Aquaponics: Current state and prospectives

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- Aquaponics combines the strategies of aquaculture and hydroponics
- In principal aquaponics should offer a more sustainable method of food production
- Aquaponics commercial data is limited and attempting to obtain optimal yields from a complex biological system where each aspect has different demands is challenging
- Growing demand for prawns in the UK marketplace could facilitate increased research into sustainable aquaponic production with freshwater species offering the least complicated options given our current understandings in aquaponics.

What is aquaponics?

When considering the "food of the future" many people believe that minimising transport distances and providing local food in urban areas will be key to maintaining supply and demand and doing so more sustainably. For this reason, the increased presence and research into the low resource, space-saving, urban compatible alternative farming has been seen.

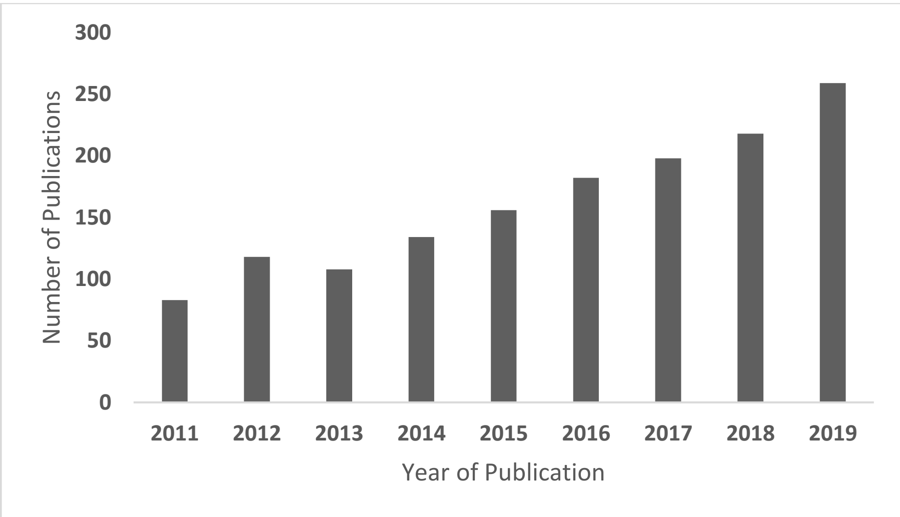

Figure 1 *Publication numbers for the last 10 years using the search term "vertical farming" on Web of science*

