Stimulating the circular economy for food production in central Mexico: integration of greenhouse cultivation, land-based aquaculture and microalgae production systems.

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Preface

The Dutch Agricultural counsel (Landbouwraad) in Mexico has, in the framework of a “Kansen voor Morgen” program, asked Wageningen University and Research (WUR-WFBR) for a study on possibilities for integration of tomato production in greenhouses and land-based aquaculture (and algae production) in the Queretaro region in Mexico. Such a coupling might lead to more food production per unit of water and provide tools towards a more circular economy in Mexico. The horticulture company United Farms - Finka, located near Queretaro, already has an established cooperation with WFBR in the project Algaelinkages. In that project, the potential of algae cultivation, and nutrient removal from, discharge water from the greenhouses is studied.
The current desk study, an inventory that may lead to an experimental cooperation project, is based on input data from greenhouses as provided by United Farms – Finka. Further analyses are based on the expertise of the participating WUR researchers as well as literature-based information from several disciplines. The cooperation between these different disciplines appears essential for the integration of multiple production systems.

Summary

This report describes the results obtained in a research project performed by Wageningen University and Research for The Dutch Agricultural counsel (Landbouwraad, LNV) in Mexico. The desk study includes the possibilities for integration of tomato production in greenhouses and land-based aquaculture (and algae production) in the Queretaro region in Mexico. Such a coupling might lead to more food production per unit of water and provide tools towards a more circular economy in Mexico.

The horticulture company United Farms - Finka, located near Queretaro, already has an established cooperation with WFBR in the project Algaelinkages. In that project the potential of algae cultivation on, and nutrient removal from, discharge water from the greenhouses is studied.
The current desk study, an inventory that may lead to an experimental cooperation project, is based on input data from greenhouses as provided by United Farms – Finka. Further analyses are based on the expertise of the participating WUR researchers as well as literature-based information from several disciplines. The cooperation between these different disciplines appears essential for integration of multiple production systems.

Water scarcity and efficient water use is a challenge in the central region of Mexico as well as in many other places in the world. In general, and also in the greenhouses of United Farms – Finka, (drain) water is recirculated within greenhouse irrigation management systems as much as possible. However, discharging large quantities of water still occurs because water quality deteriorates during recirculation as sodium and crop protection agents build up in the system. Furthermore, upon starting of the crop cultivation season, irrigation water of United Farms – Finka cannot be recirculated for 2 months because of color formation and the used disinfection system. Water discharge results in loss of valuable water and nutrients and leads to environmental impacts such as eutrophication and pollution of surface waters. Possible use of drain/discharge water to produce valuable microalgae and, at the same time, remove nutrients has been developed in the project AlgaeLinkages,

Water technologies and land-based aquaculture might contribute to more efficient use of water (i.e., more kg of food per litre of water). There is, however, a lack of concentrated knowledge on these technologies and their integration in horticulture at e.g., United Farms – Finka in Mexico. Furthermore, data about how, and to what extent these options can contribute to a more efficient water use need to be generated.

The main aim of this project is to generate the knowledge needed to combine local greenhouse production of high-quality vegetables with land-based aquaculture and algae production in the central region of Mexico. System integration is based on the concept of aquaponics to increase water use efficiency and improve wastewater management, thereby reducing the environmental impact.

Approach: A desk study has been performed on the integration of three production systems; greenhouse cultivation, land-based aquaculture (combined called aquaponics) and production of microalgae to generate knowledge on the water footprint and total biomass (i.e. crops, fish- and microalgae-products) production per litre of water. The starting point for viable aquaponic designs in Mexico lies within local conditions such as the climate, availability and quality of water, existing infrastructure and suppliers as well as market demand.
The calculations for and integration of the different production systems are based on 4 ha of greenhouse area, the expertise of participating researchers and our best estimations of (literature-based) data.

Results: An overview of land-based aquaculture production systems is presented and, based on parameters provided by United Farms – Finka, the possible integration of aquaculture is defined. For aquaculture, this includes system type (e.g., ponds, raceways or indoor RAS) and species of fish.

The integrated concept of greenhouse operations combined with aquaponics and algae production results in the improvement of water use efficiency. Depending on systems used, the amount of fish produced in such a system may range from 140 to 700 ton per year fresh weight, or (with an average dry matter content of about 25%) 35 – 170 ton of dry matter per year. When an algae production system, based on photobioreactors, is coupled to nutrient removal of discharge water, and algal production of 10 – 12 ton dry matter at a production area of about 0.215 ha is expected.

The most efficient systems configuration of combining the water and nutrient flows between these three production systems is:

- An aquaculture system at the beginning of the water system supply (decoupled aquaponics setup)
- Followed by a greenhouse production system such as United Farms – Finka has
- Use discharge water for algae production in a photo-bioreactor

Implementation of such integrated systems at scale, however, would first need pilot experiments under (highly variable) local conditions. Furthermore, information from pilot-scale could also be the input for a techno-economic evaluation.

Although not part of the specific research question, but relevant for efficient water use, a number of options and technologies available for minimizing the total need for extracting groundwater as a freshwater resource are briefly indicated:

1. Minimizing losses by good water management practices
2. Improving the quality of the used groundwater before irrigation
3. Alternative water sourcing by rainwater harvesting using basins
4. Use of more salt-tolerant crop species
5. Recovering drain water from the horticulture greenhouses

1 Introduction

Water scarcity and efficient water use is a major challenge in the central region of Mexico as well as in many other places in the world. In general, and also in the greenhouses of United Farms – Finka, (drain) water is recirculated within greenhouse irrigation management systems as much as possible. However, discharging large quantities of water still occurs because water quality deteriorates during recirculation as sodium and crop protection agents build up in the system. Furthermore, upon starting of the crop cultivation season, irrigation water of United Farms – Finka cannot be recirculated for 2 months because of color formation and the used disinfection system. Water discharge results in loss of valuable water and nutrients and leads to environmental impacts such as eutrophication and pollution of surface waters.

Water technologies and land-based aquaculture might contribute to a more efficient use of water (i.e. more kg of food per litre of water). There is, however, a lack of concentrated knowledge on these technologies and its integration in horticulture at e.g., United Farms – Finka in Mexico. Furthermore, data about how, and to what extent these options can contribute to a more efficient water use needs to be generated.

The Dutch Agricultural counsel (Landbouwraad, LNV) in Mexico has asked Wageningen University and Research for a study on possibilities for integration of tomato production in greenhouses and land-based aquaculture in the Queretaro region in Mexico. Such a coupling might lead to more food production per unit of water and provide tools towards a more circular economy in Mexico. The horticulture company United Farms – Finka, located near Queretaro, already has an established cooperation with WFBR in the project Algaelinkages. In that project, the potential of algae cultivation, and nutrient removal from, discharge water from the greenhouses is studied. Within the current desk study, United Farms – Finka was willing to share input data from their greenhouse systems.

Aim
The main aim of this project is to generate the knowledge needed to combine local greenhouse production of high-quality vegetables with land-based aquaculture and algae production in the central region of Mexico. System integration is based on the concept of aquaponics to increase water use efficiency and improve wastewater management, thereby reducing the environmental impact.

Approach
A desk study has been performed on the integration of three production systems; greenhouse cultivation, land-based aquaculture (combined called aquaponics) and production of microalgae, to generate knowledge on the water footprint and total biomass (i.e., crops, fish- and microalgae-products) production per litre of water. The starting point for viable aquaponic designs in Mexico lies within local conditions such as the climate, availability and quality of water, existing infrastructure and suppliers as well as market demand.

The current study is based on input data from greenhouses as provided by United Farms – Finka and local conditions. Further analyses are based on the expertise of the participating Wageningen University and Research researchers as well as literature-based information from several disciplines. The research was conducted independently and the cooperation between these complementary disciplines appeared essential for the integration of multiple production systems.

This report presents information on land-based aquaculture production systems and, based on parameters provided by United Farms – Finka, its possible integration with horticulture and algae cultivation.

2 Methods

2.1 Assessment of the local situation at United Farms, Mexico

Basic information is compiled for the local situation at United Farms - Finka, Queretaro, Central Mexico via open questions. Examples of such questions include:

1. What are the sources of water used?
2. Which volumes are used, recirculated and discharged?
3. What is the quality of ingoing and outgoing flows of water?
4. Which species of fish are interesting for United Farms – Finka from an economic point of view?

2.2 Suitable land-based aquaculture production system(s)

An overview of land-based aquaculture production systems is presented and based on the local conditions at United Farms – Finka, the possible integration of aquaculture is defined. This includes system type (e.g., ponds, raceways or indoor RAS) and species of fish. Important inputs to support the proposed system integration are for example, how many litres of water are discharged from the greenhouse- and algae systems, the quality of this water and what kind of water treatment facilities are already in place. This will be matched with how much water leaves the land-based aquaculture system, its quality and whether it can be reused by plants and/or microalgae. These are key outputs that provide insights on how to best align the three production systems.

2.3 Connecting horticulture, land-based aquaculture and microalgae production

A theoretical calculation, using an aquaponics mass flow model, is made for the land-based aquaculture production system based on its inputs (i.e. water and feed) and outputs (i.e. water and nutrients). Furthermore, the theoretical possibilities to use sludge from the aquaculture system in the greenhouse as fertigation are included. Quantitative results were used to match ingoing and outgoing flows of water and nutrients between the three production systems, aiming at a circular system. As a result, this provides answers towards the question if and to what extent land-based aquaculture can contribute to a higher water use efficiency.

2.4 Strategies to increase overall water use efficiency

Besides integration with other food- or feed production systems to increase water use efficiency, there may also be some improvement possible concerning the current (greenhouse) water management system. Therefore, the state of the art on water and nutrients in horticulture production of tomatoes is derived from the results of the EU FERTINNOWA thematic network and compared with the situation at United Farms – Finka. EU FERTINNOWA, in which Wageningen University & Research was one of the leading partners, created a meta-knowledge database and reference information on innovative technologies and best practices for the fertigation of horticultural crops (https://www.fertinnowa.com).

