBT	
Lettuce	<i>Lactuca sativa</i>	6.0–7.0	15–22	MB, NFT, FRT	
Cucumber	<i>Cucumis sativus</i>	5.5–6.5	22–28/18–20 ^a	MBT, FRT	
Eggplant	<i>Solanum melongena</i>	5.5–7.0	22–26/ 15–18 ^a	MBT	
Peppers	<i>Capsicum</i>	5.5–6.5	22–30/14–16 ^a	MBT	
Tomato	<i>Solanum lycopersicum</i>	5.5–6.5	(22–26)/(13–16) ^a	MBT, FRT	
Beans and Peas	–	5.5–7.0	22–26/16–18 ^a	MBT	
Head Cabbage	<i>Brassica oleracea</i>	6.0–7.2	15–20	MBT	
Broccoli	<i>Brassica oleracea</i> var. <i>italic</i>	6.0–7.0	13–18	MBT	
Swiss Chard	<i>Beta vulgaris</i>	6.0–7.5	16–24	MBT, NFT, FRT	
Parsley	<i>Petroselinum crispum</i>	6.0–7.0	15–25	MBT, NFT, FRT	
Water spinach	<i>Ipomea aquatic</i>	5.6–7.3	27.5–28.8	–	Endut et al. [10]
Mint	<i>Mentha arvensis</i> L	6.1–7.12	26.4–28.9	FRT	Wahap et al. [57]
Pak choi	<i>Brassica rapa</i> L. <i>chinensis</i>	6.7–7.2	25–30	FRT	Wongkiew et al., [60]
Chieve	<i>Allium schoenoprasum</i> L	6.6–7.0	23–28	FRT	Wongkiew et al. [59]
Okra	<i>Abelmoschus esculentus</i>	7.0–8.5	29–35	FRT	Salam et al. [48]
Aubergine	<i>Solanum melongena</i>	7.0–8.0	–	MBT	Graber and Junge [17]
Water celery	<i>Oenanthe javanica</i>	6.8–7.2	24 ± 0.5	FRT	Paudel [41]

Data source except Somerville et al. [53] is non-generalized experimental set-up values. Values in parentheses refer the optimal temperature range

MBT media-based technique, NFT nutrient film technique, FRT floating raft technique, respectively

^aThese values show the day and night temperature range

3.1.3 Bacteria

Bacteria, the third candidate in the aquaponics after fish and plant, culture in biofilter that generally located in between clarifier and grow beds. They convert fish wastes into consumable nutrients for plants by a process called nitrification. Nitrification in aquaponics is facilitated by the bacterial community in two intermediate and sequential steps. First, TAN is oxidized to nitrite (NO_2^-) by ammonia-oxidizing archaea (AOA) and then ammonia-oxidizing bacteria (AOB) (e.g., *Nitrosomonas*, *Nitrosococcus*, *Nitrospira*, *Nitrosolobus*, *Nitrosovibrio* sp., etc.). However, AOA oxidizes ammonia in low NH_4^+ concentration and is rare in aquaponic systems. Sequentially NO_2^- is oxidized to NO_3^- by nitrite-oxidizing bacteria (NOB), e.g., *Nitrobacter*, *Nitrococcus*, *Nitrospira*, *Nitrospina* sp. etc [59]. Schmutz et al. [52] analyzed microbial diversity in various compartments of an aquaponics system. Microbes like *Fusobacteria*, *Proteobacteria*, *Firmicutes*, *Planctomycetes*, *Bacteroidetes* may also be present but they have minimal or no influence in the aquaponic performance.

3.2 System components

3.2.1 Fish tank

Fish tank is a container to rear fish in aquaponic systems. Size of the tank should be sufficient enough to supply feed and hold the estimated fish quantity in the system. Generally, the effluent drain is located at the center of the tank. It is better to adopt a circular tank, as water approaches the center with low turbulence, and facilitates efficient removal of effluents. Also, radius to height ratio is of 3:1–4:1 which allows centripetal forces to bring the solid toward the central drain. Fiber glass is commonly used for fish tanks, but owing to its high price, high-density polyethylene (HDPE) and ethylene propylene diene monomer (EPDM) liners are also used in commercial scale systems [38]. Size of fish tank is also governed by hydrobed area and plant density to be maintained in the system.

3.2.2 Biofilter

Biofilter is a device used to control the concentration of toxic nitrogenous wastes from fish tank in a closed system. Basically, it is a media with large surface area per unit volume so that many bacteria can grow and adhere over the large surface. Ammonia released from fish metabolism is toxic to fish even in low concentration of 1 mg/L [38]. Higher stocking density of fish can cause quick rise in ammonia concentrations. Biofiltration mainly involves *nitrosomonas* and *nitrobacter* to convert ammonia into nitrite, and nitrite into nitrate by simultaneous process of nitrification and denitrification, respectively [43]. Thus, the resulting NO_3^- concentration ($< 300 \text{ mg/L}$) is less toxic to fish than NH_4^+ and NO_2^- [59]. Common biofilter media includes sand, gravel, shell, plastic media, sponge, and bio-balls etc. [38, 39, 43]. Filter media with higher surface area is highly preferable.

