Tampere University of Applied Sciences

Aquaponics

Optimizing the energy consumption of a water treatment apparatus in a novel multi-loop aquaponic system

Jani S.R Aziza

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ABSTRACT

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Aquaponics
Optimizing the energy consumption of a water treatment apparatus in a novel multi-loop aquaponic system

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The main aim of this thesis was to optimize the energy consumption of a pre-studied novel multi-loop aquaponic system by operation and design modification, with a purpose to advance aquaponics as a method towards sustainable food production.

Compared to traditional aquaculture and hydroponics, practices that do not share their resource utilization, aquaponics can be an energy efficient method for food production. Though aquaponics is a major area of interest, is insufficient study has been carried out on the optimization of the systems overall energy consumption.

A project was initiated for a medium-scale deep water culture (DWC) novel aquaponic system in the National Center for Mariculture (NCM) in Eilat, Israel. The research institution is a branch of the non-profit governmental corporation Israel Oceanographic and Limnological Research (IOLR). The corporation works under the Ministry of Environment regulations.

A preliminary study was conducted on the novel aquaponic system during the construction process. The system was characterized, and the novel aquaponics water treatment apparatus was investigated for energy efficiency improvements. A Recirculating Aquaculture System (RAS) in NCM premises was utilized to conduct necessary analytical research on-site.

Unit power and operation time was characterized. Nitrogen treatment units were evaluated, specifically analysing protein skimmer and nitrification biofilter. Alternative technologies were examined for the biofiltration unit.

The direct outcome of this study enhanced the approach towards alternative solutions for the water circulation treatment system of the initial model. The results of this thesis optimized aquaponics energy efficiency and were applied in practice on the design and construction of the novel multi-loop aquaponics system. Furthermore, the thesis results further assisted in the development of a novel RAS with onsite nutrient recovery concept.

Key words: aquaponics, hydroponics, mariculture, energy efficiency, aquaculture, recirculating aquaculture systems, biofilters, protein skimmer

CONTENTS

ABBREVIATIONS

CSTR	Continuously Stirred-Tank Reactor
DO	Dissolved Oxygen
DP	Dissolved Protein
DWC	Deep Water Culture
FBBR	Fixed Bed Biofilm Reactor
IOLR	Israel Oceanographic and Limnological Research
MBBR	Moving Bed Biofilm Reactor
NCM	National Center for Mariculture
PBR	Packed Bed Reactor
PFR	Plug Flow Reactor
RAS	Recirculating Aquaculture System
TAN	Total Ammonium Nitrogen
UASB	Up-flow Anaerobic Sludge Blanket reactor

1 INTRODUCTION

Aquaponics is the combination of mariculture (fish cultivation) and hydroponics (soil-less plant cultivation), where symbiosis occur by bacteria in a closed loop environment. Fish excrement is used as a source for plant nutrients, whilst plants uptake nutrients that are harmful for the fish. Braungart, McDonough & Bollinger (2007) described aquaponics as a resource efficient closed loop food production system that relates to cradle-to-cradle design and considers social, economic, and environmental benefits.

Compared to traditional aquaculture and hydroponics, practices that do not share their resource utilization, aquaponics is an energy efficient method for food production. It is compiled of energy consuming components that require continuous control, especially in industrial scale, where automation is highly demanded, and larger flows are required. (Karimanzira & Rauschenbach 2018)

Improving the energy efficiency of aquaponic systems can contribute to the sustainability of future food production ensuring food security, advancing aquaponics research and provide alternatives for conventional aquaculture and agriculture. Studies on the globally increasing food demand present a gap that needs to be covered with alternative innovations, and to reduce the environmental impact of current traditional agriculture. (Tilman, Balzer & Befort 2011)

Even though aquaponics is a major area of interest, is insufficient study has been carried out on the optimization of the systems overall energy consumption, mostly consumption related to continuous operation of the water treatment units (Yogev, personal communication, April 11, 2022). This may well be due to the fact that there are various practices and models that address the same output with different processes and are based on numbered system designs (Thorarinsdottir 2015). There may be several cause factors such as climate control, where systems are in demand for cooling or heating, relative humidity, or other variables that are depended on the geographical location (Alkhalidi, Khawaja & Abusubaih 2020).

This thesis concentrates on a medium-scale research aquaponic system, where energy efficiency was improved successfully by altering operation methods and components of the water treatment apparatus.