3 Results

3.1 Local situation at United Farms – Finka

The starting point of this design study is the greenhouse production company United Farms – Finka which is in Queretaro, Central Mexico. United Farms – Finka operates about 65 ha of greenhouse divided over several locations. About 60 ha are used to grow several varieties of tomato and 5 ha are dedicated to the cultivation of cucumber. Water scarcity is a challenge for greenhouse production in the central region of Mexico. So, to increase water use efficiency United Farms – Finka recirculates fertigation water (i.e., water containing dissolved nutrients) within their greenhouses. Unfortunately, the drain water from irrigation cycles cannot be recirculated indefinitely because sodium (Na^+) accumulates in the system. To avoid the negative effects of sodium on crop growth and development the drain water is (partially) discharged regularly. This loss of water and nutrients to the environment led United Farms – Finka to explore the potential of greenhouse discharge water for use in other food production systems.

They participated in the project AlgaeLinkages where it was established that microalgae can successfully be produced using the greenhouse discharge water as a growing medium. The harvested algae contain essential omega-3 fatty acids and can be used as a supplement in chicken feed (Mens et al., 2020) In this report, it is investigated whether land-based aquaculture could also be integrated to increase water use efficiency. A first step in the design process is to consider the local availability and quality of water as well as greenhouse water management.

3.1.1 Water availability and quality

For all crops and cropping systems, it is essential to maintain an acceptable quality of irrigation water with regards to salinity and the composition of chemical elements and compounds. In addition to crop species, the type of cropping system influences the required water quality. For soilless growing systems with recirculation of drain water, the requirements for the quality of irrigation water regarding salinity are high in order to ensure that the accumulation of these components during recirculation commences from relatively low base values. For instance, in the Netherlands irrigation water is considered high quality if EC is below 0.5 mS/cm and concentrations of sodium (Na^+) and chloride (Cl^-) are below 0.2 mmol/l (Raaphorst & Benninga, 2019).

Where groundwater is used, commonly, the salinity and chemical composition are issues that must be taken into consideration as the water may require treatment before being suitable for irrigation. These issues are particularly important in Mexico where groundwater, with higher salt content, is widely used. This is also the case at United Farms – Finka where groundwater is the main source of water for irrigation. Table 1 shows an overview of water quality parameters for the available groundwater as well as the fertigation- and drain water at United Farms – Finka.

The water quality values of the groundwater indicate an EC of 0.6 mS/cm, a sodium concentration of 2.7 mmol/l and a chloride concentration of 0.4 mmol/l. According to standards in the KWIN, the groundwater has to be considered as low-quality water (class 3.2) which means that United Farms – Finka has to (partially) discharge its drain water regularly. Table 1 also shows that the groundwater has a pH of 7.6. This is too high for soilless cultivation of tomatoes and therefore sulfuric acid is added to lower the pH to 5.5 – 6.

Table 1 Water quality parameters for the groundwater, fertigation- and drain water at United Farms – Finka.

Water quality parameter	Unit	Groundwater	Fertigation water*	Drain water*
EC	mS/cm	0.6	1.9	3.4
pH		7.6	5.9	6.3
NH_4^+	mmol/l	< 0.1	< 0.1	< 0.10
K^+		0.5	4.4	6.7
Na^+		2.7	2.5	7.0
Ca^{2+}		1.0	3.8	6.1
Mg^{2+}		0.4	1.5	3.9
Si		1.4	1.5	2.9
NO_3^-		0.6	10.8	16.6
Cl^-		0.4	3.4	7.5
S		1.2	1.9	4.7
HCO_3^-		2.0	<0.15	<0.15
P		0.07	0.7	0.9
Fe	μmol/l	0.5	16.0	18.9
Mn		0.2	30.3	8.2
Zn		0.2	6.0	6.6
B		6	69.2	164.5
Cu		< 0.1	2.8	3.0
Mo		< 0.1	1.7	1.3

[*] Water quality values of fertigation- and drain water fluctuate throughout the year depending on the needs of the crop. Data provided by United Farms – Finka indicates that EC of the fertigation water fluctuates between 1.9 and 2.8 mS/cm. Fertilizer concentrations fluctuate accordingly.

3.1.2 Greenhouse water management

Apart from adjusting the pH and nutrient profile of the groundwater, it is also cooled down using a cooling tower. The groundwater is 28 °C when it exits the well and is cooled down to 25 °C before it enters the greenhouse. Figure 1 shows an overview of the current water and nutrient flows at United Farms – Finka.

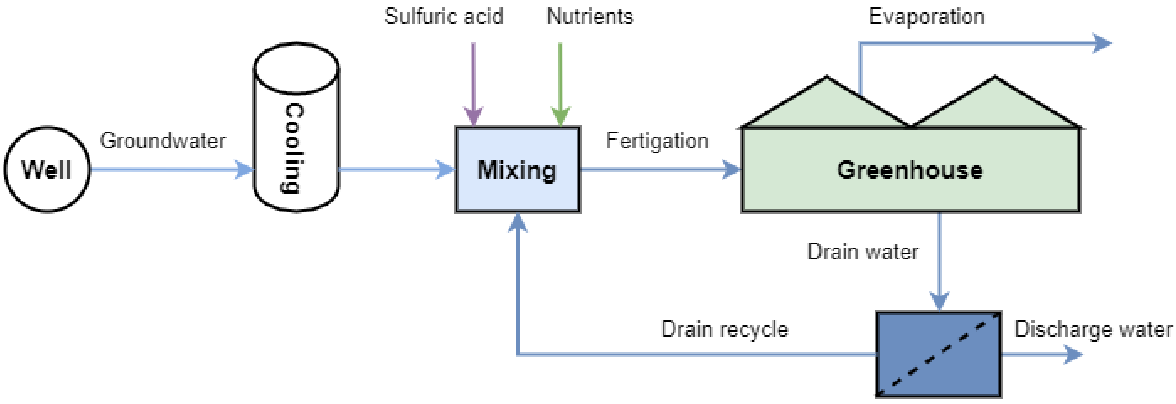

Figure 1 Schematic overview of the soilless greenhouse cultivation at United Farms - Finka including recirculation of drain water and cooling of groundwater.

To integrate other food production concepts into the existing greenhouse water management system, not only water quality is of importance, but a quantitative indication of the water flows is also needed. For instance, in the case of algae production the greenhouse discharge water must contain sufficient nutrients but the amount of discharge water that is available per day will determine the potential scale of production. Figure 2 gives a schematic overview of the quantitative water flows based on input from United Farms - Finka.

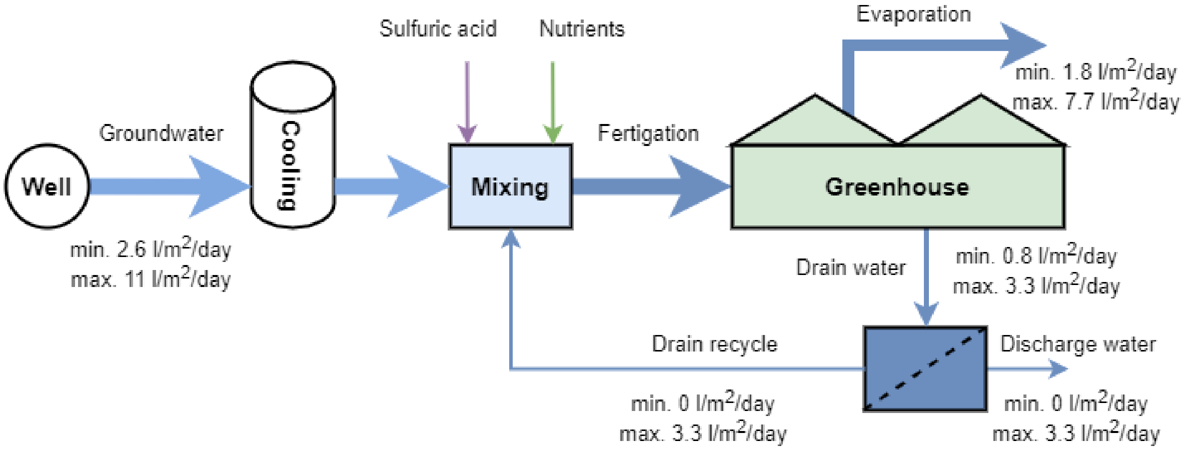

Figure 2 Schematic overview of quantitative greenhouse production water flows.

From figure 2, it becomes clear that most of the water that enters the greenhouse for irrigation leaves the greenhouse as evaporation (about 70 % of total water use). A minimum and maximum water use per flow per day are indicated because evaporation by the crop fluctuates depending on the available solar radiation; on sunny days the crop evaporates a lot more water to keep cool than on overcast days. Water use is also lower at the start of the cultivation since young plants have less leaf area to evaporate water with. Considering the quality and quantity of greenhouse water flows, the next step in the design process is to define the boundary conditions of an aquaculture system that can be integrated to increase overall water use efficiency.

3.2 Fish production and aquaponics

3.2.1 What is aquaculture?

Aquaculture in general is the cultivation of aquatic animals and plants in natural or controlled marine or freshwater environments. Aquaculture as defined by the FAO is: "The farming of aquatic organisms, including fish, molluscs, crustaceans and aquatic plants". The word farming implies ownership of the animals or plants being cultivated and that some kind of intervention in the rearing process takes place to enhance production. As United Farms – Finka is situated inland and not close to large natural water bodies, their potential aquaculture activities are limited to so-called land-based aquaculture. Land-based aquaculture systems can be more or less divided into three different types of systems: pond systems, flow-through systems and recirculation aquaculture systems.

Pond systems (see figure 3) are constructed water bodies with limited water exchange during the culture period. However, pond systems need to be filled at the start of the production cycle and continuously supplemented with water to compensate for evaporation and seepage during the production cycle. Depending on the type of pond, earthen or lined, the number of production cycles per year, culture insensitivity and of course climate, the water use of a pond system can range from 1 m^3 per kg of fish up to 45 m^3 per kg of fish produced (Verdegem et al., 2006). This makes fish production by the use of a pond an inefficient system with respect to the use of freshwater (FAO, 2001).

Figure 3 Feeding time at a pond system for the production of fish. Source: Unknown.