3.2.3 Plant grow bed

Plant grow bed is basically a container for the growth of plant in aquaponic systems. The design and function of the grow bed in aquaponic systems is no different than that of the hydroponic system [38]. Growing bed provides static, continuously flowing or aerated nutrient solution for the plant roots in suspension [4]. Although, being a hydroponic subsystem, growing bed does not involve soil, it contains pipes, raft and media materials like gravels, sponges. In this component, plants after germination are transferred to grow until harvesting time.

4 Types of aquaponics

4.1 Nutrient film technique

Nutrient film technique (NFT) is a type of aquaponics in which the plants are placed in small plastic cups with their roots submerged in the water through which they can absorb nutrients (Fig. 2). Source of nutrient rich water is either pumped through small enclosed gutters contained synthetic nutrient solution or other source such as

aquaculture tank. A thin film of water is continuously supplied to the channel through which oxygen and nutrients are provided to the plants. This system, generally used to grow green leafy vegetables [2] is easy to operate, clean and maintain. NFT generally utilizes plastic pipes for nutrient supply as they are light weight and also enables the adjustment of pipe as per plant density according to the growth stage of the crop. Owing to lack of enough area for the flourishing of bacterial community in such small pipes, a separate biofilter component is essential in such systems [38]. Nutrient film technique requires continuous flow of nutrient to the plants thus it is vulnerable to pump failures. Such disruption in the water flow results in the wilting of plants [43]. Lennard and Leonard [27] found that NFT hydroponic system is less efficient at removing nutrient from fish culture water and producing plant biomass than other two systems (FRT and MB). Nutrient uptake in NFT is low due to smaller root-water contact area [16]. NFT provides high oxygen to plant roots but is unfit for culturing of large rooted plants that is mainly due to potential blockage of nutrient supply pipes.

4.2 Floating raft technique

Floating raft technique (FRT) consists of floating polystyrene boards/rafts (Fig. 3) allowing the roots to suspend in the water. This hydroponic subsystem is suitable for both leafy vegetables as well as large plants like tomato or okra [43]. In this system, the raft floats on top of the large tank, so that there is no clogging effect [59]. FRT uses large volumes of water in hydroponic subsystem, which also increases the buffer capacity against ammonia and reserves nutrients for longer periods of time, even during pump disruption or reduction in fish biomass [38]. On other hand, heavy water requirement demands pumps operation and higher cost of energy. FRT may be more susceptible to breeding of mosquito larvae due to large water area. Moreover, this system becomes unsuitable for roof-top aquaponics, since it has heavy components [16]. A major demerit of FRT is that the roots in the raft could be exposed to harmful organisms associated with the aquaculture system. Also, if the fishes have access to the hydroponic system, they

Fig. 2 Schematic of generic design of NFT aquaponic system

Fig. 3 Schematic of generic design of FRT aquaponic system

will consume the plant roots and thus can cause significant hindrance on the plant growth [43]. FRT, however, has some cons is largely used for commercial scale due to additional benefits.

4.3 Media-bed technique

Media-bed technique (MBT) is the simplest form of aquaponics, which contains a large container with growth media (Fig. 4). For small systems, gravel is a common hydroponic media. However due to several problems like clogging, anaerobic zone formation, sturdy infrastructure requirements, etc. other inorganic media such as sand, perlite, pea gravel, tuff, and clay are also used [38, 43]. Organic hydroponic media includes sphagnum peat moss, pine bark, or coconut fiber. Media beds are suitable for leaf, fruit and root vegetables [38]. Major advantage of media-bed technique is its ability to work without biofilter [59]. Also, this system requires less management and fewer components. Nutrient uptake is also high in media filled technique [16]. Media like gravel provides calcium during nitrification for plant growth. However, accumulation of organic matters in the media bed causes formation of anaerobic zones affecting plant roots. Planting in hard media is also difficult as compared to other aquaponic systems. Continuous flow of water to the media is required in the system. Therefore, this system is relatively inconvenient in the case of where power supply is irregular.

Fig. 4 Schematic of generic design of media-bed aquaponic system

5 Factors affecting aquaponics performance

Healthy growth of both fishes and plants depends upon water chemistry, which in turn depends on the quality of the feed, stock of fish, functioning of settling tanks, biofilters, grow beds, aeration devices, and build-up of organic materials and associated bacteria anywhere in the system. The important environmental and operational factors that affect aquaponics performance are discussed below.