The thesis is conducted for the National Center for Mariculture (NCM) in Eilat, Israel. The research institution is a division of the non-profit governmental corporation Israel Oceanographic and Limnological Research (IOLR). The corporation works under the Ministry of Environment regulations.

1.1. Experimental model and scope of study

In the Grow-out Systems division of NCM, a project was launched in early 2022, with a mission to build a novel multi-loop aquaponics. The system was designed by Uri Yogev, principal investigator of the division. The system was under construction during the research process, and it is planned to operate in the beginning of 2023. The preliminary study in this thesis is conducted on the novel multi-loop aquaponic system.

Furthermore, there are egg-to-plate Recirculating Aquaculture Systems (RAS) in the NCM institution. The practical (analytical) part of this work is based on a particular semi-commercial RAS in the premises of the institute that shares a similar concept with the water treatment unit of the pre-studied, multi-loop aquaponics.

The scope of the work done in this practical thesis includes the water treatment units of both the semi-commercial RAS, and the novel multi-loop aquaponics in NCM Eilat, Israel.

1.2. Study objectives

The main purpose of this study is to improve the energy efficiency of the pre-studied novel multi-loop aquaponic system, and to advance circular economy-based food production technology.

Hypothesis

Energy consumption of the pre-studied aquaponic system can be reduced by operation and modification of the water treatment unit.

Goals

Scope of study is established to answer the research question by the following specific goals:

- Characterize energy usage of water treatment components in the studied aquaponic system. Both in term of the unit energy consumption (power) and time of operation.
- Testing nitrogen treatment units. Specifically analysing organic matter removal efficiency of the protein skimmer and nitrification biofilter units.
- Review and possibly test less energy demanding alternatives for the nitrogen treatment units.

2 LITERATURE REVIEW ON AQUAPONICS

This chapter is dedicated to aquaponics research and development related literature from the point of view of energy consumption.

It is found that many experimental aquaponic systems are built around design and modelling of nutrient utilization, increased fish or plant growth, smart water consumption, sludge treatment and efficient removal of toxic compounds (Thorarinsdottir 2015). Likewise assumed, literature itself advises to continuously improve and optimize aquaponic systems (Junge, et al. 2017), and does not discuss particularly on energy efficiency matters in a profound approach. Moreover, aquaponics energy efficiency is mostly a variable of geographical location, where challenges of cooling or heating are tackled (Alkhalidi, Khawaja & Abusubaih 2020).

Discussed issue between professionals from sectors of both agriculture and mariculture, is the paradox of mariculture experts that grow plants as opposed to agriculture specialists who farm fish, a pattern that may reason the development of various distinctive practices. However, optimising the system energy efficiency without altering the values of water quality, nutrient utilization, fish, or plant production, is a field that requires further investigation in order to find a common update to all forms of aquaponic systems by means of global standards. (Yogev, personal communication, April 10, 2022).

2.1. Main nitrogen transformations

Fish feed in RAS is the sole nitrogen supply to the system. Approximately 25 percent of the feed is assimilated as fish biomass (Boyd, 2015; Neori et al., 2007; Yogev et al. 2017). The fate of the remaining 75 percent is in the fish excretion, where 35 percent comes from the fish gills as unionized ammonia and 40 percent as sludge (Boyd, 2015; Heinsbroek and Kamstra, 1990; Neori et al., 2007; Yuen and Chew, 2010). Ammonia (NH_3) at low concentrations as 0.08 mg/L, is extremely toxic for fish. Concentrations of 1.43 mg/L is already fatal for most fish

species (Randall and Tsui, 2002; Timmons and Ebeling 2013). The interaction of water with ammonia produces ammonium (NH_4^+) when it is in equilibrium (Formula 1). Ammonium is considered to be less poisonous to fish.

$$NH_3 + H_20 \leftrightarrow NH_4^+ + OH^- \quad (1)$$

The sum of both nitrogen forms is called Total Ammonium Nitrogen (TAN) and can be described as in Equation 2 below.

$$TAN = NH_3 + NH_4^+ \quad (2)$$

In RAS, there are several types of biological filters used for the nitrification process, such as trickling filters, floating bed filters, moving bed reactors, fixed bed reactors and bio disks (Guerdat et al. 2010; Malone and Beecher 2000; Pfeiffer and Wills 2011; K.I. Suhr and Pedersen 2010). Variables that affect the functionality and efficiency of the biofilters ammonia removal are alkalinity, pH, dissolved oxygen (DO), and temperature.