Flow-through systems (see figure 4) are in many cases based on concrete channels as they have relatively fast-flowing water. In a flow-through system, 'clear' water flows in and will be discharged after a single use to remove the fish metabolites and uneaten feed. The water use of a flow-through system can range from 30-50 m^3 per kg fish (Heldbo, 2014; Verdegem et al., 2006) and is, except for some extreme cases, more or less comparable with the water use of an extensive pond system.

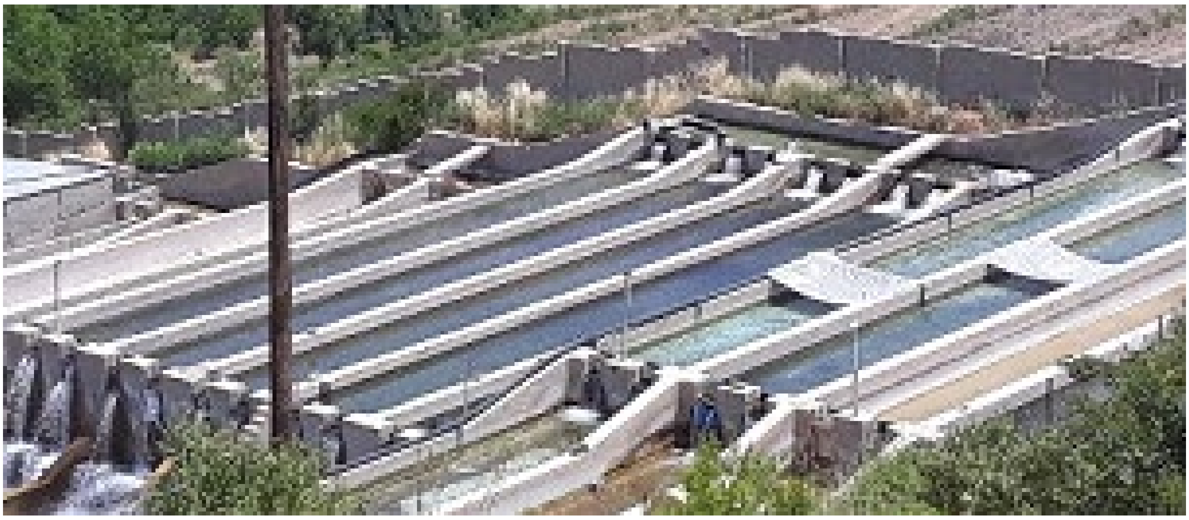

Figure 4 Flow through aquaculture system in which the fish are reared in concrete raceways. Source: Jeroen Kals, Wageningen Livestock Research.

In a recirculation aquaculture system or RAS (see figure 5), the water is continuously reused after treatment through various biological and mechanical filtration, disinfection and aeration devices within the system itself. By using a RAS, the water use can be extremely reduced, even up to 0.15 m^3 of water per kg of fish produced and if denitrification is applied a water use of just 0.05 m^3 can be achieved. Highly intensive RAS are the most water-efficient animal food production systems available (Verdegem et al., 2006; Goddek et al., 2019). Therefore, looking at the main objective of this project to maximize the water use efficiency, the use of a RAS system is the obvious pick. In addition, a RAS has the advantages of production under controlled conditions, protected from outside risks to optimize productivity, feed efficiency and limited land use.

Figure 5 Recirculating aquaculture system at Kingfish Zeeland. Source: Kingfish Zeeland.

3.2.2 What is a recirculating aquaculture system or RAS?

A RAS is a closed system in which, for example, fish can be farmed. In a RAS, the water is filtered and pumped around so that it can be used again and again, or in other words, recirculated. Growing fish in a RAS is the most efficient production system for food at the moment in terms of water use (Goddek et al., 2019). Figure 6 shows a schematic overview of a RAS. The system consists of at least fish tanks as the grow-out section, a mechanical filter, a biological filter,a system for aerating the water and, if needed, a temperature control system. The fish is kept in the grow-out section and fed with feed specially formulated for the fish. The feeds are eaten by the fish so that it can grow. The fish uses oxygen (O_2), produces solid parts (feces), soluble parts, including ammonium nitrogen (NH_4-N) and carbon dioxide (CO_2). The mechanical filter removes the suspended solids. The biological filter converts the ammonium nitrogen via nitrite (NO_2^-) into nitrate (NO_3^-) and the system for aerating the water removes the carbon dioxide and reintroduces oxygen, after which the water is recycled back to the fish tanks or grow-out section and the circle is complete. Optionally, the water can be enriched with pure oxygen to increase productivity because a higher number of fish can live in a m^3 of water as long as oxygen levels are acceptable. The recirculating water can also be treated with ozone or UV light to minimize the risk of pests and diseases.

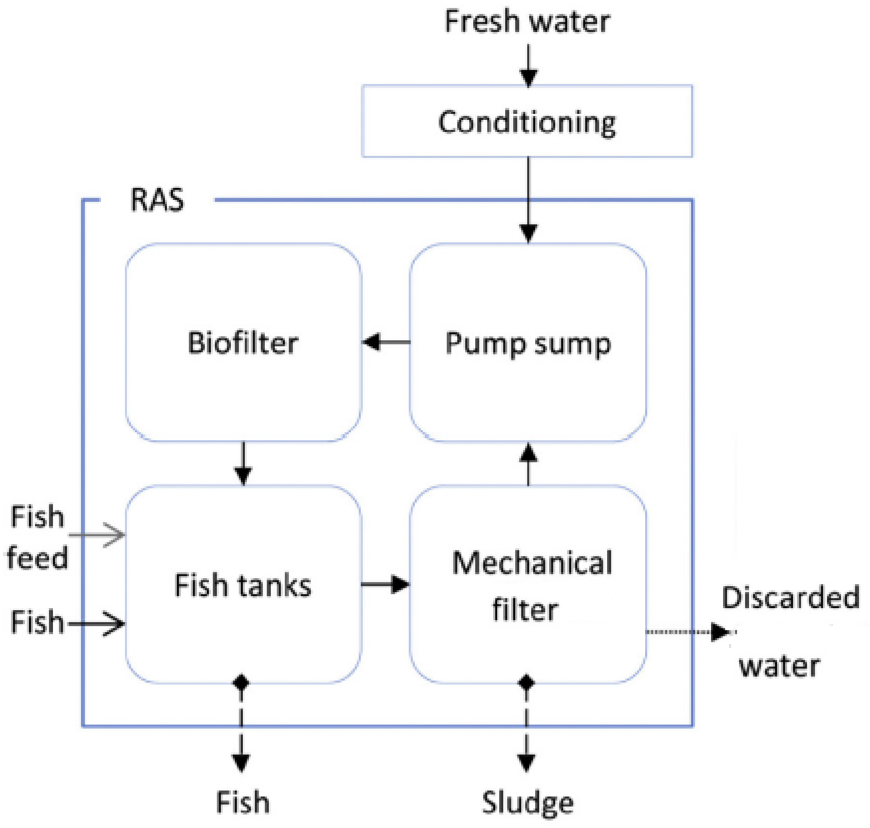

Figure 6 Schematic presentation of a RAS. Source: adapted from Suhl et al. (2018).

3.2.3 Can a RAS be integrated as an end-of-pipe solution that uses greenhouse discharge water?

The main question initially put forward by United Farms – Finka is whether the discharge water of their greenhouses can be used to grow fish. In that case, a RAS would be implemented as an end-of-pipe solution as is illustrated in figure 7.

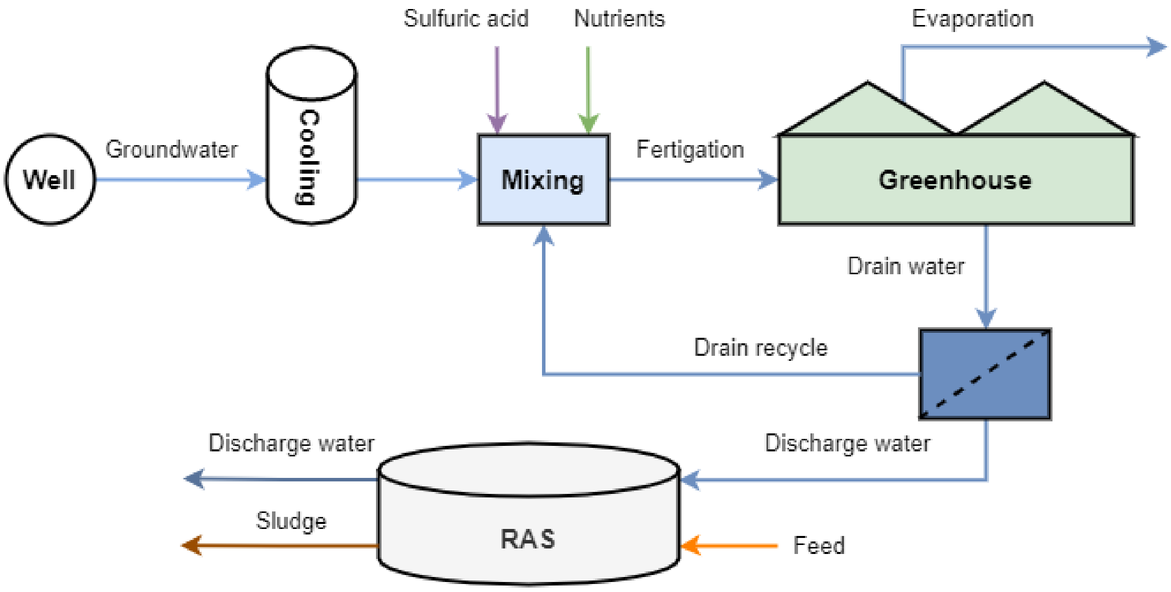

Figure 7 Schematic overview of implementation of RAS as an end-of-pipe solution for greenhouse discharge water.

For such a setup to be viable, the quality of the greenhouse discharge water must be suited to produce fish. Unfortunately, this is clearly not the case. Table 2 compares the values from water quality analyses of drain water samples at United Farms – Finka with corresponding quality criteria for fish production as proposed by Timmons et al. (2018). The elements that are highlighted in orange in table 2 are all above the safety thresholds for fish production. Meaning that the greenhouse discharge water contains too much potassium, sodium, calcium, magnesium, nitrate, sulfur, phosphor as well as heavy metals such as iron, manganese and copper.