5.1 pH

The regulation of pH is crucial in aquaponics systems. The required pH value has to be maintained in order to create a balanced and stable environment for the fishes, plants and bacterial community. As the nitrification process occurs, the pH value declines due to the increase in concentrations of H^+ and NO_3^- ions. pH level also affects plant performance. The optimum pH for plant health and nutrient uptake is usually in the range of 5.5–6.5 [43]. Nitrifying bacteria, on the other hand, perform best (in terms of ammonia reduction) at pH levels of 7–8.5. Nitrification almost stops at pH below 6 [49]. For the optimum growth of fishes, pH requirements are usually intermediate, generally preferring pH of 6.5–8.5 [62]. Essential minor nutrients such as iron, manganese, copper etc. are less available to plants at a pH higher than 7.0, while the solubility of phosphorus, calcium, magnesium and molybdenum sharply decreases at a pH lower than 6.0 [43]. The pH of 6.5 or lower is preferred for solubility of micro nutrients [45]. Therefore, pH value should be adjusted so that ammonia

cannot accumulate in the system. The optimal permissible value of pH in aquaponic systems is 6.8–7.0. Therefore, pH is usually maintained and is regularly monitored at a tolerable range of 6.4–7.4 in aquaponics by regular dosing of lime.

5.2 Feed quality and feed rate

Fish feed is the major source of nutrient input in an aquaponic system. Healthy growth of fishes and plants depend upon the quality of feed being used. Enhanced feed quality reduces fecal solid production and improves feed efficiency [62]. Poor quality of feed results in more fecal wastes which cause disturbance in the whole system, especially if there is absence of well efficient settling equipment. Also, it results in poor growth of both plants and fishes, and possibly degrades the taste quality of the food products generated [20]. Quality of fish feed is also essential for the balanced and healthy environment, and better performance of both fishes and plants. In fact, different diets are required for different growth stages of fish. Feed requirement for adult and juvenile fish are 1–3% and about 7% of their body weight, respectively [58]. Diets for pre-adult fish are richer in crude protein (40–50%) for their growth meanwhile feed with crude protein (30–40%) might be sufficient for mature adult fish [20]. During the mature growth phase of plants, they need more nutrients and hence higher feeding rate requires to be supplied. Graber and Junge [17] observed the positive influence of feeding load on nutrient availability to plants. Hence, in addition to the quality of feed, feeding rate also plays a crucial role in the aquaponics which is also influenced by plant culture method.

5.3 Nutrient concentration

In aquaponics, nutrients necessary for plants are delivered via aquaculture wastewater. Fish excreta contain sufficient levels of ammonia, nitrate, nitrite, phosphorus, potassium, and other micronutrients for the hydroponic plants [8]. Nutrient requirements in aquaponic systems vary according to the growth stage of plants. For instance, nitrate requirement is more during the vegetative growth of leafy plants while lower concentrations are appropriate during ripening of fruiting vegetables [56]. To stabilize an aquaponic system, higher nutrient concentration is not desirable as most fish can normally tolerate nitrate (NO_3^-) levels up to 200 mg/L while concentrations above 300 mg/L are toxic [30, 58]. To overcome this difficulty of nutrient balance between fishes and plants, supplement nutrients like chelated iron, calcium hydroxide and potassium hydroxide can be externally provided to supply other important nutrients like iron, calcium, potassium, etc. [43].

Hence, nutrient concentration will be another key player for nitrogen recovery by plants.

5.4 Temperature

The aquaponics performance is mainly governed by growth temperature for both fishes and plants. Therefore, an optimum temperature is also required to maintain for creating healthy environment in the system [14]. Temperature selection depends on the species of plants and fish used in the system. Also, upraised aquaponic temperature increases metabolism, respiration and oxygen demand of fish [62]. An optimum temperature for Tilapia (*Oreochromis niloticus*) growth is 25–30 °C; for most lettuce species is 17–25 °C; and for Carp (*Cyprinus carpio*) is 20–26 °C [20]. To maintain the optimum water temperature heating system requires during the winter while year-round cooling in tropical zones. General water temperature for hydroponic plants is 16–30 °C (21–23 °C optimum). Temperature adaptability of warm water and cold water fish varies between 22–32 °C and 10–18 °C, respectively [49, 62], whereas biofilter performance thrives well in temperatures between 25 to 30 °C [49]. Thus, temperature plays vital role for nitrogen transformation which ultimately affects potential nitrogen recovery of the system.

5.5 Dissolved oxygen (DO)

In aquaponic system, it is also important to maintain the DO levels in culture water for the optimal growth of both plants and fishes. Fishes breathe the dissolved oxygen through cellular respiration and hydroponic plants undergo intense root respiration to extract the dissolved oxygen from the available water [14]. In low DO concentrations, energy conversion ability of fishes is reduced, thus resulting in decline in growth rate and feed efficiency [62]. Deficiency of dissolved oxygen impacts the plant growth as nutrient uptake decreases due to the reduction in water absorption which results in loss of cell tissue from roots. Also, deduction in DO level enhances growth of pathogens. Cold water fishes require more DO concentration (6.5 ppm) than that of warm water fishes (5 ppm) [49]. Optimum DO level for optimal growth of biomass should be maintained which is usually greater than 5 ppm [45]. DO level is a key factor that affects nitrogen transformation and potential nitrogen recovery via aquaponic system too.