A primary method to microbiologically oxidize ammonia to nitrate (NO_3^-) in a RAS is the nitrification process (Guerdat et al. 2010; van Rijn 1996). An aerobic chemosynthetic autotrophic bacterium obtains energy from inorganic compounds in the nitrification phase, where ammonia is utilized as an electron donor and carbon dioxide (CO_2) as carbon source. Few bacteria, found in the aquaculture systems, can complete the nitrification process. Ammonia is first oxidized to nitrite (NO_2^-) (Formula 3), and then nitrite is oxidized to nitrate (Formula 4). This process occurs in two phases as demonstrated below. (Timmons and Ebeling 2007)

$$55 \cdot NH_4^+ + 5 \cdot CO_2 + 76 \cdot O_2 \rightarrow C_5H_7NO_2 + 54 \cdot NO_2^- + 52 \cdot H_20 + 109 \cdot H^+ \quad (3)$$

$$400 \cdot NO_2^- + 5 \cdot CO_2 + NH_4^+ + 195 \cdot O_2 + 2 \cdot H_20 \rightarrow C_5H_7NO_2 + 400 \cdot NO_3^- + H^+ \quad (4)$$

Simplified Molecular formula for the oxidation of nitrite to nitrate (Formula 5), excluding cell formation, can be written generally as:

$$NH_4^+ + 2 \cdot O_2 \rightarrow NO_3^- + 2 \cdot H^+ + H_20 \quad (5)$$

Given from the upper mentioned formulas, one can observe that two moles of DO are consumed per one mole of TAN removed. Typically, biofilters are supplemented with aeration to provide efficient TAN removal.

2.2. Recirculating aquaculture systems

RAS is the most popular alternative for traditional fish farming out of several commonly used practices outdoors such as raceways, lake, or ocean fish cages. RAS is an inland tank-based system that grows fish in high density at a controlled environment. RAS method is based on aeration, particulate matter removal, biofiltration and pH buffering, where fish excrement is constantly releasing ammonia to the water cycle. The biofilters convert the ammonia into nitrate in two phases. Water with non-toxic concentrations of ammonia is fed back to the fish tank. (Halvorson & Smolowitz 2009)

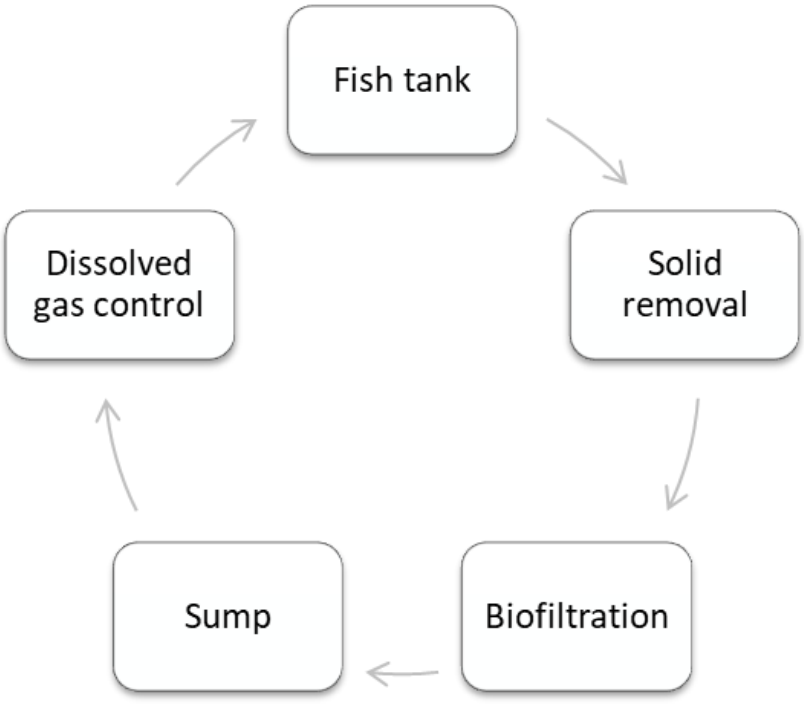


FIGURE 1. Schematic overview of a RAS

Reducing water consumption through circulation and increasing fish production in a controlled environment, led to increased interest in the recent years, whilst developing RAS technology in the process. Quality maintenance of the circulating

water is controlled via solids, ammonia, and CO_2 removal. Similarly, feed, temperature, DO, and pH are monitored and controlled. Improvements of RAS technology, with emphasis on biofiltration and sludge management, gained popularity in the field of aquaponics, where RAS and hydroponics are integrated to a multitrophic production system. (Thorarinsdottir 2015)

