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RESEARCH PAPER

Integrated aquaculture in arid environments

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الاستزراع السمكي المائي المتكامل في البيئات القاحلة

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Abstract. Around one third of the globe is classified as desert or arid (<200 mm rain annually) and most such regions lack food security. Traditional freshwater aquaculture is often a marginal activity and competes with agriculture for limited water resources. Developing technologies offer new opportunities to increase farm productivity through integration with vegetable production in aquaponic systems and to reduce water requirements through the application of biofloc technology. Aquaponic systems combine aquaculture and hydroponic plant production and are integrated within a re-cycled water system. Fish waste metabolites provide the nutrients for plants grown in soil-less, hydroponic systems. Biofloc fish production systems operate with minimum or zero water exchange. Suspended biofloc particles develop in fish tanks under conditions of full aeration and controlled carbon to nitrogen ratios. They comprise algae, bacteria, protozoa and particulate organic matter held in a loose matrix. They provide *in-situ* treatment of harmful fish metabolites, are protein rich, contain essential fatty acids, vitamins and minerals and supplement the diets of filter-feeding farmed species. The integration of fish culture with vegetable production provides new opportunities for small and medium enterprises. Integrated farms occupy a small footprint, optimise the use of resources and can be built close to population centres. This paper reviews current developments in aquaponics, including recent research into the incorporation of biofloc technology in aquaponics, against the background of food security needs in arid regions.

Keywords: water conservation; food security; aquaponics; bioflocs

المستخلص: يصنف حوالي ثلث الكرة الأرضية على أنها صحراء قاحلة او شحيحة الماء (<٢٠٠ مم من الامطار سنويا) وتفتقر معظم هذه المناطق إلى الأمن الغذائي. غالباً ما يكون الاستزراع السمكي التقليدي للمياه العذبة نشاطاً ويتنافس مع الزراعة محدودية لموارد المياه. حيث ان التكنولوجيا المتقدمة توفر فرصًا جديدة لزيادة الإنتاجية الزراعية من خلال نظام المتكامل مع إنتاج الخضروات في أنظمة الاستزراع السمكي المائي وتقليل متطلبات الماء من خلال تطبيق التقنية الحيوية التي تجمع بين تربية الأسماك وإنتاج النباتات المائية في نظام إعادة تدوير المياه. حيث انها توفر من مخلفات الأسماك العناصر المغذية للنباتات التي تزرع في النظام المائية من دون تربة. كما ان مخلفات الأسماك الموجودة في خزان الأسماك تحت ظروف التهوية الكاملة والكربون المتحكم فيها يتحول إلى عنصر النيتروجين. وكما ان الطحالب والبكتيريا والكائنات الأوليات والجسيمات للمواد العضوية الموجودة في خزان الأسماك تنتج مخلفات سامه وغنية بالبروتين حيث انها تتحول هذه المخلفات إلى سماد مغذي للنباتات وهذا مما يوفر ثمن التسميد كما ان النباتات تنقي المياه من مخلفات الأسماك التي قد تضر بها، حيث انها تحتوي على الأحماض الدهنية الأساسية والفيتامينات والمعادن المتكاملة في النظام الغذائي لتغذية النباتات. كما ان هذا النظام يعد متكامل الذي يدمج بين تربية الأسماك وإنتاج الخضروات ويوفر فرصًا جديدة للمؤسسات الصغيرة والمتوسطة. ويشجع هذا النظام على استغلال المساحات الصغيرة والتي يمكن بناؤها بالقرب من المجمعات السكانية. تستعرض هذه الورقة التطورات الحالية والمستجدات في النظام الاستزراع السمكي مع النباتات، بما في ذلك البحوث الأخيرة التي تدمج التكنولوجيا في الاستزراع السمكي مع الزراعة المائية بدون تربة، والذي يتماشى من احتياجات الأمن الغذائي في المناطق القاحلة.