5.6 Hydraulic loading rate

Liquid flow rate per unit surface area of grow bed is termed as hydraulic loading rate (HLR). Favorable time of contact between nutrients, microbes present in the aqueous phase, and plant roots is mainly guided by the value

of HLR [29]. Low HLR results in deficiency of oxygen inducing denitrification and loss of nitrogen from the aqueous phase. On the other hand, high HLR reduces the contact time between the recirculating water and the plant roots, and washes out the microbes and sediment attached to the plant roots and biofilter media [10]. Optimum HLR under different environmental conditions in aquaponics has not been investigated yet. Therefore, it is also required to examine for optimal growth of aquaponic biomasses (fish and plant). Overall, HLR—a key design parameter—can also affect fate of nitrogen including potential nitrogen recovery via aquaponic system.

6 Discussion

6.1 Nitrogen transformation in Aquaponic system

Nitrogen is regarded as the building block for all life forms. Nitrogen transformations are the key biochemical processes in an aquaponic system (Fig. 5). Fish feed, which is rich in protein helps in the cellular growth and energy assimilation, hence providing free energy for metabolism and heat losses [26]. Part of the fish feed remains unconsumed. The consumed food is partly converted into fish biomass, partly defecated, and partly excreted as un-ionized ammonia through gills. The sum of un-ionized ammonia (NH_3) and ionized ammonium (NH_4^+) in the aqueous phase is termed as total ammonia nitrogen (TAN) [22].

In an aquaponic system, nitrification is the main phenomena for converting NH_4^+ to NO_3^- . There are basically

two steps involved in this conversion: firstly, TAN is oxidized into nitrite (NO_2^-) by ammonia-oxidizing bacteria (AOB) (e.g., *Nitrosomonas*, *Nitrosococcus*, *Nitrosovibrio* sp., *Nitrosolobus* etc) and then the NO_2^- is changed into nitrate (NO_3^-) by nitrite-oxidizing bacteria (NOB) (e.g., *Nitrobacter*, *Nitrospira* etc) [9]. In an aquaponic system, NO_3^- concentration limit is about 300 mgN/L, above which is harmful to fish [30]. However, studies show that TAN and NO_2^- concentrations should be kept at comparatively low levels in order to maintain the amount of NO_3^- in the system [5]. The residual TAN and unused feed are hence filtrated in biofilter, and solids are separated.

Thus, formed NO_3^- is consumed by plants for their growth which is referred as nitrogen uptake. Photosynthesis takes place in the plants with the help of water and minerals in the roots transported via xylem. NO_3^- is converted into organic nitrogen with the help of many enzymes such as nitrate reductase (NR), nitrite reductase (NiR), glutamine synthetase (GS), glutamate synthase (glutamine: 2-oxyglutarate aminotransferase, or GOGAT), glutamate dehydrogenase (GDH), aspartate aminotransferase (Asp-AT) and asparagine synthetase (AS) [54]. During the process of translocation and assimilation, influx and efflux of inorganic nitrogen also takes place between the roots and the recirculating water. In suitable environmental conditions, plant roots are vital in regulation of nitrogen in aquaponics via nitrification and denitrification process under flourishing microbial activity. In fact, biofilm of exopolymeric substances (EPS) formed on root mats mainly contributes on nitrification and denitrification processes [41].

Fig. 5 Possible nitrogen transformation pathways in aquaponics

Nitrogen loss occurs in the system mainly due to some reasons: one of them is denitrification which aids to nitrogen loss of about 25–60% [21]. Nitrogen use efficiency (NUE) is decreased due to the losses from the system [58]. Denitrifiers transform NO_3^- to NO_2^- , nitric oxide (NO), nitrous oxide (N_2O) and finally to nitrogen gas (N_2) under anoxic condition (low dissolved oxygen conditions). This is also carried out by nitrifier denitrification process [61]. Various archaea, facultative heterotrophic bacteria such as *Achromobacter*, *Aerobacter*, *Acinetobacter*, *Bacillus*, *Brevibacterium*, *Flavobacterium*, *Pseudomonas*, *Protus* and *Microoccus sp.* help in this process. Other losses occur via assimilation of heterotrophic bacteria, anaerobic ammonium oxidation and ammonia volatilization [58, 60]. In fact, nitrogen recovery potential by hydroponic plants mainly depends on fate of nitrogen and its species concentration too. And, critical analysis of isotopic signature or abundance of nitrogen isotopes—however, little study has begun to investigate it—in aquaponics can help find the exact pathway of fate of nitrogen in the system.