2.2.1 Three loop RAS

The system is composed of a fish tank, solid filter, two biofilter units, Up-flow Anaerobic Sludge Blanket reactor (UASB), and denitrification unit (Figure 2). The first loop serves as the basic RAS, where water treatment occurs via nitrification. The second loop uptake the nitrate rich water and the backwashed solids from the first loop to the denitrification process. The third loop is pumped with the biomass effluent from the second loop to the UASB for biogas production. (Yogev et al. 2017)

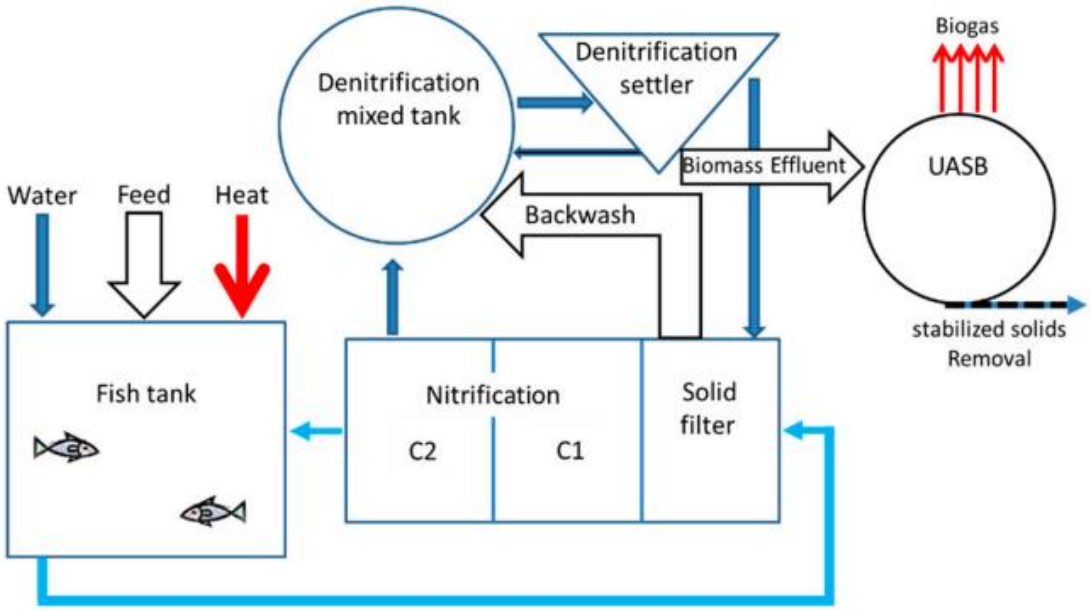


FIGURE 2. Near zero waste RAS (Yogev 2017)

Though three-loop RAS is efficient in nitrogen removal, the denitrification process has two main challenges to be addressed, nitrogen loss as potential feed (up to 70 percent) (Yogev et al. 2017), and emissions of nitrous oxide (N_2O) to the atmosphere (Bouwman, 1998).

2.3. Basic aquaponics

In a one-loop aquaponic system (Figure 3), described as a coupled system, there is a continuous circulation of water between the fish tank and the plants. The water is treated before reaching the plant roots and typically treated again before the water returns to the fish tank.