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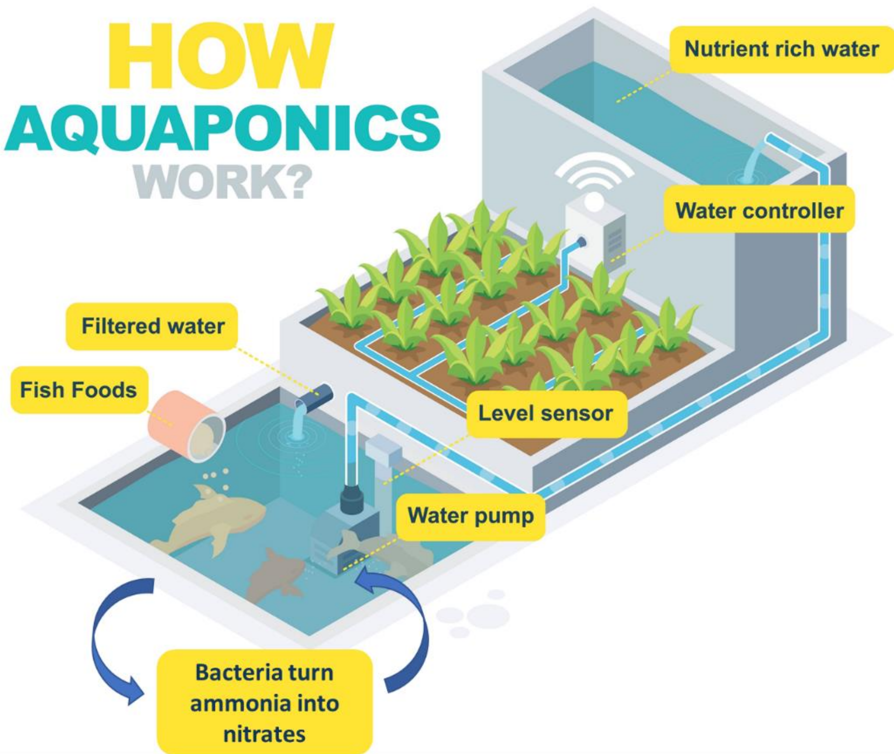
Technologies/strategies associated with this include indoor vertical farming (which can involve different growth media, most commonly, substrate, water/hydroponics or air) and aquaponics (the combination of aquatic organisms, bacteria and plants to have a self-cycling, low input system). Such systems tend to work on the principles of mutualism and symbiosis by linking an ecological food web to provide cycling benefits to all involved in the web. A key to these systems is they are "controlled-environment agriculture" (CEA) where the indoor nature allows constant production cycles which are not influenced by local environmental conditions and seasonality, though at the costs of generally higher energy inputs. Aquaponics is essentially the combination of aquaculture and hydroponics whereby the excretions from fish are available as fertiliser nutrients for the plants to utilise. Beneficial bacteria then help to convert potentially detrimental and toxic ammonia in fish excretions into nitrates via nitrification for utilisation by plants and ammonia-free water is recycled back to the fish. Furthermore, in some substrate-based systems worms can be incorporated in a "vermiponics" strategy where these further degrade waste plant material and provide nutrients to the plants and in some systems could be used to supplement feed for fish.



The 4 main components of an aquaponics system are:

1) **A biomass converter** – tank where fish/aquatic species are grown.
2) **A waste processor** – Takes water and filters out solid waste (fish excretions and any uneaten food) ~40% of the carbon supplied in feed gets separated as "sludge".
3) **An aerobic converter** – A bio-filter incorporating bacteria to oxidise ammonia (which is toxic) to nitrates that the plant systems can use.
4) **A phototrophic (plant biomass) converter** – beds in which to grow plants these take nutrients from the fish waste and stabilise and purify the water which is recycled.

Despite the first developments in aquaponics being seen as long ago as the 1970s, large scale industrialised output is still low with recent figures suggesting only 2% of all aquaculture farms in the US were aquaponics and these enterprises were small (75% having sales less than $25,000). As a small and developing sector it is difficult to find data on efficiencies and outputs other than in predicted model forms. Aquaponics can take place across different scales, from mini-hobby levels to small scale semi-commercial systems and up to large commercial systems. Various aquaponics systems exist which utilise different combinations of aquaculture principles and plant culture principles (see table 1). Within these different systems, a key aspect is whether systems are coupled or uncoupled, where coupled means a closed system where the only nutrient source in the system is via fish feed or decoupled systems where you essentially have separately managed aquaculture and hydroponics units where nutrients and water control are supplemented.

Table 1. Aquaponic systems, markets used, fish rearing principles and main plant culture principles where DWC = deep water culture and NFT = nutrient film technique taken from Palm *et al.*, (2018)

Aquaponics system	Markets	Fish rearing principle	Main plant culture principle
Open aquaponics	Home use/direct sales	Batch	Hydroponics and substrate based
Domestic systems (mini/hobby/backyard-coupled)	Home use/direct sales	Batch	DWC, NFT, ebb-flow, media bed
Demonstration aquaponics (e.g. living walls-coupled)	Education, exhibition	Batch	DWC, NFT, ebb-flow, media bed, aeroponic, vertical
Commercial aquaponics and aquaponics farming			
Small/semi-commercial systems (coupled or decoupled)	Retail/wholesale	Batch/staggered	DWC, NFT, ebb-flow, drip, aeroponic, vertical, substrate/soil
Large-scale systems (coupled or decoupled)	Wholesale	Staggered	NFT with full nutrient management, substrate/soil