6.2 Potential nitrogen recovery from aquaponics

Aquaculture solely is an unsustainable practice of production, because large amount of nitrogen is lost as effluents. In order to minimize that loss, aquaculture can be combined with hydroponic subsystem. For estimating numeric values of nitrogen recovery, nitrogen loss scenario via aquaculture and potential nitrogen utilization/recovery by plants in aquaponics was considered. Aquaculture production data was exploited from Food and Agriculture Organization [11] for the years, 1980–2016. Then, the amount of waste nitrogen from aquaculture in aqueous phase can be estimated using Eq. 1 [22].

$$N_{\text{aqueous}} = 0.77 \times N_{\text{input}} \quad (1)$$

where N_{aqueous} is the quantity of nitrogen being rejected to water after assimilation by fish; N_{input} is the total nitrogen introduced in the system as fish feed. Equation (1) is significant in illustrating the potential nitrogen loss from existing aquaculture. The study can be further expanded based on fish production where N_{input} in the system can be estimated using Eq. 2.

$$W_{\text{fish}} = 8.18 \times N_{\text{input}} \quad (2)$$

where W_{fish} is amount of fish production from aquaculture; N_{input} is the total nitrogen introduced in the system as fish feed. Overall development of this equation depends upon the assumption that fish feed is the only source of nitrogen, and that all of the fish feeds are ingested by the fishes (i.e., there is no any residual feed). Potential N_{aqueous} was estimated based on the predicted data for the years 2020 and 2030 [40]. As the aquaculture production was increased over the years, the estimated annual variation of aqueous phase nitrogen (potential waste) was also significantly increased over the years (Fig. 6).

Nitrogen effluent from aquaculture can be utilized for vegetable production in recirculating system. Nitrogen input is distributed in various components of aquaponic system with partial loss to surrounding environment. Nitrogen distribution can be well understood by the study of Wongkiew et al. [59]: lab experiment on floating raft aquaponic system revealed the nitrogen recovery by tomato and chive to be 44% and 1.7% of total nitrogen input, respectively; similarly nitrogen recovery by lettuce and Pak Choi was found to be about 20%. Considering fish tank as an isolated system (i.e., nitrogen effluent from both aquaculture and aquaponic system remains

Fig. 6 Estimated annual variation of aqueous phase nitrogen in Nepalese aquaculture

equal), and nitrogen effluent as the only source of nitrogen for plants tentative, the quantification of nitrogen recovery can be developed based on the total nitrogen input in aquaculture with corresponding nitrogen utilization by plants in aquaponics.

It can be estimated that Nepal has the potential to recover as high nitrogen as 3509t and 7157t through aquaponic aquaculture for the year 2020 and 2030, respectively (Table 2). Aquaponic system can be practiced as a measure of sustainable fish and plant production in future. Current soil-based agriculture practice in Nepal uses excessive chemical fertilizer that increases an alarming rate of 882.43t per year, urea being most widely consumed fertilizer with NPK (Nitrogen–Phosphorus–Potassium) ratio of 46–0–0 [37]. Considered this fact, aquaponic aquaculture practice could be the organic substitute of urea fertilizer. Nitrogen recovery from aquaponics is equivalent to 7628t and 15558t of urea fertilizers for year 2020 and 2030, respectively (Table 2). Hence, aquaponics can emerge as suitable organic vegetable production with independent nutrient supply over soil

demanding farming which requires chemical fertilizer supplement.

On the global scenario, N loss from aquaculture is considerably high. China is a major source of aquaculture production, and resultantly major source of N_2O –N emission from fishery sector. Nitrogen loss of 7.52×10^6 t was estimated across the world for year 2016 (Table 3). In order to meet environment and production sustainability, this number has to be minimized. Developing countries like Nigeria, Bangladesh, India, and Indonesia struggling for nutritional security have not been able to utilize/manage the existing nitrogen loss as a resource. Aquaponics is a potential source of waste stream of nitrogen utilization for the production of organic vegetables and plant species. Besides the existing fish production, additional plants production can be achieved which could be supportive for meeting global food demand and nutritional security.

The estimation of nitrogen loss and its potential recovery are theoretically approached in order to perceive the necessity of nitrogen effluent management. The data are pertinent mathematically, but the exact figures cannot be

Table 2 Estimation of potential nitrogen recovery from aquaponics in Nepal

Year	Aquaculture production (t) ^a	Estimated N input in water bodies (t)	Estimated N recovery via different plant species (t) ^b			
			Tomato	Pak choi	Lettuce	Chieve
2020	65,200	6122.41	3508.55	1594.79	1594.79	135.55
2030	133,000	12,488.98	7157.00	3253.18	3253.18	276.52

^aData source: Paudel et al. [40], 't' is weight unit (tonnes)

^bEstimated nitrogen recovery using N content of plant species in FRT

Table 3 Global nitrogen loss and its potential recovery scenarios via aquaponics from aquaculture practice, 2016