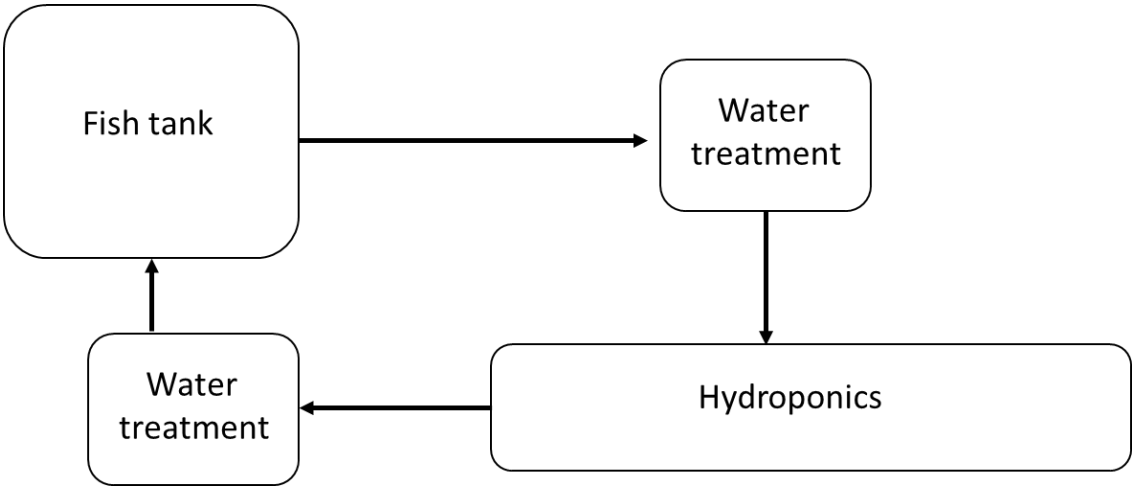


FIGURE 3. Schematics of a basic aquaponics system.

However, in a coupled system where plants and fish share the same environment, there is always a risk for potential pathogens. When a fish or plant pathogen is introduced into the water cycle, logically, obtaining an optimal growth becomes economically cost ineffective. Therefore, a physical separation was in demand to overcome this limitation. (Thorarinsdottir 2015)

2.4. Decoupled aquaponics

Multi-loop aquaponic system (Figure 4), described also as decoupled aquaponics, is the development of a one-loop aquaponic system. Decoupled system provides the solution for mitigating the risk where a pathogen is released into the water circulation by physical separation. The water flow is controlled to override the circulation of the infected unit whenever in need, and optimal growth is maintained cost effectively. (Thorarinsdottir 2015)

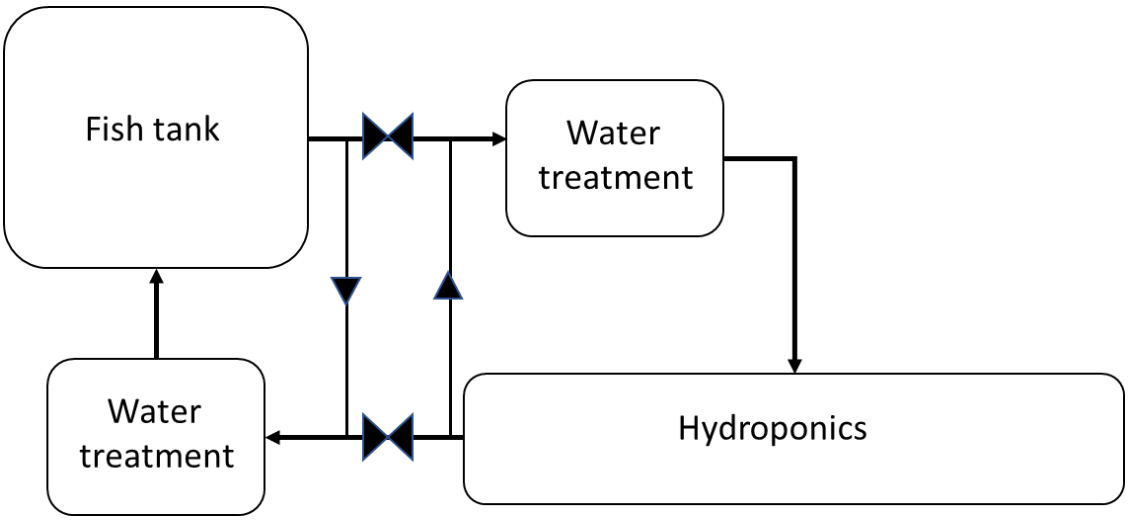


FIGURE 4. Schematics of a decoupled aquaponics.

However, studies have shown that there are improvements needed regarding the sludge management processes. Therefore, to address organic matter separation, a novel multi-loop aquaponic system was introduced. In aquaculture, approximately 40% of the organic matter is processed as sludge discharge. Typically, the sludge is utilized as fertilizers, compost, or discharged to water sources. (Yogev et al. 2016)

The composition of many aquaponic models are enhanced with renewable energy sources, and the focus is on Hybrid Energy Systems (HES) operation efficiency (Karimanzira & Rauschenbach 2018). The pre-studied system in this thesis is based on the development of a near-zero exchange RAS, also called three-loop RAS (Figure 1).