Batch = rearing of one fish population or one fish age group

Staggered = rearing of more than one fish age group with intensification of fish production over the whole year

The limitiation in the current development of commercial aquaponics systems are said to be largely related to current technologies and strategies lacking cost efficiency (currently raising fish indoors can be 2-3 times more expensive than in outdoor ponds) and technical capabilities. This links through to difficulties in obtaining buisness funding through banks and also struggles to have national legislations adjusted to facilitate the ease of aquaponics development. Furthermore, for best commercial gain specific markets need to be established where increased value is placed on aquaponics, this could be through renewable concepts of their production or the ease in which a fresh (non-frozen) product can be supplied. Also as noted in limitations below pathogens can severely hamper commercial systems and until solid strategies of management are developed this will likely act as a concern for those considering adoption.

Why it could be great?

The main message portrayed with aquaponics is that, compared to aquaculture, aquaponics has reduced/zero waste concerns (although sludge waste is always produced and its specific management should be considered, see below) and, compared to hydroponics, it has reduced nutrient input concerns. As such this should make aquaponic systems far more attractive during our current shift towards sustainability in food production.

Aquaponics has the potential to use otherwise underutilised urban spaces in the form of urban rooftop aquaponics. In such systems, the supply of light is natural rather than supplemented (as in many indoor vertical farming systems) minimising energy requirements. The comparative economic, social and environmental benefits of such systems over direct rooftop hydroponics or renewable energy development via solar panels are, however, unclear in the scope of this study. In a direct comparative LCA study, however, it is suggested that aquaponics outperforms hydroponics with regards to climate-related impacts with almost half the impacts in some studies (partly due to the higher product values at the end of the chain in aquaponics).

Smart aquaponics integrates precision technologies to optimise conditions and provide fine control within a complex system. Such systems can have an array of sensors to minimise the need for labour, including; water density sensors, humidity/temperature sensors, pH sensors and light sensors to provide automation of the best conditions for both plant and fish growth. Furthermore, behaviour analysis via image or movement technologies linked to machine learning have already been assessed for both prawn and fish aquaculture systems. Such monitoring could help to improve efficiency with regards to inputs and energy wastage which are often high and costly in indoor farming systems.

Coupling energy requirements from aquaponics-based systems to more renewable sources could provide advantages towards sustainable farming, several papers note the inclusion of solar and wind energy generation, whilst others indicate incorporation with on-farm anaerobic digestion units or combined heat and power generators utilising farm waste or even aquaponic non-edible plant and sludge waste itself as feedstocks which could be a functional solution for smaller-scale aquaponics. Largely this sludge waste is either directly removed in the water supply and can act as a contaminant or is applied as a manure source on soils.

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Current limitations

Nutrient supply for fish is the main driver of an aquaponics system and often a limiting factor in the recirculation process in regards to the nutrient quality of the excretion of fish based on the feed input. This can be seen as commercially successful modern aquaponics need to control nutrient levels of plants specifically and must often supplement these with additional fertilisers/nutrients which are lacking in the fishes waste. A clear example of this is how the definition of aquaponics has changed in literature over time from;

"wherein the majority of nutrients required for plant growth arise from wastes derived from feeding fish"

to,

"where the majority (> 50%) of nutrients sustaining the optimal plant growth derives from waste originating from feeding the aquatic organisms"

Nutrient control can also be hampered by the ability to accurately assess nutrient content in a live fashion, to assess which nutrient is lacking in fish excretions and which require supplementing for most efficient and productive plant growth. Many current techniques for assessing such nutrient levels require the extraction of samples and addition of reagents, for true accuracy though, conductive electrochemical detection can be a live analysis possibility which can be improved by modern nanomaterial modifications. Alongside this, the recent advances in optical fibre sensors may have a potential role in improving future nutrient management accuracy. Nutrient levels being limiting (particularly phosphorus in plants) has been noted in recent studies which state the decoupling of aquaculture and hydroponics separately from an integrated aquaponics cycle would be more efficient in achieving highest production levels in each separate sector.