Continent/region	Country	Aquaculture fish production ($\times 10^3$, t)	Estimated N release in water bodies ($\times 10^3$, t)	Potential N_2O –N emission (t)	Estimated N recovery from aquaponics ($\times 10^3$, t)
Asia	China	49,244	4624.11	83,222.36	2649.92
	India	5700	535.24	9633	306.72
	Indonesia	4950	464.81	8365.5	266.36
	Vietnam	3625	340.39	6126.25	195.06
	Bangladesh	2204	206.96	3724.76	118.60
Europe	Norway	1326	124.51	2240.94	71.35
	EU-28	1292	121.32	2183.48	69.52
Africa	Egypt	1371	128.73	2316.99	73.77
	Nigeria	307	28.82	518.83	16.52
America	Chile	1035	97.18	1749.15	55.69
Oceania	–	210	19.71	354.9	11.30
Global	–	80,031	7515.07	135,252.39	4306.63

^aData source: FAO [13]

^bEstimated N_2O –N emission using emission factor 1.69 g/kg fish

^cEstimated N recovery from aquaponics using 44% N content of tomato in FRT

established with ample confidence. Fish biomass is greatly affected by the parameters like pH, DO, water exchange, etc. of the fish tank. Plant species also alter the fish biomass under different environmental conditions. Higher feed consumption and higher fish biomass has been observed in tomato-based aquaponics due to better water quality [21], thereby, indicating to the possibility of less fish biomass if there is non-recirculation and accumulation of NO_3^- . Nitrogen content of fish in aquaponics was found in between 21.0 and 27.9% of the total nitrogen input through fish feeds [59]; hence, the representative value of 23.22% was used to calculate the nitrogen effluent, and consequently to estimate the potential recovery. Nitrogen content of 23.22% had been developed on the basis of study over 80 different kinds of fish species, of which only 60 different species of fish are reared in Nepal [40]. Amount of nitrogen in plant body was found to be 44% (of the nitrogen input in the system through fish feeds) for tomato, 20% for pak-choi and lettuce, 1.97% for chive, which are subject to variations with change in experimental conditions. Aquaponics is a bio-integrated and multiple component system in which change in parameters and conditions of individual component noticeably affect the output of system. Such parameters include pH and water temperature that should be maintained in certain range as mentioned above in Sect. 5. For the successful operation of the aquaponic system, the balance of feed rate ratio is one of the guiding factors, which depends on the species of plants grown as well. Fruiting vegetables require about one third more nutrients than leafy greens to support flowers and fruit development [53]. Nitrogen content in tomato and pak-choi was found as low as 17% and 15%, respectively, under different experimental conditions [21]. Their experimental set-up may not accurately replicate the value for commercial production. However, tentative data reinforce the necessity of alternative approaches to utilize nitrogen effluent of aquaculture and to develop sustainable production practices.

Likewise, fish biomass (wet body) on average contains $17.22 \pm 2.97\%$ proteins, and nitrogen content of many proteins is 16%. Hence, theoretically, 2.84% of nitrogen is present in fish, i.e., for one tonne of the fish to be harvested; about 28.4 kg of nitrogen feed can be recovered. Also, studies have documented that about $23.22 \pm 6.88\%$ of nitrogen consumed by fish is converted to fish biomass. Hence, every metric tonne of fish consumes a total of 122.3 kg of nitrogen. On the assumption that all the feed is consumed by fish (no residual feed), 93.9 kg is produced as nitrogenous waste in production pond [22, 40]. As ammonia rich water in aquaculture undergoes nitrification and denitrification that results in emitting N_2O in the atmospheric. The average N_2O emission factor of aquaculture system is 1.69 g N_2O -N/kg fish [22]. Based on

the emission factor, Paudel et al. [40] estimated potential nitrous oxide emission from aquaculture in Nepal to be $2.25 \times 10^2 \text{ t } \text{N}_2\text{O}$ -N by 2030.

N_2O is a potential global warming gas and also is the most dominant ozone layer depleting gas in the twenty first century [46]. Atmospheric traces of N_2O are pivotal in regulating stratospheric ozone layer, contributing to greenhouse phenomenon and resulting acid rain [3]. We can approach aquaponics as an alternative to existing aquaculture practices: nitrogen uptake by plants can reduce the nitrogen content of aquaculture wastewater thereby resulting in reduction of potential nitrous oxide emission. The aquaponics is not an absolute solution of N_2O emission; however, Paudel [41] observed 17% reduction in N_2O emission from aquaponics with water celery. Under individual review, nitrogen loss (N and N_2O) does occur from aquaponic system as well. Study of Hu et al. [21] found the N_2O emission, 1.5% and 1.9% of total N input from tomato and pak choi-based floating raft method, respectively. However, these values further vary with rate of nitrification and denitrification under changes in environmental and operational parameters like pH, DO, and temperature. Past study reported that there are lower concentrations of NH_4^+ , NO_2^- and NO_3^- at aqueous phase in aquaponics as compared to aquaculture [40]. As the concentration of NO_3^- is high compared to NH_4^+ and NO_2^- in aquaponics [58], which is likely a dominant source of nitrogen for plants, and its utilization depends upon concentration, growing stages, and plant genetic factors [59]. The reduction in NO_3^- concentration through plant uptake likely leads to lower N_2O emission from aquaponics over conventional aquaculture practices, since denitrification of NO_3^- in anoxic conditions is a possible pathway to N_2O emission [22]; however, measurement of reduction factor for N_2O emission is difficult due to uncertain pathways of nitrogen transformation though few study was investigated in this field.