2.5. Water treatment – solids removal

The first process of filtration in aquaponics is the physical separation of solids. Several filtration methods are used in different aquaponic systems worldwide. Choosing a solid filter unit is a matter of feasibility and volume of water filtered. (Thorarinsdottir 2015)

Following solid filtration methods are characterized in Table 1 below for their advantages and disadvantages.

TABLE 1. Characteristics of commonly used solid filters in aquaponics.

Type	**Advantages**	**Disadvantages**
Settling Tank	• Cheap • No electricity • Low maintenance	• Low water volume • Particle size dependent water retention time
Drum Filter	• Suitable for big farms • High water volume	• Electricity • High maintenance • Solid load depended on backflush
Sand Filter	• Easy operation • Removes fine particles	• Electricity • Pressurized • Clogging

The characteristics of solid filters are further described in several works (Lekang 2007; Timmons et al. 2007) where solid filtration of aquaponic systems is examined for their physical layouts and issues of cost effectiveness.

2.6. Water treatment – organic matter removal

Protein skimming, also called foam fractionation, is based on Adsorptive Bubble Separation (ABS) method, where fine particles and colloids are removed by introduction of micro-air bubbles to the water column (Lekang 2007; Timmons et al. 2007). Aeration produces bubbles into the water column and foams amphipathic organic molecules, such as proteins (Zimmerman et al. 2008). The elevated foam accumulates the fine particles and colloids before it is discharged from the water column by overflow to a collecting vessel (Picture 1).

PICTURE 1. Foaming protein skimmer in RAS (Yogev 2022)

Concentrations of suspended solids and dissolved proteins (DP), together with surface chemistry of the solids, affect the formation of foam in the unit. Protein skimmer removes efficiently fine particles and dissolved solids with particle size of under 100 micrograms (Brambilla et al. 2008).

A study done by Salameh (2016) on the removal efficiency of organic matter by a protein skimmer unit of a RAS in the University of Ben Gurion in Israel, demonstrated a notable potential in removing suspended solids and protein from aquaculture water. The study revealed potential energy demand reduction by removal of nitrogen rich organic matter and preventing ammonia.

Furthermore, foam formation itself occurs in the protein skimmer mostly after feeding. Many RAS operators have reported on the absence of foam formation in the protein skimmer during the day. It has been studied, that foam formation occurs mostly when DP concentration is more than 10 mg/L. Therefore, foam fractionation is feasible and practical only after 10 mg/L DP concentration is

reached. In terms of energy efficiency, the demand for continuous aeration of the protein skimmer should be investigated (Salameh 2016; Pers. Comm. Yogev 2022)

2.7. Water treatment - biofilters

The conceptual part of implementing aquaponics commercially in larger food production scales, lies in the management of the nitrogen cycle (Wongkiew et al. 2017). Most of the nitrifying bacteria is taking place in the aquaponics biofiltration unit (Bracino et al. 2020).

However, aquaponics has different technologies for biofiltration (Van Rijn 1996). According to the literature available, common biofilters in use are moving bed-bioreactor (MBBR), fixed bed-bioreactor (FBBR), trickling filter and sand filters (Thorarinsdottir 2015; Abubakar et al. 2022). Biofilters associated with the thesis are briefly covered below. Schematics of the units are visualized in Appendix 4.

Trickling filter - Utilizing gravity, the trickling filter function as a stationary media, where the water flow is downwards through the filter. The trickling filter is a cost-effective method since it has low maintenance and installation costs. Trickling filters are durable to organic loads and are efficient due to their ability to remove CO2 and oxygenation.

However, designing a RAS with trickling filter can be challenging since there is the aspect of surface area and size, which can be a limiting factor for an optimized APs. Moreover, weight, space ratio, homogenous water flow are aspects that should be addressed. (Greiner & Timmons 1998)

Moving Bed Bioreactor (MBBR) - The MBBR is a type of a continuous stirred-tank reactor (CSTR). The impeller located in the bottom of the reactor distributes the air, and it is powered typically by air pressure from a blower. The impeller has to provide enough mixing turbulence within the reactor to prevent sludge scale-up and settling or clogging of the nitrifying bids.