To provide correct conditions for crops and fish the environment needs controlling. In temperate areas, this involves cultivation within greenhouse structures to minimise energy requirements in maintaining higher temperatures for increased plant and fish growth year-round. Papers have noted that stable climate regions such as in the Caribbean Virgin Islands or the Canary Islands allow for further reduced energy inputs due to plants being able to be grown outdoors in direct sunlight whilst fish are shaded to maintain optimal temperatures. In regions which switch between hot and cold climates increased energy will likely be required in the summer months for cooling of greenhouses and then again in colder months for heating, so this is an important consideration (see table 2). However, technologies do exist which could help facilitate this in a more environmental manner (including solar heating and heat exchangers). An overview of multiple LCA's suggests that around 81% of the energy used in aquaponics systems are used on water pumping and lighting whilst 19% are used for heating water and air.

Pests of both fish and plants are always an issue, along with anything that could upset the balance of incorporated beneficial microbes. In smaller systems these can be less of a risk as the losses incured and actions of resetting small stocks to hygienically remove the contaminant/pest is less time consuming and costly. In larger systems, however, this might require carefully controlled traffic and personal protective equipment for all staff involved to prevent catastrophic pest/disease losses occurring. Furthermore, some chemical treatments which might remove pests for plants could be toxic to fish and as such largely integrated pest management controls are preferred. Despite this, however, current legislation (apart from in the US) prevents plants which are grown through hydroponics (as is the case for most aquaponics systems) from being eligible for organic certification (removing a potential increased source of improved revenue) despite the fact systems can often utilise even fewer chemicals than organic systems and if run correctly have low environmental impact.

Table 2. Global warming potential (GWP) of 1kg of produce cultured by CEA across regions Chen *et al.,* (2020)

Production system	Produce	Region and yearly temperature (min/max ºC; adapted from Weather Spark)	GWP (kg CO_2 eq)	Reference
Aquaponics	Tilapia and six species of vegetables	Indiana, US; −2/14 (March)	104	Current study
Hydroponics	Seven species of vegetables	Indiana, US; −2/14 (March)	152	Current study
Commercial aquaponics	Tilapia, basil	US Virgin Islands; 22/31	8.64	(Boxman et al., 2017)
Recirculating aquaculture systems	Trout	Toulouse, France; 2/28	2.0	(d'Orbcastel et al., 2009)
Hydroponics	Tomato	Mediterranean areas (spring to summer)*	0.0814	(Antón et al., 2005)
Hydroponics	Tomato	Columbia; 9/22	0.074	(Bojacá et al., 2014)
Hydroponics	Tomato	Sweden or nearby countries; −3/21	3.3	(Carlsson-Kanyama, 1998)
Hydroponics	Tomato	Italy; 7/29	0.74	(Cellura et al., 2012)
Hydroponics	Rose	Netherlands; 1/22	80	(Torrellas et al., 2012)
Hydroponics	Tomato	Northern Europe*	9.4	(Williams et al., 2006)

*Region covering multiple countries, so no specific temperature range provided

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Relatively few studies have looked at aquaponics with regards to return of investment (ROI), where it has been attempted to be assessed, the figures fall between 6 – 8 years before a return is seen and in many instances, the best economic outcomes are only achieved if users also spin-off to provide sales of the system components used (aquaponics pumps, tanks etc) and sell their knowledge as aquaponics consultants/advisors. Difficulties also arise in the freedom of information in assessing the economics of aquaponics. Commercial companies who have success are often guarding their data to maintain dominance or portraying it in the best light to facilitate selling their products or services. Those which fail are an example of likely negative data and tend to not wish to share their failures.