6.3 Current status and prospects of aquaponics

The primal idea of aquaponics dates back to 1000 A.D. when plants were grown on rafts, while the term aquaponics was coined in 1970s. In recent times, various research works have been investigated over the last three decades across the globe. However, in Nepal, aquaponics is at its rudimentary stage of development with only few domestic practices in cities like Syangja, Surkhet, and Kathmandu. "Hope Nepal Bioaponics", an agri-business private company, has been pioneering aquaponic food production in Nepal since 2006 while Scott Wilson (SW) Nepal (private company) is also working on flourishing aquaponics in Nepal. The Rotary Club of Patan, Nepal and the Rotary Club of Brussels has run an aquaponics unit which is funded by

Rotary International and is supported by The Social Enterprise, Aquaponics [31]. Experimental evaluation of Gyawali et al. [19] at Institute of Agriculture and Animal Science, Tribhuvan University, Pakhahawa, Nepal on Outdoor Barrel Aquaponics can be taken as major significant step toward advancement in Aquaponics in Nepal [19].

Nepal has been working on aquaponics in a comparatively slower pace, but a positive growth can be expected in future because of its benefits and adoptive suitability. Food and nutritional security and poor diet diversity has been a critical issue for Nepal in present scenario. Nepal is unlikely to achieve daily standard requirement of 30 g of fish or meat protein any time soon [18]. On average, national dietary energy intake is 2536 kcal per capita per day which is higher than minimum average requirement of 2220 kcal set by Government of Nepal. On the other side, around 38% of people are found with food energy deficient [6]. Inadequate fruit and vegetable consumption are the major reason for nutritional disorders such as lack of iron and vitamin A [12] which is found in fish in the form of retinol and dehydroretinol isomers [18]. Vegetables are also rich in vitamin A, vitamin C, iron, zinc, etc. [25]. In the existing Nepalese nutritional scenario, aquaponics can be a suitable source for both fish meat and vegetables to achieve national food and nutritional security.

Urban agriculture requires specific control measures and technologies different to that of rural agriculture. Rapid urbanization and land transformations are continuously reducing arable land; therefore roof top aquaponics can be a sustainable urban start up in the cities like Kathmandu. Junge and Graber [23] demonstrated that feasible production practice, market acceptance, and performance for possible commercialization of aquaponics in urban city with reduced transport dependency and market hikes enhanced the public health in vicinity. Aquaponics can also contribute in organic production which can avail for additional nutritional supplement since they possess greater nutritional value and lower toxic chemicals [7]. Generally, organic certified rock potassium sulfate containing 50% K₂O and kelp powder may be added as adequate potassium supplement [51]. Organic product finds premium market in urban cities of Nepal. A case study of Aryal et al. [1] revealed that around 58% of people in their study are willing to go 6–20% price premium to get organic food indicating sufficient and feasible market for organic food products.

Furthermore, aquaponics: (1) can be substantial in economic development and utilization of unemployed manpower and land area [28]; (2) can act as synergistic system, thus reducing the shortcomings of individual units; and (3) helps reduce water use due to its inherent recirculating nature utilizing waste nutrients [55]. Aquaponics requires only about 10% of the water needed to grow the same

plant in soil-based agriculture. Thus, it can be advantageous for countries like Nepal where scarcity of water has continually hampered the production of soil-based agriculture [38]. In addition, it is a proven technology for high nitrogenous waste remediation with simultaneous production of high-quality fishes and vegetables. Past studies have demonstrated that aquaponics has higher production performance over traditional soil-based farming. Experiment by Rakocy et al. [42, 44] reported that the yield of basil (1.8–2.0 vs. 0.6) kg/m² and okra (2.67–2.87 vs. 0.15) kg/m² in aquaponics are three times higher compared to field production. McMurtry et al. [32] and Resh [47] in their studies have also found the higher yield of lettuce and cucumber, respectively, in soilless system over soil farming. Thus, soilless growing system exhibits good potential for an effective food production source over existing system of soil-based production.

Aquaponics is further easier than in-ground cultivation as it reduces work-loads since no plowing; tilling, mulching or weeding is required. Also, monoculture can also be continually practiced in aquaponics which is not possible in soil-based agriculture because soil becomes tired, loses its fertility and starts to be diseased. Overall, aquaponics is a lucrative modern technology with high commercialization possibility in Nepal. Further advancement and expansion of aquaponics with a sustainability development approach can be well expected in the near future provided that Government of Nepal (GoN) formulates supportive policy toward aquaponics.