MBBR is cost effective, easy to operate and maintain, because of a low head loss and no need for backwash. (Pulkkinen et al. 2019)

However, aeration in the MBBR is mostly a function of sludge scale up prevention and it consumes energy. The aeration for the purpose of nitrification itself needs to be addressed when designing an optimized aquaponics system. (Yogev, personal communication, April 11, 2022)

FBBR - The FBBR is type of a packed bed reactor (PBR). It covers larger area that is treated, has high nitrification conversion rate. It has low-cost operation and can be easily made of recycled materials. However, FBBR demand for backwash is frequent and in typical RAS waters it is vulnerable to clogging. (Pulkkinen et al. 2019)

2.8. Dissolved oxygen demand in aquaponics water treatment unit

A vital parameter in aquaculture and hydroponics, hence in aquaponics, is dissolved oxygen. However, is insufficient study has been carried out on DO management in aquaponics (Bodenmiller 2017).

DO concentration control in aquaponics water treatment processes is crucial for the efficient removal rate of TAN. Due to fish health and welfare, DO and TAN concentrations should be maintained above 5 mg/L and below 1.5 mg/L respectively. The DO levels in aquaponics range typically between 7.5-8.5 mg/L. (Yogev et al. 2017).

Studies concerning the removal rate of TAN concentrations in RAS were conducted by Fernandes, Pedersen, and Pedersen (2017), and by Pulkkinen et al. (2019). The results of both studies implied that using FBBR or MBBR biofiltration method, are effective in producing recirculating water within acceptable limits. However, MBBR nitrification performance surpassed other biofiltration systems. (Abubakar et al. 2022)

3 MATERIALS AND METHODS

3.1. System overview – Novel multi-loop aquaponics

In February 2022, construction phase for a novel small-scale multi-loop aquaponic system was launched. The system is based on the integration of a three loop RAS and a decoupled aquaponics, hence novel multi-loop aquaponics. Moreover, the system was designed to tackle the challenges of nutrient loss and greenhouse gases (GHG) in RAS.

A layout for the system was designed (Figure 5) and the construction area was prepared accordingly to the plan. The aquacultural part of the system, or RAS, includes a fish tank and a water treatment unit with integrated HES (UASB reactor). The hydroponics unit is composed of five DWC growing beds in a separate green house, supplemented with fans, anti-infrared radiation sheets, pumps, air stones and moisturizing curtains. The whole system was monitored and controlled via control cabin, where a field laboratory was placed.

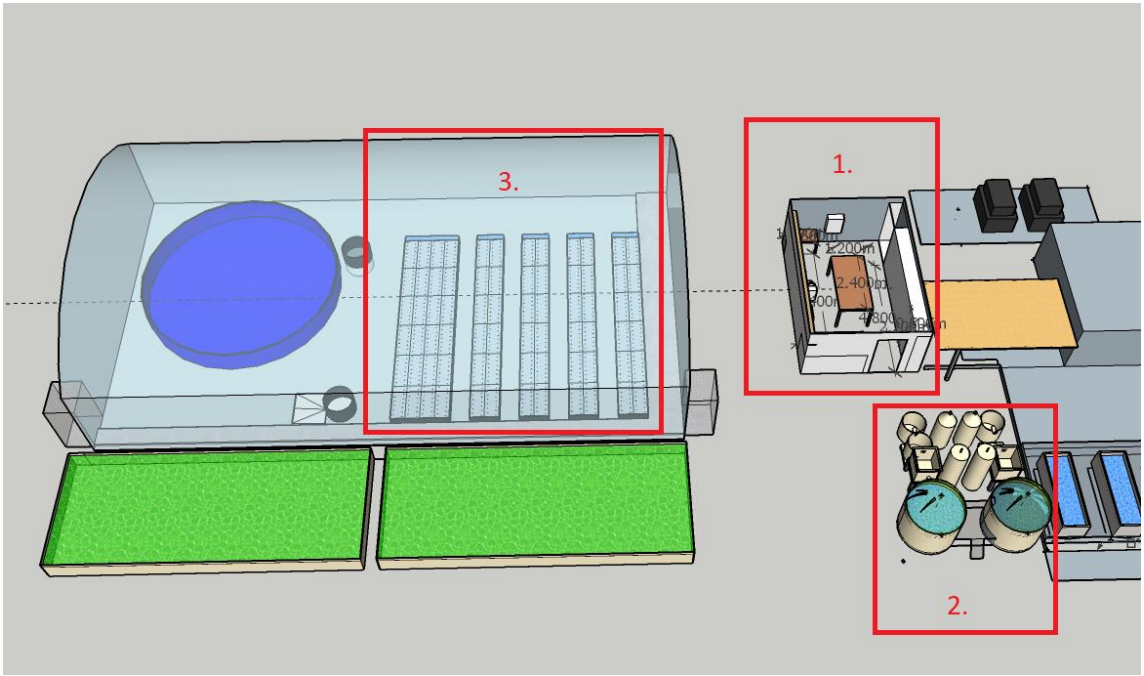


FIGURE 5. A model for the layout of the multi-loop aquaponics. 1. Control and in situ laboratory cabin. 2. Aquaculture and water treatment. 3. Hydroponics (Yogev 2022, edited)