If the greenhouse discharge water would be used for fish production, it would therefore first have to be diluted or treated in order to lower the concentration of the mentioned components. Depending on the chemical elements to be removed, different options for treatment of the discharged can be considered, varying from reverse osmosis, producing near pure water and removing all chemical elements, to the selective removal of nutrients and metals using technologies such as ion-exchange or electrodialysis. All water treatment technologies come at a certain cost in both operating expenses and capital investments. In conclusion, based on the quality of the greenhouse discharge water it does not make sense to reuse it for aquaculture**. This is not a conclusion that only applies to United Farms – Finka, but applies in general to soilless cultivation that uses recirculation; the concentration of nutrients in the drain- and discharge water is too high for use in aquaculture.**

Apart from water quality issues, the overview in figure 7 indicates that discharge water from the RAS does not circle back to the greenhouse. This is logical because the sodium concentration of the discharge water from the RAS will not be lower than that of the greenhouse discharge water. In fact, the salinity will most likely increase due to the sodium present in the fish feed. So, this type of RAS integration potentially offers a higher biomass production per m^3 of water, but it does not solve the issue of discharge water. The environmental impact would most likely increase because the discharged water from the RAS has a higher salinity and contains more nutrients (especially nitrates) than greenhouse discharge water.

Table 2 Comparison of water quality analyses of discharge water samples at United Farms – Finka with water quality criteria for aquaculture as proposed by Timmons et al. (2018).

Water quality parameter	Drain water		Quality threshold	
	mmol/l*	mg/l*	mmol/l*	mg/l*
NH_4^+	< 0.10	< 1.8	-	-
K^+	6.7	262	< 0.13	< 5
Na^+	7.0	161	< 3.3	< 75
Ca^{2+}	6.1	244	0.1 - 4	4 – 160
Mg^{2+}	3.9	95	< 0.62	< 15
Si	2.9	81	-	-
NO_3^-	16.6	1030	0 – 6.5	0 - 400
Cl^-	7.5	266	-	-
S	4.7	151	< 0.03	< 1
HCO_3^-	<0.15	9	-	-
P	0.9	28	0.0003 – 0.1	0.01 – 3.0
	µmol/l*	µg/l*	µmol/l*	µg/l*
Fe	18.9	1055	2.7	150
Mn	8.2	450	0.18	10
Zn	6.6	432	1.84 – 7.04**	120 – 460**
B	164.5	1778	-	-
Cu	3.0	191	0.14 – 0.55**	9 – 35**
Mo	1.3	125	-	-

* Horticulturists are used to express concentrations in mmol or µmol per litre whereas aquaculturists are used to mg or µg per litre. Often this causes some issues in communication. Therefore, both units are shown in table 2.

** The thresholds for copper and zinc in fish production depend on the hardness of the water. Toxicity of both elements is lower when hardness is higher.

3.2.4 RAS within a decoupled aquaponic system

This does not mean that a RAS cannot be integrated. More logical would be to place an aquaculture system at the beginning of the water system supply line since the groundwater is more suitable for aquaculture use. Of the water quality parameters that are known only sulfur and manganese may be an issue (see table 3).

Table 3 Comparison of water quality analyses of groundwater samples at United Farms – Finka with water quality criteria for aquaculture as proposed by Timmons et al. (2018).

Water quality parameter	Groundwater		Quality threshold	
	mmol/l[*]	mg/l[*]	mmol/l[*]	mg/l[*]
NH_4^+	< 0.1	< 1.8	-	-
K^+	0.5	20	< 0.13	< 5
Na^+	2.7	62	< 3.3	< 75
Ca^{2+}	1.0	40	0.1 - 4	4 – 160
Mg^{2+}	0.4	10	< 0.62	< 15
Si	1.4	39	-	-
NO_3^-	0.6	37	0 – 6.5	0 - 400
Cl^-	0.4	14	-	-
S	1.2	38	< 0.03	< 1
HCO_3^-	2.0	122	-	-
P	0.07	2	0.0003 – 0.1	0.01 – 3.0
	µmol/l[*]	µg/l[*]	µmol/l[*]	µg/l[*]
Fe	0.5	28	2.7	150
Mn	0.2	11	0.18	10
Zn	0.2	13	1.84 – 7.04[**]	120 – 460[**]
B	6	65	-	-
Cu	< 0.1	< 6	0.14 – 0.55**	9 – 35**
Mo	< 0.1	< 10	-	-

[*] Horticulturists are used to express concentrations in mmol or µmol per litre whereas aquaculturists are used to mg or µg per litre. Often this causes some issues in communication. Therefore, both units are shown in table 2.

[**] The thresholds for copper and zinc in fish production depend on the hardness of the water. The toxicity of both elements is lower when hardness is higher.

Figure 8 illustrates how a RAS can be integrated into the existing greenhouse water management system. In such a setup both the greenhouse and RAS recirculate their own water, but the discharge water from the RAS, including nutrients, can be reused by the greenhouse. Before any water from the RAS enters the greenhouse, it can first be disinfected (e.g., UV light), filtered and treated to adjust pH and hardness. This way optimal water conditions can be achieved for both the plants and the fish. The design is also referred to as a double recirculating aquaponic system or ‘DRAPS’ (Goddek et al., 2016; Goddek et al., 2019; Kloas et al., 2015; Monsees et al., 2017; Suhl et al., 2016).

There are a few other points to take away from figure 8. First, not only the water quality of the groundwater is better suited for aquaculture production, but the temperature of 28 °C is suited for several warm water species. And though a pH of 7.6 (see table 1) is too high for tomato cultivation, it is within range for most species of (freshwater) fish. Second, depending on the filtration steps and system design, the sludge may consist mostly out of water and when it leaves the RAS, it results in a loss of water. However, sludge also contains valuable nutrients which can be (partially) recovered using various techniques such as aerobic digestion (Inagro, 2019, Goddek et al., 2018, Panana et al., 2021). Water and nutrient loss can therefore be mitigated by further treatment of the sludge flow.

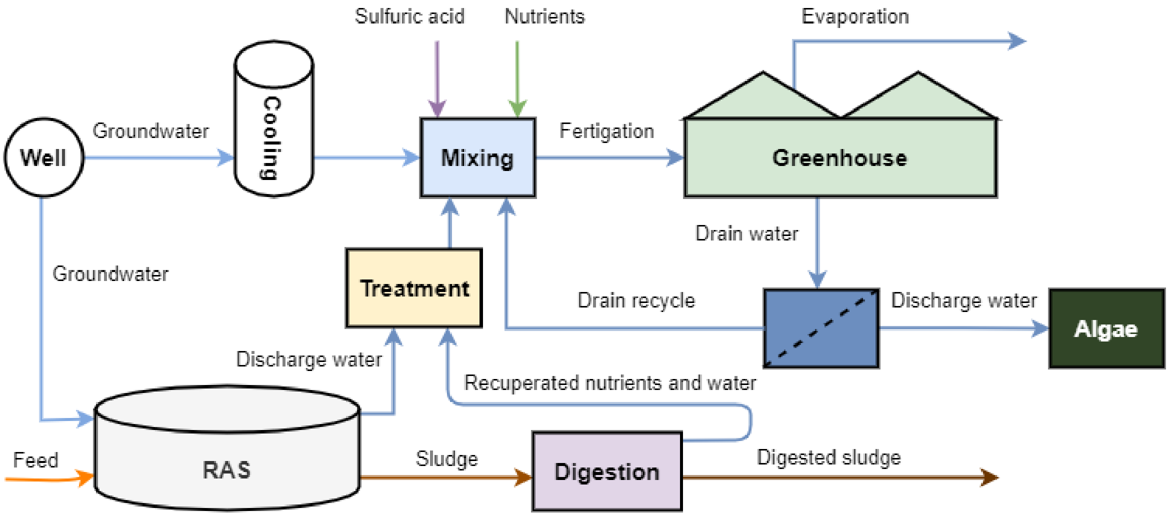

Figure 8 Schematic overview of implementation of RAS within a decoupled aquaponic system setup.

Notice that a decoupled aquaponics setup still does not solve the original issue of water loss due to greenhouse discharge. However, the water use efficiency in terms of kg food per m^3 is increased by producing fish and vegetables using the same amount of water. Furthermore, compared to standalone RAS and greenhouse operations, a decoupled aquaponic system also offers an efficient use of nutrients. In chapter 4 some alternative strategies are discussed to increase the overall water use efficiency by decreasing discharge water.

3.2.5 Quantitative flows in a RAS system

The next logical question would be what a potential RAS at United Farms – Finka could look like in terms of water and nutrient flow. The quantitative in- and output flows in a RAS depend on the (fish) species that are farmed in the system, the quality of the incoming water, the quality of the feed, the design of the system and its management. In some cases, it is possible to grow 1 kg of fish with less than 1 kg of feed. The ratio between the biomass increases or growth and the amount of feed is called the feed conversion ratio. Figure 9 gives a schematic overview of the in- and output flows of a RAS.

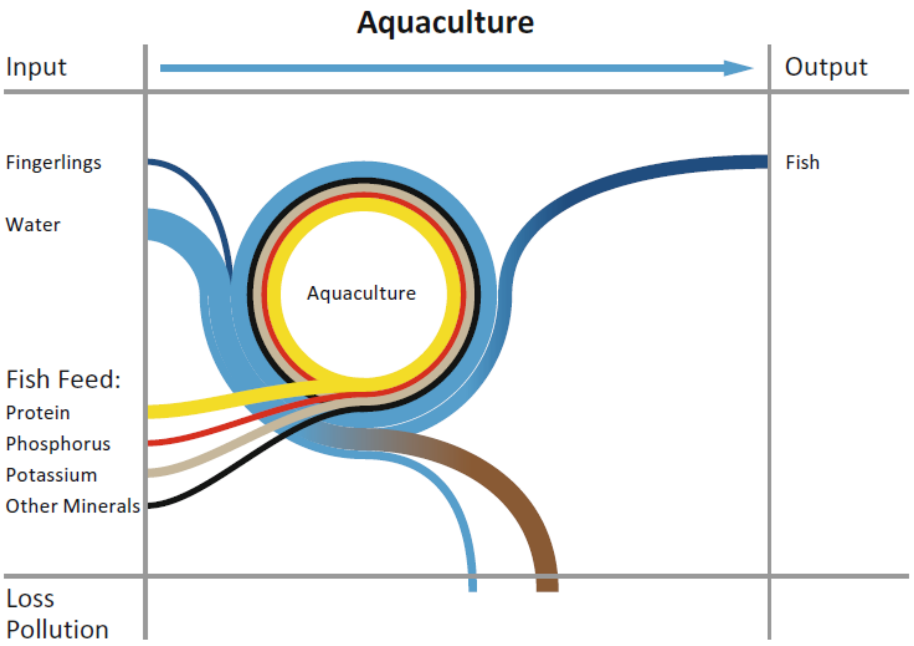

Figure 9 Input, output and losses in a standalone RAS. Source: Goddek et al., 2019.