Prawns and aquaponics

The giant river prawn (though more related to lobsters) *Macrobrachium rosenbergii* is a species of high interest and research due to its high nutritional values, taste and demand on the market being produced in over 35 countries throughout the world. Normally river prawns are imported frozen due to limited growth in the UK, with fresh imports having higher values. Combine this with figures that demonstrate an increasing demand for shrimp and prawns by the UK population with a retail worth of £528.5 million it is clear to see why this could be an area of interest. As stated above with sustainability being key on the agenda of food growers, consideration surrounding aquaponics and river prawn production has already been seen. As with all systems, assessments must be made regarding optimal conditions of growth with recent studies having looked at levels of nutrients, stocking density and filtration levels. There is also a wealth of previous aquaculture specific data available which could be directly utilised. One group of figures suggests total yields of 5250–7500 kg/ha for river prawns in heated greenhouse aquaculture systems with a sales price of ≥ $15 per kg. In comparison, Nile Tilapia one of the most common fish in aquaculture and aquaponics, have been observed with yields of ~10,000 kg/ha in intensive aquaculture and sale prices of $2-4 per kg, suggesting the potential of up to 3 times the profit for river prawn systems. Previous studies have also assessed co-production of fish and prawns suggesting this can optimise production of both species and could be a consideration for future aquaponics. Freshwater prawns, however, come with more complex management behaviour and maintenance as they undergo moulting during which periods they reduce or stop eating (thus feeding should be halted to prevent waste during such periods), they have a low tolerance for low temperatures, they can also be highly aggressive and cannibalise each other so stocking density should be considered to reduce this and they also have more complicated storage/harvest considerations than other prawns to avoid lowering meat quality.

While other marine prawn species are considered, these can only be cultured in aquaculture by providing a saline environment, which adds an extra level of complexity to aquaponics coupled systems due to the need for saline/salt-loving/tolerant crops of high economic value. There is evidence of such systems with halophyte (salt-tolerant) plants which are becoming desirable in human cuisine and animal fodders (seaweeds, though not a halophyte as these are macroalgae, could be grown as a methane reducing supplement for livestock) however, these are in the early stages of development. Alongside this, attempting an uncoupled system with marine products would lead to added energy requirements in separating nutrients from the saline water environment before its utilisation on plants (and subsequently causes higher water inputs and waste compared to freshwater aquaponics systems).

Summary

Aquaponics in principle appears to be a highly sustainable self-sufficient way of producing food with lower environmental impacts than current methods. However, as a concept, it has been circulating for almost 50 years and is still lacking in the levels of refinement required to make it as appealing as current food production techniques. Whilst optimal systems may well have the potential to produce significant levels of food in a beneficial way the evidence of large-scale manufacturing success is limited, with most system data being related to smaller ventures. Several papers state the high levels of specific knowledge required to run aquaponic systems well (as you essentially require knowledge in aquaculture, hydroponics and microbiology and all the nuances of interactions between these systems), and as such this

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limits the ease of uptake of such systems by enthusiastic individuals. Development of smart aquaponic automation system packages could help to alleviate some of these knowledge related concerns, however, these appear to be only in the early stages of development currently. Where aquaponics truly appears to have benefits is in locations where supplementary energy for heating (water/air) and lighting (plants) are reduced or not required. Furthermore, current legislation is not up to date for a world utilising aquaponics, as despite its potential highly environmentally beneficial output (if run well) it is barred from the benefits of increased prices found with organic labelling simply as it does not involve plant growth in soil substrates. Where prawns are concerned as a specific element of aquaponics these could have potential as areas of high market growth and consumer demand in the current climate. However, whilst aquaculture conditions are well established across both marine and freshwater species, their direct interaction in aquaponics has only more recently undergone assessment. As such optimisation of such systems might take time before these become a more viable aquaponics production species.

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