الكلمات المفتاحية: المحافظة على الماء، الامن الغذائي، الزراعة التكاملية بين الأسماك والنبات

Introduction

Global population growth, coupled with increasing water demands, present a major challenge in the provision of future food security. It has been predicted that by 2050 50% more food will be needed to feed a world population exceeding 9 billion (Godfray et al., 2010). This will necessitate intensification of food production, sustainable practices and more efficient use and protection of natural resources. Aquaculture plays a key role in eliminating hunger, promoting health and creating economic benefits and expanded at an average annual rate of 5.8% in the period 2005-2014, to a total of 73.8 million tonnes (FAO, 2016). Inland aquaculture is a major sector although its development in desert and arid regions faces considerable obstacles, particularly with regard to feed and water supplies. The combined production of fish and vegetable crops in integrated systems, with multiple use of water and other resources, holds the potential to increase food productivity in such regions (Crespi and Lovatelli, 2011).

Aquaponics

Whilst aquaponics may have ancient antecedents it was likely first developed in its modern form in the mid-1970’s by scientists researching methods for treating re-cycled water in fish culture systems (Love et al., 2015). In these studies edible plants, including tomatoes and

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Figure 1. Al-Arfan Farms, Oman. A commercial aquaponics farm operating in a hot arid environment. The farm is protected by a shade house and the fish unit produces 4-5 tonnes of Nile tilapia each year. A wide variety of vegetables, fruits and culinary herbs are grown throughout the year in a combination of deep water culture and media filled beds. Picture credit: Arvind Venkataraman

lettuce, were used to remove waste products from carp and tilapia production tanks (Naegel, 1977). Early pioneering work on aquaponics was pursued by various university research groups, most noteably the group led by James Rakocy at the University of the Virgin Islands in the USA. Aquaponics combines the benefits of fish production (aquaculture) with the soil-less production of plants (hydroponics) using the same water. It operates within a closed-loop system where fish feed provides most of the nutrients required for healthy plant growth. These nutrients, excreted directly by the fish, or generated by the microbial breakdown of organic wastes, are absorbed by growing plants. Research is generally aimed at refining methods for improved output (Rakocy, 2006).

The use of soil-less culture techniques and water re-cycling provide considerable benefits for long-term sustainability (Bernstein, 2013). Water consumption is less than 10% of normal levels for horticultural production and can be provided from potable supplies or pathogen-free groundwater (Somerville, 2015). There are no direct mineral or fertilizer costs since the primary mineral source is the fish feed provided to support fish growth. Some small additions of alkaline salts, to maintain a stable, neutral pH and ferrous salts, to maintain the necessary iron content, are the only mineral additives used in aquaponics. The intensive nature of aquaponic production greatly reduces the amount of land necessary for commercial production units and there is no requirement for arable land. Water recirculation technology has seen significant progress in recent years with some standard methods emerging and equipment supplies becoming more available and cost efficient (Martins et al., 2010; Bregnballe, 2015). The combination of aquaponics with water recirculation technology has opened the way for aquaponic developments on large commercial scale.

Further possibilities exist to conserve water through the application of biofloc technologies. These are zero or minimum water exchange systems production systems in which the carbon nitrogen ratios are adjusted to provide optimal conditions for the growth of bioflocs: small aggregates (<1 mm) of waste food, fecal material, phytoplankton, zooplankton and bacterial communities (Hargreaves, 2013). In well balanced systems the bacterial communities take up the nitrogenous compounds, which are otherwise harmful to fish, and produce microbial protein, lipids, vitamins and minerals. Fish production, using biofloc systems, linked to hydroponic plant production in aquaponic systems holds the potential to minimise water use and to reduce feeding costs through improved food conversion ratios. Initial trials have demonstrated the availability of minerals from bioflocs in integrated fish and vegetable production (Chappell and Brown, 2010) and the potential to develop aquaponics, based on fish production in biofloc systems, is being researched, with positive results (Pinho et al., 2017).