For this study, the in- and output flows of a RAS containing the fish tilapia as a model species have been mapped. Tilapia was chosen because this species can be cultivated in water with relatively high nitrate (NO_3^-) values, which is interesting for greenhouse horticulture and specifically for the cultivation of tomatoes (Monsees et al., 2017). With the choice of tilapia, a feed conversion ratio of 1.25 can be achieved. This means that 1 kg of fish can be grown with 1.25 kg of feed. When the fish consume 1 kg of feed, the RAS system uses ± 0.5 kg of oxygen. We write RAS system because, in addition to the fish, the biological filter also uses oxygen. From 1 kg of feed, the fish produces ± 35 grams of ammonium nitrogen (NH_4-N), ± 690 grams of carbon dioxide (CO_2) and ± 200 grams of feces (dry) in the form of sludge. Schram et al. (2006) mentioned a sludge production of 5 m^3 per ton of fish, but this highly depends on the type of system, especially regarding the type of mechanical filter.
In this example, it is assumed that all ammonium (NH_4^+) is converted to nitrate (NO_3^-) and no nitrogen gas (N_2) is produced. The renewal of the circulating culture water is based on the nitrate concentration in the water. The concentration used depends on the (fish) species to be farmed. As indicated, tilapia has a high tolerance for nitrate; even up to values of 2200 mg/l, yet too high values are not preferred as they can limit feed intake and therefore growth. However, according to Monsees et al. (2017) nitrate levels up to 2200 mg/l (≈ 500 mg NO_3-N/l or ≈ 36 mmol/l N) can be applied without negative effects on growth and the feed conversion rate. In this project, a maximum nitrate concentration of 750 mg/L or 12 mmol N is used to calculate the in- and output flows of the system. This corresponds to the desired value for the tomato plant. However, fish-wise a higher concentration is possible.

With a nitrate concentration of the incoming groundwater of ± 37 mg/l (see table 3), the required amount of refreshment water is calculated at ± 217 litres per kg of feed. According to the values mentioned in Schram et al. (2006), this amount of water per kg of feed is on the high side of tilapia. This is mainly because we chose a relatively low NO_3-N concentration of 12 mmol N to refresh the water. In addition, it is assumed that all ammonium is converted into nitrate and that denitrification, the process by which bacteria convert nitrate into nitrogen gas (N_2), does not play a significant role. In practice, it is expected that the nitrogen concentration to refresh the culture water could be set higher (up to a max of 36 mmol N), which will result in a lower amount of water needed per kg of feed (up to a minimum of ± 75 l/kg feed) and consequently a higher production of fish per m^3 of water. The water use efficiency would then reach an approximate maximum of 11 kg of fish per m^3 of water, almost 3 times more than in the current example. Therefore, for the design of the system one can discuss or make a tradeoff to optimize water use efficiency, nitrogen use efficiency and/or CO_2 footprint.

3.2.6 What is possible and what are the benefits?

Calculations show that interesting savings appear to be possible with the cross-over tilapia and tomatoes using the double recirculating aquaponic system or 'DRAPS' design. The connection is designed based on the water consumption of the hydroponics system. In this example, the starting point is a greenhouse area for the soilless production of tomatoes of 4 hectares. The water use of this hydroponics system is ± 2.6 l per m^2 per day or ± 104 m^3 per day, which is based on the minimum water use per day of United Farms – Finka. Later we discuss the possibility to optimize the connection of the two production systems. Assuming that all water that is taken in by the horticulture system comes from the RAS system, the RAS system can refresh an average of ± 104 m^3 per day. This allows the operator of the RAS system to feed ± 480 kg of feed per day to the tilapias, giving a production of ± 384 kg per day or up to an estimated 140 ton of tilapia per year.

Assuming that tilapia is produced, maintaining a maximum nitrate (NO_3^-) concentration of 750 mg/l (12 mmol/l) and a water use of the hydroponics system of 2.6 l m^2/day, this cross-over between aquaculture and hydroponics, could increase the biomass production per m^3 of water with ± 4 kg fish on ± 46 kg tomatoes to a production of ± 50 kg biomass per m^3 water. The expected increase in the production of dry matter, protein and fat per m^3 of water is shown in table 4. This to illustrate that the production of fish makes a major contribution to the increase in the production of proteins and fatty acids essential for humans. In addition, 9-13* to a maximum of 32-46** tons of CO_2 y^{-1} can be saved by saving synthetic nitrogen fertilizers through the use of nitrate (NO_3^-) from the discharge water of the RAS system. (in these calculations the CO_2 requirements for N in the fish feed are not included).

Table 4 Estimated biomass, dry matter, protein and fat production in kg/m^3 of water.

	Biomass	Dry matter	Protein	Fat
Tomato	46	2.5	0.46	0.09
Tilapia	4	1	0.56	0.20
Total	**50**	**3.5**	**1.02**	**0.29**
Increase (%)	**8.7**	**40**	**122**	**222**

Figure 10 indicates how several material flows can be connected in a decoupled aquaponic system. Notice that, compared to figure 9, a standalone aquaculture system loses more water and all dissolved nutrients to the environment compared to aquaponics. In summary, the benefits of a successful connection between horticulture and aquaculture are an increased water- and nutrient use efficiency as well as a lower environmental impact due to reuse of RAS discharge water.

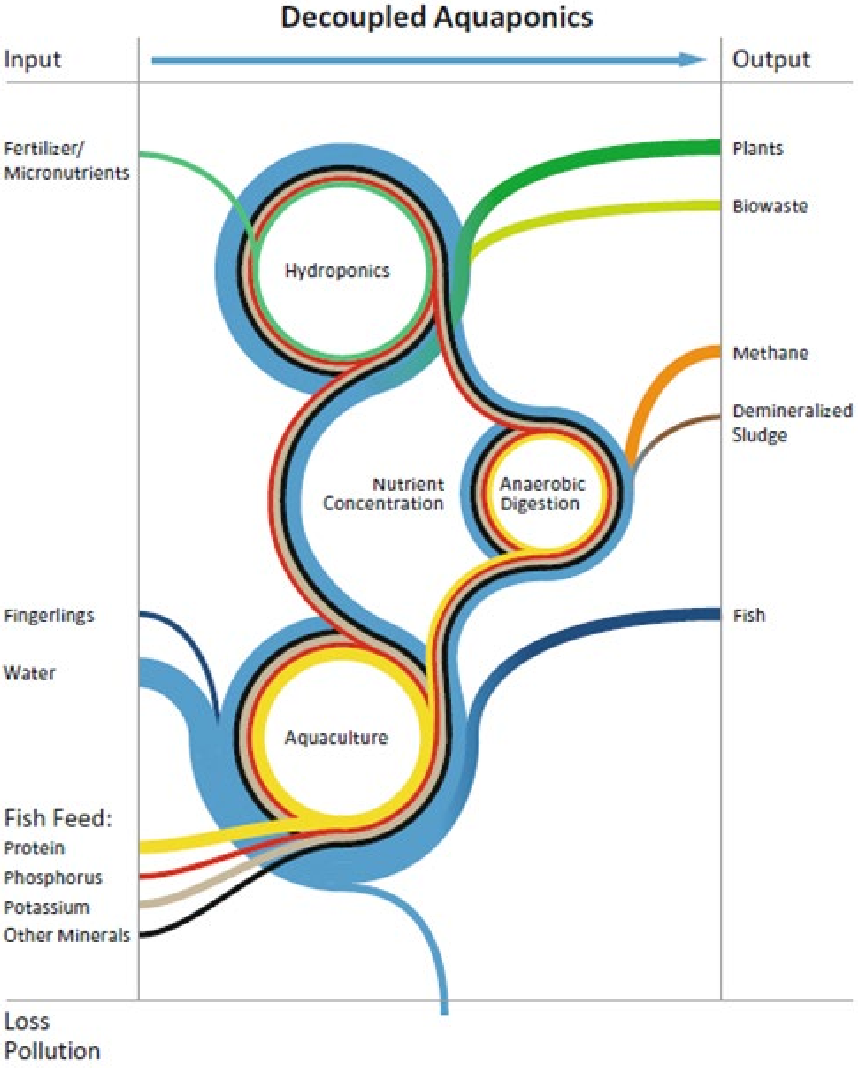

Figure 10 Input, output and losses in a decoupled aquaponic system RAS. Source: Goddek et al., 2019.

3.2.7 Options to further increase fish production

The use of water buffer system to increase fish production

In the example described earlier, the water use of the hydroponics system is ± 2.6 l per m^2 per day or ± 104 m^3 per day, which is based on the minimal water use of United Farms – Finka. One could also choose to decide to design the RAS system for the production of fish based on the average water use per day, which for United Farms – Finka is around 6 l per m^2 per day. Using this average and again assuming that all water that is taken in by the horticulture system goes through the RAS system first, the RAS system can refresh an average of ± 238 m^3 per day. This allows the operator of the RAS system to feed ± 1100 kg of feed per day to the tilapias, giving a production of ± 875 kg per day or up to an estimated 320 ton of tilapia per year. Though, to make this possible a buffer system is needed to be able to store the water from the RAS when the demand of the horticulture system is less than 6 l per m^2 per day and be able to supply the extra water when the demand of the horticulture system exceeds 6 l per m^2 per day. The volume of this buffer system is estimated to ± 49056 m^3 or for example a basin of 1 hectare of ± 5 meters deep. Figure 11 shows several options that are available to buffer water.