6.4 Challenges of aquaponics

Aquaponics is a complex and demanding food production technology because of its integrative and multi component nature. Aquaculture and hydroponics are familiar disciplines; problems arise when two systems merges; one of them is pH stabilization. Symbiotic system of fish, bacteria and plant possesses very narrow range of pH (6.4–7.4) for optimal performance. This necessitates frequent measurement of pH as it normally declines daily in response to nitrification process [16]. Other operation and environmental parameters like HLR, DO, temperature, hardness, ammonia concentration etc. also requires regular monitoring and control. Moreover, an effluent from fish tank does not contain sufficient nutrients for optimum plant performance. Additional nutrients like potassium (K), calcium (C) or iron (Fe) should be supplemented in regular basis to keep up the growth. Thus, effectiveness of organically derived nutrients over readily soluble mineral fertilizers is still debatable [35]. Besides, the application of antibiotic resistance for disease management is another challenging aspect of aquaponics. Owing to the toxicity risk to fish, nitrifying bacteria, nutrient solubilizing and

biofilm forming organism, the use of standard pesticides has been almost prohibited [15]. Hence, it is challenging to select suitable control measure compatible to the entire living organisms in the system. Other technical issues with associated challenges generally appear in short or long run in the system has already been discussed previously in Sects. 4.1–4.3.

Besides generic technical issues, developing country like Nepal faces possible challenges such as; social, economic, and educational aspects too. Aquaponics is an emerging practice and is not widely familiar in Nepal. In absence of feasibility studies and experiments with locally available fish and plant species, it could be inconvenient to establish commercial aquaponics in large scale. This system also requires skilled manpower for operation: especially to implement aquaponic farming in local scale requires excessive and rigorous training for local farming communities. Subsistence farming practice in Nepal may discourage implementing the innovative techniques in aquaculture. Also marketing strategy of Nepal is very poor, hence farmers find themselves in questionable production conditions in absence of secured market and marketing system [24]. Aquaponics itself is a sophisticated system of farming that requires relatively huge amount of capital investment which could also be a hurdle for a developing country like Nepal.

7 Recommendation

Government of Nepal has prioritized fisheries and vegetable sectors in its periodic plan. However, their potential integration through aquaponics has not been given the top priority. Sustainable Development Goals (2016–2030) by the Government of Nepal aims to end hunger, achieve food security, improve nutrition and promote sustainable agriculture [36]. Also, the government has endorsed Agriculture Development Strategy (ADS) in 2015 which will accelerate agriculture sector growth [34]. We suggest aquaponics as an essential supplement for achieving the established targets by Government of Nepal. Enough resources and funds should be allocated to develop aquaponics toward its commercial success. However, feasibility of aquaponics in Nepalese context; both physically and economically on local species of fish and vegetables should be investigated for sustainable production practice. Pre-production requirements like sustainable supply of fingerlings, fish feeds, fertilizer and supplement etc. should be evaluated and necessary resources should be planned. Post-production strategies should also be developed so that farmers can sell their products in sustainable market system, especially highlighting the development of cold storage facilities, marketing infrastructure, processing

facilities etc. Training facilities and educational services (formal and informal education) should be provided to local farmers in order to promote aquaponics in rural level. Community-based farming system should be encouraged to overcome the possible obstacle of capital investment. Government should provide subsidies and support in local level for this innovative production. The local and federal government along with metropolitan city, sub-metropolitan city and municipality should come up with the congenial plan and promote aquaponics to make the cities self-reliant on the production of vegetables and fishes. Nitrogen isotopic analysis remains critical to find the exact pathways of nitrogen transformation in the system.

8 Conclusion

Global and national potential of nitrogen loss and recovery via aquaponics was estimated. Aquaponics demonstrates high potential for nitrogen recovery from aquaculture wastewater via nitrate reduction and nitrogen assimilation into organic vegetables and plants. There are several factors that affect the performance of the system. Thus, maintaining optimal environmental and operational condition, symbiotic species can develop successful production system. The review discussed different types of aquaponic systems with their suitability, including different plants and fish species. Possible nitrogen transformation pathway in aquaponic system is also explained, however, the exact identification of nitrogen pathways requires isotopic analysis—investigation of stable isotopic signature. On theoretical perusal of global aquaculture scenario, high amount of nitrogen loss was observed. Sudden thriving of aquaponics and surpassing aquaculture practice is almost impossible. For now, the urgency is to minimize the existing environmental impacts, but in long run, the priority is nitrogen utilization for environmental and production sustainability. The paper, however, has discussed the status and prospects of aquaponics in Nepal with associated possible challenges; also has highlighted the observations that can be extrapolated to gain insights into the existing conditions of other minor developing countries like India, Bangladesh and Nigeria etc. These countries are also struggling with nutritional and food production security. Nitrogen recovery from aquaponics can be positively considered as a sustainable technology across the globe. The formulation of global policies and strategies with long-term vision for sustainability enhancement of aquaponics are essential.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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