Table 1. Solids waste in fish tank effluent

Solids type	Size (μm)	Treatment
Dissolved	< 0.001	Ozone
Colloidal	0.001 – 1	Foam fractionation
Supra-colloidal	1 – 100.	Screen filter or sand/bead filters
Settleable	> 100	Swirl filters or radial flow settlers

Vegetable production

A wide range of vegetables and fruits are grown in aquaponic systems, including include lettuce, chard, pak choi, spinach, kale, basil, tomatoes, peppers and micro-greens. Three systems are available for hydroponic plant production. These are described in detail by Somerville et al., (2014) and are summarised below.

Nutrient film systems (NFT)

These are based on conventional hydroponic systems in which plants grow in long narrow channels. Water flows down each channel, providing plant roots with water nutrients and oxygen. NFT Systems must also include tanks for settlement of solids and a bio-filter for the breakdown of ammonia. The systems are prone to blockage with circulating organic materials and are less commonly used in aquaponics than deep water culture and media-filled systems.

Media-filled systems

In these systems crops are produced in shallow grow-beds (50 cm), using media to provide support for root systems. Expanded clay balls or graded gravel are commonly used. The system is typically operated with a flood and ebb system controlled by a bell siphon, where each bed is filled with nutrient-rich water and drained 2-3 times each hour. The media provides large surface area which promotes biological filtration, reducing ammonia to nitrite and nitrate. The media also provides support to plant root systems and enables relatively tall plants to be grown. All of the organic waste is broken down in the grow beds and worms are often added to enhance the breakdown. The overall productivity of plants is generally less than in NFT and floating raft systems, although a greater variety of plants can be grown.

Deep water culture systems

This method is used for smaller plants such as herbs and salads, which grow floating in a styrofoam raft. The plants are initially contained in small coir pots and receive their necessary minerals from the fish tank via the water which circulates around their exposed roots beneath the floating rafts. The fish are held in a separate tanks and water from the fish tank circulates continuously through the system. Beneficial bacteria live throughout the system and the extra volume of water in the grow beds provides a buffer for fish, reducing stress and potential water quality problems.

Deep water culture and media-bed systems are most commonly used in aquaponics. They may be used singly or in combination. Deep water culture methods are commonly used in large commercial units for the production of large quantities of mono-crops, such as lettuce, salad greens and culinary herbs.

Fish production

A limited range of freshwater fish species is grown in aquaponics. Tilapia (*Oreochromis* spp) is most commonly grown since it is hardy, readily available, grows rapidly under optimal conditions and is familiar to consumers (Bernstein, 2013). Other warm-water species include Asian seabass, catfish and carp, including ornamental varieties of koi carp. The volume and value of food fish grown in aquaponics is small in comparison with plant production. Plants reach harvest faster, which permits multiple plantings and have higher value per unit weight than fish. Typically, profits are gained on plant yield rather than fish production and fish are primarily used as a source of bio-available plant nutrients.

Water re-use and treatment

The essential requirements for treatment of recycled water depend primarily on the plant growing system selected. Small scale, media-filled grow beds will remove solids and function as biofilters. In contrast deep water culture systems require additional solids separation and biofiltration. Water flows from the fish tanks in a cycle through solids separation equipment, followed by biofilters and then through the plant grow beds. It is then collected in a sump and pumped back to the fish tanks. Air, generated by blowers and delivered through fine bubble diffusers, is applied directly in the fish tanks and in deep water culture beds. More efficient oxygenation using oxygen generators or stored liquid oxygen is necessary for fish cultured at high stocking densities.

Solids removal

Separating solids from fish tank effluent is a key part of water management in commercial deep water culture aquaponics. Accumulation of solids in the water can cause irritation and gill damage in most fish species and within the hydroponic system can accumulate around the root systems of growing plants impairing the uptake of water and dissolved nutrients. A range of sizes of solid particles are excreted by feeding fish and various systems are available to separate the various solid fractions (Table 1).