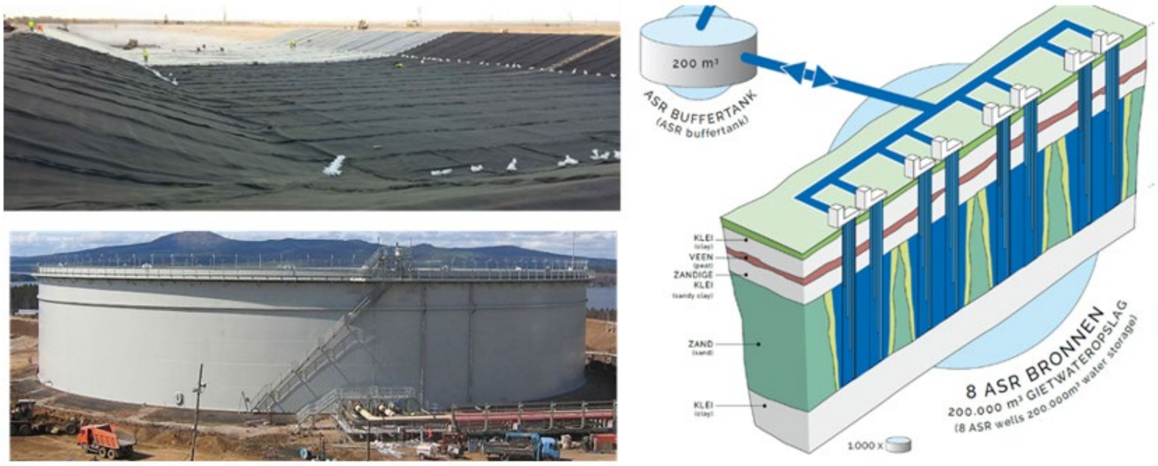

Figure 11 Types of water buffer solutions: upper left, a lined lagoon in construction, an example taken from Industrial & Environmental concepts, inc.; lower left, a steel tank 50000 m^3, an example taken from EuroTanksWorks and on the right an impression of an ASR well storage system, taken from Glastuinbouw Waterproof.

Use of higher NO_3^- N concentration in RAS to increase fish production

As mentioned earlier it is expected that the nitrogen concentration to refresh the culture water could be set higher which will result in a lower amount of water needed per kg of feed and consequently a higher production of fish per m^3 of water. In the current example, the nitrate concentration is set at 12 mmol/l because it is a favourable concentration for the tomato plant (Kreij et al., 1999). The maximum allowable concentration for tilapia would be 36 mmol/l (Monsees et al., 2017), yet we would advise to be on the save side and chose for example for 26 mmol/l NO_3^- or ± 1600 mg/ l of NO_3. In this case, the water use of the hydroponics system is kept at ± 2.6 l per m^2 per day or ± 104 m^3 per day. Again, assuming that all water that is taken in by the horticulture system comes from the RAS system, the RAS system can refresh an average of ± 104 m^3 per day. With the higher NO_3-N concentration this will now allow the operator of the RAS system to feed ± 1025 kg of feed per day to the tilapias, allowing a production of ± 822 kg per day or up to an estimated 300 ton of tilapia per year, with a fish production of 8 kg per m^3 water.

The combination of a higher *NO_3^-*N concentration and buffer system to increase fish production

If the above options; the design of the RAS system based on the average water use of United farms per day of 6 l per m^2 and a NO_3^- concentration of 26 mmol/L or ± 1600 mg/L of NO_3^-, are combined the amount of feed able to be fed to the tilapia will rise to ± 2400 kg per day, allowing a production of ± 1900 kg or up to an estimated 700 ton of tilapia a year. Again, to make this possible a buffer system is needed to be able to store the water from the RAS when the demand of the horticulture system is less than 6 L per m^2 day and be able to supply the extra water when the demand of the horticulture system is higher than 6 L/m^2 per day. The fish production stays at 8 kg per m^3 of water.

3.2.8 What are the challenges?

As shown, interesting savings appear to be possible with the crossover tilapia and tomatoes using the double recirculating aquaponic system or DRAPS design. The coupling is designed on basis of the water consumption of the hydroponics system. However, different configurations are possible as one can play with different parameters (water refreshment, nitrate concentration, use of buffer system etc.) to optimize the design. In this respect, the design is dependent on the trade-off to optimize water use efficiency, nitrogen use efficiency and/or CO_2 footprint. Of course, both systems, the RAS and the horticulture system must be economically viable independently of each other.

Before a crossover of tilapia and tomatoes can be tested on pilot scale, it is important to further investigate a number of aspects. This also concerns research into possibilities for the optimal removal of suspended solids of the water from the RAS system and optimization of the design of the RAS and the hydroponic system.

Need for removal of suspended particles

The optimal removal of the suspended solids serves multiple purposes:
a) The removal of suspended solids to an acceptable level is important to reduce the biological oxygen demand of this water. This in order to avoid the development of an environment with insufficient oxygen for the roots of the tomato plant (Suhl et al. 2019).
b) By reducing the biological oxygen demand of the water from the RAS system, the chance of denitrification, the process by which bacteria convert nitrate into nitrogen gas (N_2), will decrease. In this way, the maximum possible amount of nitrate (NO_3^-) becomes available for the cultivation of tomatoes (Suhl et al. 2018).
c) The optimal removal of suspended solids can also result in water savings as the water lost in a RAS system by removing suspended solids is highly dependent on the type of mechanical filter installed.

Removal of particles present in the irrigation water is also a fundamental requirement for drip irrigation to avoid clogging problems (taking into account the small size of the dripper outlet). Clogging reduces irrigation uniformity and can provoke a decrease in water and nutrient use efficiency and crop yield. As a general rule, it is recommended to install a filtration system after the fertigation equipment with a maximum gap size of 1/10 of the dripper outlet. However, special attention must be paid to closed soilless growing systems using organic substrates because drain water tends to contain organic particles which can interfere with some disinfection techniques such as UV disinfection. Technologies available for crude filtration are Sieve bend screen Filters or Hydrocyclones and for fine filtration Rapid sand filtration, Cloth filtration, Disc filtration, SAF filtration, Drum filtration and Microfiltration (Fertinnowa, 2018).

Optimization dimension RAS and hydroponics system

The RAS system produces independently of the season and in principle supplies the same amount of water every day. The water requirement of the hydroponics system for the cultivation of tomatoes, however, varies as it does not concern continuous cultivation. In the main example of the cross-over, the RAS part is designed on basis of the minimal water use of the hydroponics system and the assumption that all water required for the cultivation of fish is reused for the cultivation of tomatoes. Yet, as shown in the other examples other options are possible (e.g. water buffer system).

3.2.9 Possibilities for further embedding in the circular economy

Use of CO_2 from the fish by the tomato plants

The production of ± 140 tons of tilapia releases ± 120 tons of carbon dioxide (CO_2). This is now removed from the system via ventilation. In the Netherlands, fossil fuel is currently used to increase the CO_2 concentration of the greenhouse air to benefit the tomato plants. This addition of CO_2 into the greenhouse varies between 25-40 kg CO_2 per m^2 per year or 1000-1600 tons per year for a cultivation area of 4 hectares. When the CO_2 from the fish can be used for tomato cultivation, this can result in significant savings on the use of fossil fuel and thus the production of CO_2.

Possibilities for reuse of phosphate and other nutrients from the RAS system

The current model for the cross-over is based on the production of nitrate (NO_3^-) in the RAS system. The production of nitrate in the production of ± 140 tons of tilapia is ± 27 tons. However, the production of ± 140 tons of tilapia also releases ± 0.8 tons of phosphate and 0.6 tons of potassium. If all or part of this can be captured and used for the cultivation of tomatoes, further savings may be made on the use of fertilizers.

Table 5 ***Impact and possible savings of integration of aquaponics with tilapia and greenhouses tomato production.***

Design option	1	2	3	4	Unit
Main design parameters					
Water use horticulture	2.6	2.6	6.0	6.0	l m^2 d^{-1}
NO_3-N concentration	12	26	26	12	mmol l^{-1}
Area greenhouse	4.0E4	4.0E4	4.0E4	4.0E4	m^2
Water buffer	No	No	Yes	Yes	
Size water buffer	NA	NA	4.9E4	4.9E4	m^3
Evaporation RAS system*	5.1E2	1.1E3	2.6E3	1.2E3	m^3 y^{-1}
Production parameters					
Fish	140	300	700	320	ton y^{-1}
Dry matter from fish	35	75	170	80	ton dm y^{-1}
Protein from fish	21	45	110	49	ton dm y^{-1}
Fat from fish	7.7	16	38	18	ton dm y^{-1}
WUE tomatoes	46	46	46	46	kg m^{-3}
WUE fish	3.7	8.1	8.1	3.7	kg m^{-3}
WUE total	50	54	54	50	kg m^{-3}
Water	3.8E4	3.7E4	8.6E4	8.7E4	m^3 y^{-1}
N	6.1	13	31	14	ton y^{-1}
P	0.8	1.8	4.1	1.9	ton y^{-1}
K**	0.6	1.4	3.2	1.4	ton y^{-1}
CO2 fertilizer	9-13 to 33-47	21-31 to 70-100	50-72 to 162-232	9-13 to 33-47	ton y^{-1}
CO2 GH enrichment	120	260	600	280	ton y^{-1}
Mineral parameters					
Ca	1.1	2.4	5.5	2.5	ton y^{-1}
Mg**	0.2	0.4	0.9	0.4	ton y^{-1}
Cl**	1.0	2.2	5.1	2.3	ton y^{-1}
Cl**	0.4	0.8	0.8	0.4	mmol l^{-1}
Fe	67	140	330	150	kg y^{-1}
Na**	5.1E2	1.1E3	2.5E3	1.2E3	kg y^{-1}
Na**	0.6	1.3	1.3	0.6	mmol l^{-1}
Cu	3	6	14	6	kg y^{-1}
Sludge parameters					
Estimation 1					
Sludge production (20% dm)	45	96	220	100	m^3 y^{-1}
Water loss	36	77	180	82	m^3 y^{-1}
Dry matter	9	19	45	20	m^3 y^{-1}
Estimation 2					
Sludge production (2.5% dm)	9.0E2	1.9E3	4.5E3	2.0E3	m^3 y^{-1}
Dry matter	22	48	110	51	ton y^{-1}
Estimation 3					
Based on 80% dm digestibility	35	75	180	80	ton y^{-1}

* Estimated using average air humidity (inside vs. outside), temperature (inside vs. outside) and ventilation loss due to aeration (CO2) in the RAS system, E2=100, E3=1,000, E4 = 10,000

** Maximum. With these figures the retention of these minerals in the fish that is produced and harvested from the system has not (yet) been taken into account. In addition, these numbers are amongst other things, highly dependent on the formulation of the feed and should therefore be seen as an indication.

In table 5, four designs with different NO_3^- concentrations or different amounts of water use, including water buffering, are taken into account. Option 1 represents minimal water use, a low NO_3-N limit and no storage of water. In option 2, the NO_3- N concentration is higher whereas water use and water storage is similar to option 1. Options 3 and 4 include water buffering systems and both have high water uses but differ in NO_3-N concentration

3.3 Algae production within aquaponics

Within the project AlgaeLinkages (TKI-AF14322) the potential for the production of algae on discharge water from greenhouses of United Farms – Finka in Queretaro Mexico is being investigated. The algae studied is *Nannochlopsis limnetica*, a freshwater microalga that contains valuable proteins and omega-3 fatty acids. AlgaeLinkages has demonstrated that algal biomass can be produced at pilot-scale thereby reducing nutrients such as NO_3^- and PO_4^{-2} in the discharge water. The harvested biomass was oven-dried in Mexico, transported to the Netherlands and included in feed for laying hens. Laying hens fed with 1-3 % algal biomass (dry weight) produced eggs that were enhanced in omega-3 fatty acids, in particular docosahexaenoic acid (DHA) (Mens et al, 2020).

To integrate algal production and removal of nutrients from discharge water, with horticulture and aquaculture, the water and nutrient demand of algal production needs to be related to the availability of discharge water and its composition throughout different time periods. As indicated in earlier sections the amount of discharge water and its composition vary during the year and depend on the growth status of the plants, weather conditions, nutrient feeding and recycling strategies.

In this section, calculations have been made based on of the amount of discharge water that needs to be treated in a certain period, estimates and assumptions for algal productivity and production per year as well as algae biomass production and water demand in several days (harvests).

Cultivation time: In practice, algal growth is a semi-continuous batch process where part of the bioreactors is harvested at certain time intervals. Depending on the status of the culture, processes can run for a few weeks or for several month's but frequently the reactor needs to be completely harvested and cleaned for a new batch after 2-4 month. In general, 300 algal production days per year are considered as effective cultivation period.

Nutrients: In general, the amounts of nitrogen and phosphate in the greenhouse discharge water are above the needs for algae cultivation.

Production and productivity: An overall algal production per ha, when Nannochloropsis algae are produced in vertical photobioreactors (PBR) in Queretaro, is estimated at **54.000 kg dry biomass per year**. In the winter period, when less light is available, and temperatures are lower, productivity is lower than in summer. Although economics is not included in the current report, productivity in wintertime can be enhanced when cultures are heated early in the morning. In the summertime, in contrast, cooling of the bioreactors is needed. Upon harvest with centrifugation, the algal biomass has a dry matter content of about 25%. Consequently, on a hectare base, for 54 tons dry algal biomass, 216 tons wet biomass is harvested. This amount, however, is negligible when compared to the total amount of water in bioreactors.

Depending on conditions, the maximum amount of the microalga *Nannochlopsis limnetica* (based on dry weight) in a bioreactor may range between <1-5 gram per litre with a daily production ranging from 0.06 to 0.6 gram/l/day. In our calculations, we used an average biomass concentration of 1.44 gram per litre at harvest.

Calculations were based on:
- An algal production facility of 1 ha with photobioreactors (PBR)
- 25 PBR's with each a volume of 50 m^3; total volume of 1250 m^3
- Operational days per year: 300
- 100 harvests per year at 1.44 g dry matter algal biomass per litre
- A harvest of 375 m^3 per 3 days; (30% of total reactor volume of 1250 m^3)
- Total algal biomass production (dry matter basis) per year per ha:
    100 harvests per year x 375 m^3 x1.44 g/L= 54000 kg

Greenhouse water and nutrient supply

Based on the figures known from greenhouse management and as supplied by United Farms – Finka, and depicted in figure 2, the supply of water, as well as the available amounts of discharge water, may strongly vary. In summer, more cooling is required and consequently, more evaporation will take place. Furthermore, the concentration of minerals may vary. For nitrogen, we used the info from Table 2.

Our calculation of available discharge water per period is based on a 4 ha greenhouse area. With an estimated high-water input of 10 l/m^2/day, of which 75% will be evaporated and 5% used by plants, an amount of drain water of 80 m^3 or 2 l/m^2/day can be expected when no discharge water is circulated. (discharge water = input water - evaporation – plant utilization = (10 l/m^2/day x 40.000 m^2) – (0.75*400.000 l/m^2/day + 0.05*400.000 l/m^2/day) = 80000 l/m^2/day = 80 m^3). However, based on information from United Farms - Finka, this drain water is stored and reused several times before it is discharged. Consequently, 80 m^3 water is discharged (or available for algal production) per **3 days** instead of 1.

For re-utilization and nutrient removal of 80 m^3 discharge water (produced in 3 days) an area of about 80/375 x 1 ha = 0.215 ha PBR's is required.

Calculation: At 0.215 ha the total volume of PBR's is 0.215 x 1250 m^3 = 269 m^3. With 30 % harvest at harvesting time (i.e. every 3 days), the harvested volume is 0.3 x 269 = 80.6 m^3. With a biomass concentration of 1.44 g/l, 80.6 m^3 yields 116 kg dry algal biomass. Under conditions where algal growth and production is lower, this area needs to be enlarged.

Nutrient (NO3$^-$) removal from discharge water.

With 0.215 ha PBR's, and a harvest every third day, a yield of **116 kg algal biomass** is calculated. With an estimated protein content of 40 % the 116 kg algal biomass contains 46 kg protein. With a nitrogen to protein conversion factor of 5.8 and nitrogen to NO_3^- conversion of 4.43 (i.e. 62/14), an amount of (46/5.8) x 4.43 = 35 kg NO_3^- is required only for protein production in the harvested biomass when very efficient conversion takes place. Such an amount corresponds to **440 mg NO_3^-/l or 7.1 mM NO_3^- that can be removed** from discharge water by algae on basis of the indicated estimates and optimal conditions.

As discharge water from the greenhouses contains, on average 16.6 mM NO_3, the production of algae on discharge water can reduce its nitrogen content from 16.6 to 9.5 mM. A further reduction could be achieved when the algal water obtained after centrifugation is reused for a new batch of algal production. When this algal 'centrifugation water' would be used twice, the algal area to clean discharge water from the greenhouse could be doubled resulting in more algal biomass and even cleaner water. Such an approach, however, should also consider other relevant nutrients such as phosphorus. Furthermore, as algae production strongly varies during seasonal changes, crashes, maintenance, the amount of nutrients that would actually be removed can vary.

4 Measures to increase water use efficiency

This chapter focuses on general measures that can be taken to reduce the need for freshwater. It also reviews the consequences of total water use of horticulture integrated with aquaponics and algae production in the United Farms – Finka system settings.

For all crops and cropping systems, it is essential to maintain an acceptable quality of irrigation water with regards to salinity and the composition of chemical elements and compounds. In addition to crop species, the type of cropping system influences the required water quality. For soilless growing systems with recirculation of drain water, the requirements for the quality of irrigation water, regarding salinity, Na and Cl, are high in order to ensure that the accumulation of these components during recirculation starts from relatively low base values.

Based upon the current situation at United Farms – Finka (as an example situation) and with the aim for integration of aquaponics and algae production with greenhouse horticulture, there are a number of options and technologies available for minimizing the total need for extracted groundwater as a freshwater resource:

1. Minimizing losses by good water management practices
2. Improving the quality of the used groundwater before irrigation
3. Alternative water sourcing by rainwater harvesting using basins
4. Use of higher sodium levels in irrigation water
5. Recovering discharge water from the horticulture greenhouses

4.1 Minimizing water losses by good water management

When considering the reduction of water intake, the first step to investigate is the prevention of water losses by good housekeeping measures. Good housekeeping measures are relatively simple and cheap measures that reduce the need for the intake of freshwater resources. Examples of this can be to minimize losses in drainage (lining storage basins) or by evaporation (covers, underground storage). In order to do this, the different water flows at the specific location first have to be identified. In all previously known cases, the participating companies gained a greater insight into the water flows that in many companies had become increasingly complex over time. Simplifications sometimes turned out to be possible and led directly to savings in water use.

4.2 Improving the quality of the water used for irrigation

Another measure that is relatively easy and adequate to take, is to improve the quality of the well-water used as the source for irrigation water. The supply of irrigation water of adequate quality is a fundamental factor for horticultural crop production. Crops differ appreciably regarding their sensitivity to salinity. Consequently, quantitative criteria have been established for individual crop species, related to the chemical quality of the irrigation water for optimal growth and production. The chemical quality of irrigation water can differ considerably depending on the region, water type, the nature of the aquifer etc. One of the fundamental issues is the presence of sodium in the ingoing water. Decreasing the sodium level in input water will decrease the amount of water to be discharged. This could be done **by capturing rainwater** to mix with well water **or installing a reverse osmosis** system right after the well.

In general, optimal water quality management requires maintaining the concentration of nutrients and salinity at the desired level, and the removal of unwanted components, such as particular elements and compounds. When nutrient solutions are recirculated, accumulation of ballast salts occurs. These ballast salts are salts that are consumed only in minor amounts by the crops. When the concentration of these salts increases appreciably, phytotoxic effects can occur.