Settleable and supra-colloidal solids form the bulk of solids excreted by fish and can be removed by gravitational devices and micro-screens. Circular fish tanks with flat bottoms are generally used in large installations. Water circulates uniformly and centripetal forces transport solid wastes to the centre from where they can be

Table 2. Characteristics of 4 biofilter types used in aquaponic systems

Type	SSA (m^2/m^3)	Characteristics
Trickle filter	200	Water enters from an overhead spray pipe and cascades through a media column (e.g. corrugated plastic sheets) where nitrification occurs. Relatively inexpensive and simple to construct and operate. They self-aerate and de-gas excess CO_2
Rotating bio-contactor	200	Filter media comprises circular plates or discs attached to a horizontal shaft. The media is half submerged in the fish tank or a separate container. As the filter rotates the media is alternately submerged and exposed to the air. Passive aeration and CO_2 degassing occurs and head loss is low. Simple to operate and can powered by a small motor or air-lift. Higher initial purchase and maintenance cost than trickle filters but more compact.
Moving bed biofilm reactor	500	Filter media (small plastic spheres with surface sculpting) is held in an open tank (50% water and 50% media). The bottom of the tank is fitted with an air distribution system designed to give continuous turnover and aeration of the submerged media. Head loss is low. Various adaptations of this filter are commonly used in aquaponics on both small and large-scale.
Bead filter	3000	Filter media (tiny glass beads) is held in a pressurised vessel through which the water is pumped. Combines solids removal and nitrification. Automatic backwash. Compact but high initial cost.

separated in a small separate drain pipe from the main flow of cleaner water. Additional suspended solids can then be removed by a combination of swirl separators, radial flow filters or rotating drum filters fitted with micro-screens (40-100 µm), depending on the nature and volume of solids to be removed.

Biofiltration

The finest particles will pass through separators and micro-screens along with dissolved compounds, such as phosphorus and nitrogen. Nitrogen in the form of nitrite and free ammonia (NH_3) is toxic to fish and is oxidised by nitrifying bacteria growing in films on the biofilter surface to harmless nitrate, which is then available for plant growth. Biofilters units are designed to contain as large a surface area as possible to support the growth of bacterial films. Light, plastic media giving a high specific surface area (SSA, m^2/m^3) is commonly used (Harwati and Jo, 2011). Biofilters can be configured in varioius ways and many designs are currently used in aquaponics (Table 2). The size of biofilters is calculated based on various parameters. These include the total ammonia-nitrogen (TAN) released by the fish, hydraulic loading, water flow rates and the relative surface area of the selected filter media. TAN calculations are based on the nitrogen content of the fish feed, daily food consumption, digestibility and nitrogen content of protein. Calculating biofilter size should also take into account the available surface areas of the grow beds and styrofoam floats which will be in contact with water and will also support the growth of bacterial films.

Metrics based on feed use are fundamental to aquaponics. Determination of the quantity and quality of food used daily are used to calculate both scope of water treatment necessary and the scale of hydroponic plant growth which can be supported by the treated effluent from fish tanks. Routine monitoring of water chemistry is vital to maintain a balanced water re-use system (Colt, 2006). Recycled systems accumulate acidity which must be adjusted by base additions to maintain optimal pH for fish, bacteria and plant growth growing in the same system.

Safety

Food safety is a critical component of food production and aquaponic farmers should follow codes of good practice and apply biosecurity protocols for both aquaculture and horticulture components. Food safety and levels of food safety indicator organisms from both produce and water in aquaponic systems have been examined (Chalmers, 2004; Fox et al., 2012; Goddard et al., 2015). The bacterium *Escherichia coli* is the most widely studied potential contaminant in aquaponics. This bacterium is found in the intestines of warm-blooded animals, including birds and cattle, and has been used in developing human health-based regulatory standards as a common indicator of fecal contamination and microbial water quality in agricultural water systems. Indicator microbes and pathogenic bacteria, such as *E. coli* and *Salmonella* spp., if present in aquaponic systems, most probably originate from warm-blooded animals, such as birds, since these enteric bacteria are transient in fish gut microflora (Sugita et al., 1996). As in all crop production systems cross-contamination is possible, but the risk in aquaponics is greatly reduced when compared with field crops (Sirsat and Neal, 2013). Studies from Oman (Goddard et al., 2015), USA (Fox et al., 2012) and Canada (Chalmers, 2004) have reported negative tests across numerous aquaponic farms for *E. coli* and *Salmonella* spp.