Sodium commonly causes problems in European coastal areas but also in Central Mexico, where horticultural production takes place. By maintaining low levels of Na in the irrigation water, water can be recycled for longer, and the frequency of purging recirculating water is reduced. In soil-grown crops, Sodium accumulation can also negatively affect crop growth and production.

Numerous technologies are available to optimize the quality of water being introduced into the fertigation system for irrigation/fertigation. Water from different types of water sources can have different treatment requirements. These technologies can be considered as being in four general groups of techniques of 1) altering chemical composition such as desalination, 2) particle removal, 3) algal removal, and 4) disinfection. Some of these technologies are also applicable to recirculating nutrient solutions.

The tools and techniques for modifying chemical composition include (a) various physical methods, for the removal of unwanted chemical components, such as reverse and forward osmosis, ion exchange, electrodialysis, and nanofiltration amongst others, and (b) chemical methods such as pH adjustment. The tools and techniques for particle removal include a wide variety of filtration methods. For the control of algae in storage basins, a wide range of diverse techniques are available; amongst others, these include a control with different chemicals, the use of aquatic plants or fish, the use of introduced bacteria and enzymes, the use of blue dye, the use of introduced water fleas, and the use of ultrasound technologies. A similarly wide range of diverse techniques is available for the disinfection of incoming water or recirculating nutrient solutions where recirculation is practiced. These include chemical addition (e.g. peroxide, chlorination, and acid), filtration systems (sand, biofiltration), physical processes (thermal disinfection and ultraviolet disinfection) and physio-chemical processes (photocatalytic oxidation, ozonation, procedures). More information on these technologies can be found in The Fertigation Bible, www.fertinnowa.com

4.3 Rainwater harvesting using basins

In horticultural production, considerable volumes of water are commonly required for irrigation to ensure optimal growing conditions for the crops. The large amounts of water required and the high price of tap water in most areas force growers to use other sources of water like groundwater. Associated with increasing competition for limited freshwater resources, are the declining availability and quality of freshwater resources. This particularly applies to groundwater resources in many regions. It is not uncommon for the extraction of groundwater for irrigation, and other uses, to exceed natural replenishment, a situation known as ‘over-pumping’ which results in that the depth at which groundwater is encountered is dropping, indicating a reduction in the volume of aquifer water, which is known as ‘aquifer depletion’. Consequently, the wells to extract water must be made progressively deeper, thereby increasing pumping costs. In coastal aquifers, declining piezometric levels remove or substantially reduce the positive pressure of aquifer water at the interface with seawater. This can result in ‘saltwater intrusion’ when highly saline seawater enters the aquifer at the land-sea interface, making the aquifer in those regions unusable for irrigation. Drainage from crops receiving irrigation has a higher salt concentration than the irrigation water applied because of fertilizer addition, the leaching of salts in the soil, and crop evapotranspiration. When this more saline drainage water enters underlying aquifers, it contributes to the salinization of the aquifers. As this groundwater is later used for irrigation, a cycle of increasing salinization takes place. This is an issue in many drier regions where groundwater is commonly used for irrigation and the soils generally have higher contents of salts.

Where the climatic conditions are suitable, a good option is to use rainwater. In more humid regions, sufficient rainwater can be collected to meet the entire irrigation requirement of crops. In drier regions, rainwater collection can partially meet irrigation requirements, thereby reducing the demand on other water sources (e.g. groundwater). To enable the use of rainwater, there are practical issues that must be considered such as the collection of water, storage systems and the variability of rainwater in terms of quantity, timing and quality. Additionally, current legislation must be considered.

In Mexico, the collection of rainwater with an average yearly precipitation of 559 mm, has potential. There is a clear wet season that spans from June to September. These 4 months account for about 75% of yearly rainfall. In comparison, the Netherlands receive on average 874 mm of rain per year (Servicio Meteorológico Nacional and KNMI).

It is however a misconception to consider rainwater as 'free' or 'very cheap' water. In many regions, the use of rainwater requires large-scale water storages, for example, a net volume of 5000 m³/ha of soilless greenhouse tomato production is required in North-West Europe to fulfil the yearly freshwater demand of the crop. The construction of this storage capacity is costly (4-45 €/m³ storage capacity, land costs excluded) depending on the type of water storage considered. If you want to cover the crops freshwater demand throughout very wet and very dry years, a large volume of water has to be buffered. In the wet years or months, extra water can then be stored for use in the dry years or months. So, to fulfil the last percentages of the crops water demand by use of rainwater, a serious enlargement of the water storage, leading to higher installation costs, is required.

Table 9 Main types of water buffering solutions (Fertinnowa).

Technology	Cost installation	Costs Maintenance	Remarks
Lined water basin, >1000m^3	4-45€/m3	algae control + 5% of installation cost	
Lined water silo, <500m^3	23€/m3	idem	Depth is limited Top 0.5 m buffer area Lower 0.5 m unavailable: sediments and too hot (low water levels)
Ferro concrete reservoir (preformed)	1.5 - 2 m³: 500 €/pc.: incl. delivery, digging and installation Pipes: 5 €/m	NA	Available for water storages smaller than 20 m³
SubSoil Water Storage	25000 - 50000 € per installation	NA	Water availability depending on water layers in the underground

4.4 Allowing higher sodium levels in irrigation water

Too high levels of sodium in irrigation water can damage crops and is one of the main reasons for the discharge of the water. The cause of the damage from sodium (Na) stems from the osmotic effect (EC effect) or the specific effect of the sodium ion itself. A high sodium content displaces other cations, such as potassium (K), calcium (Ca) and magnesium (Mg). An increase in sodium levels in the root environment results in a higher absorption by the plants. In order to prevent crop damage, a grower wants to limit sodium accumulation. This can be done by using clean irrigation water with a low concentration of sodium and applying pure and low-sodium fertilizers.

The current standards most growers apply for acceptable levels of sodium were generated more than 25 years ago. In the meantime, cultivation methods and insights have changed and currently, these standards are reviewed again. To allow the plants to absorb more sodium, a grower can make use of the 'EC space', by using the difference between the target value of the EC and the minimum nutritional value of the EC. For example, with a nutritional schedule for tomatoes, with a nutritional EC of 2.8, the corresponding amount of sodium is approximately 8 mmol/l and with a maximum EC of 3.5 approximately 17 mmol/l sodium. At Wageningen University and Research, Greenhouse Horticulture, trials with pepper were conducted into the effects of a high sodium concentration up to 10 mmol/l. Until mid-October, no differences in production and no abnormal symptoms were observed on the crop. In the summer months, however, there was a slight increase in nose rot fruits, whereby the percentage increased with a higher sodium content. The effect was less when the K/Ca ratio was lowered. Currently there is a cultivation trial running with tomatoes. In the experiment with paprika, sodium values up to 10 mmol were found to cause no problems. From the current research, which will run until the end of October/beginning of November, sodium values of 20 mmol/l also seem to have little or no effect on the cultivation.

Reviewing the quality data of the drain water at United Farms – Finka, with an average sodium level of about 7 mmol/l, it can be expected that while keeping higher sodium levels, for example at a regarded as safe level of 15 mmol/l (or even 20 mmol/l), the amount of discharge water can significantly be reduced to almost half. An additional benefit of this is that also loss of nutrients can be reduced, limiting pressure on the environment and leading to cost-savings on purchase of these (Voogt, 2020, Glastuinbouw Waterproof, 2019).

4.5 Recovering discharge water

The same technologies described to improve on the quality of the irrigation water can also be used to recover purged or discharged water from the horticulture greenhouses. For the United Farms – Finka case study, the maximum amount of water discharged is about 3.3m^3/hr, mostly because it contains too much sodium. This maximum discharge flow of 3.3m^3/hr can be quite significant compared to the total intake of approximately 2.6 – 11 m^3/hr.

Various ‘end-of-pipe’ solutions are available for nutrient removal and recovery from water discharge from crops. The nutrient removal and recovery techniques include physio-chemical procedures such as adsorption media for phosphorus, electrochemical phosphorous precipitation, and modified ion exchange, and biological approaches such as nutrient removal in constructed wetlands, moving bed biofilm reactors, and the use of duckweed. For water recovery, technologies such as reverse osmosis (RO) are suitable, producing both clean and sodium lean water as well as a concentrated stream containing sodium and nutrients often referred to as RO brine.

5 Conclusions and recommendations

To reduce water consumption per kg food product and stimulate the circular economy, Wageningen University and Research conducted a study on possibilities for integration of tomato production in greenhouses and land-based aquaculture in the Queretaro region in Mexico.

The main outcome of this project is specific knowledge about how to combine and integrate local greenhouse production of high-quality vegetables such as tomatoes with land-based aquaculture and algae production in the central region of Mexico. The system integration is based on the concept of aquaponics to increase water use efficiency and improve wastewater management, thereby reducing the environmental impact.

The integrated concept of 4 ha greenhouse operations combined with aquaponics and algae production results in improvement of water use efficiency.
The water use efficiency in terms of kg food per m^3 is increased by producing fish and vegetables and algae using the same amount of water. Depending on systems used, the amount of fish produced in such a system may range from 140 – 700 ton per year wet weight, or 35 – 170 ton dry matter per year and an algal production of 10 – 12 tons dry matter. Furthermore, compared to standalone RAS and greenhouse operations, a decoupled aquaponic system also offers efficient use of nutrients.

The most efficient systems configuration of combining the water and nutrient flows between these three production systems is:

- An aquaculture system at the beginning of the water system supply (decoupled aquaponics setup)
- Followed by a greenhouse production system such as United Farms – Finka has
- Use discharge water for algae production in a photobioreactor.

Although not part of the specific research question but relevant for efficient water use, a number of options and technologies available for minimizing the total need for extracting groundwater as a freshwater resource are briefly indicated:

1. Minimizing losses by good water management practices
2. Improving the quality of the used groundwater before irrigation
3. Alternative water sourcing by rainwater harvesting using basins
4. Use of more salt-tolerant crop species
5. Recovering drain water from the horticulture greenhouses

The calculations and integration of the different production systems are based on a 4 ha greenhouse area and our best estimations of data. Implementation of such integrated systems at scale, however, would first need follow-up pilot experiments under (highly variable) local conditions. Furthermore, information from pilot-scale could also be the input for a techno-economic evaluation.

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