Biofloc farming systems

The application of biofloc technology in intensive aquaculture is in its early stages (Avinmelech, 2007). The technology is based on waste nutrient recycling, particularly nitrogen into microbial biomass. This biomass can be used directly by filter feeding species such as tilapia, carp, catfish, marine shrimp and freshwater prawns (Bossier and Ekasar, 2017). On a dry matter basis, microbial biomass has been shown to contain 20-45% crude protein, 1-5% lipids and various bioactive compounds including essential fatty acids, carotenoids, vitamins and minerals (Kuhn et al., 2009). The availability of *in situ* nutrients has opened the way for reformulation of special aquafeeds for use in biofloc systems. Protein content can be reduced and fish meals can be replaced with plant meals. This both improves sustainability and reduces cost (Martinez-Cordova et al., 2015). In practice biofloc tanks or ponds must be continuously mixed and aerated and the carbon nitrogen ratio (C:N) carefully maintained (12-20:1) to support the formation and stabilisation of a heterotrophic microbial community (Perez-Fuentes et al., 2016). Carbon content is balanced using available carbohydrate sources such as molasses or grain pellets. Total suspended solids content is monitored throughout the fish production cycle and maintained at optimal levels of 100-300 ppm. Excess biomass can be harvested and processed into feed ingredients (Kuhn et al., 2009).

Biofloc farming systems operating with zero or minimum water exchange offer greatly enhanced biosecurity, which is particularly valuable for shrimp farmers in the control of transmissable viral diseases. The role of natural probiotics and immunostimulants on survival and growth have also been reported from studies on the microbial ecology of bioflocs (Rani et al., 2017)

Planning and economics

A detailed review of planning, construction, operation and economics of small-scale aquaponic farms has been provided by FAO (Somerville et al., 2014). Capital costs can be high in relation to income and a recent survey suggest that the majority of aquaponic farms operate on small commercial scale (Love et al., 2015). Farm design should be optimised for the targeted production levels and fish species (limited choice) and plant varieties (wide choice) should be selected based on local and regional consumer demand and value. Some failures of large projects have been reported where profits could not match the demands of initial investment plans (Somerville et al., 2015).

Aquaponics in urban environments is taking the lead in large-scale developments. Disused industrial space, including rooftops, is attracting developments in many European and North American cities. They are typically based on the use of a temperature and light-controlled greenhouse structures designed to support year-round production and incorporate space-saving stacked and vertical horticulture systems (Kyaw and Ng, 2017). Capital and operating costs are high but operators benefit from a large consumer base and demand for organically produced fresh products from local suppliers. Urban projects also play an important role in education and public awareness.

Future prospects

Aquaponic developments hold great potential to contribute to food security and support sustainable development goals in hot arid and regions. They benefit from efficient water use, high productivity and low environmental impact. In these regions costly heating systems and greenhouse structures are not necessary and solar energy can be used to generate electricity supplies for water pumps, aerators and other equipment. This reduces capital and operating costs and supports the development of aquaponic enterprises as small or medium enterprises or ever large commercial ventures.

Integration of aquaponics with biofloc technologies has the potential to reduce the costs of water treatment, improve feeding efficiency and scale-up fish production. Early research indicates the bio-availability of plant nutrients in biofloc tanks and ponds. Systems will however require modification for efficient handling of solids waste and excess biofloc.

Further potential exists to apply aquaponic techniques in arid regions, where salinization of ground water restricts traditional agriculture. Many commonly-farmed fish species are tolerant of low to medium water salinities and their production can be combined with growing salt tolerant varieties of traditional crops at low salinities (Goddard et al., 2010) or edible halophytes at higher salinities (Pantanella and Bhujel, 2015).

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