The construction phase of the novel aquaponics took place during the whole research process and rated values of components were used to calculate the nominal power consumption of the water treatment system. A grow out RAS in NCM premises was utilized in practice to support or prove any theoretical assumptions, regarding the energy consumption reduction from operations of the aquaponics water treatment unit.

The system composition a fish tank, solid filter, protein skimmer, biofilters, and aerobic biofilter in the first loop. Hydroponics serves as the second loop to tackle the disadvantages of denitrification. Third loop is designed as two anaerobic digesters, where nutrients and carbon are recovered. Fish sludge enhance the plant growth and inedible plant biomass is used for biogas production.

3.1.1 Water treatment unit

The water treatment unit of the multi-loop aquaponics is partially governed by gravitational forces. Pumps were added to circulate the water to the UASB and the hydroponics unit, and back to the fish tank (Figure 6).

Initially, the water treatment unit included a drum filter, protein skimmer, two MBBR nitrification biofilters and a UASB reactor.

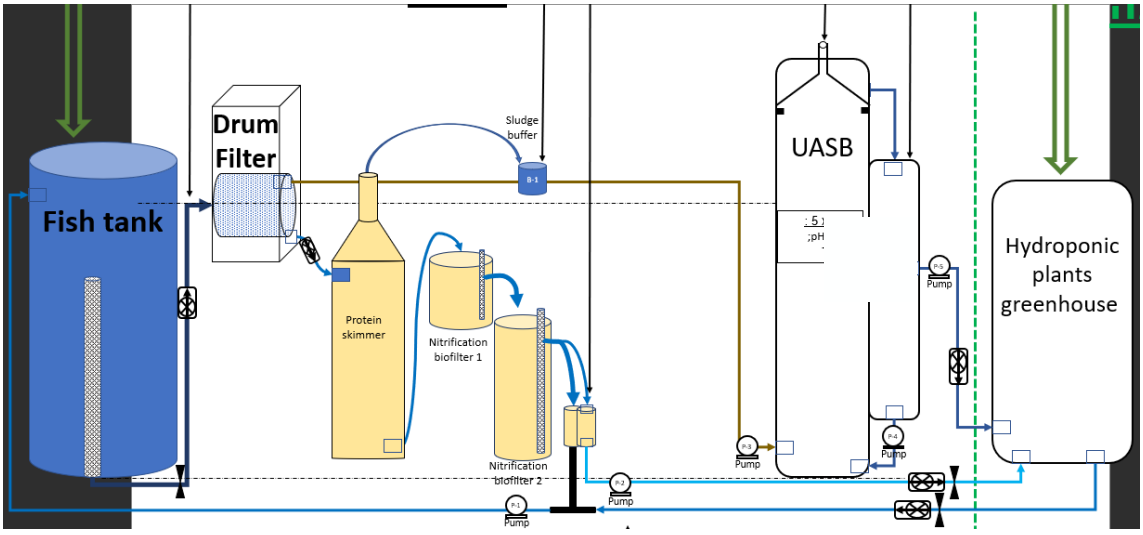


FIGURE 6. Layout of the water treatment unit. (Yogev, 2022, edited)

The water from the fish tank is transferred via airlift method towards the drum filter where solids are removed to a sludge buffer. The water flows from the drum filter to the protein skimmer, where suspended solids and DP are removed and directed to the sludge buffer. The sludge buffer discharge is pumped to the UASB. The filtered, ammonia rich water from the protein skimmer, flows to the biofiltration tanks where nitrification process takes place and ammonia is transformed to nitrite and then to nitrate. Bio filtrated water is pumped to the hydroponics unit, where plants uptake the nutrients.

Simultaneously, the UASB is fed with inedible plant biomass, and the effluent is partially pumped to the hydroponics water circulation as fertilizer for the plants, and the rest is used for biogas production. Clean water from the hydroponics unit is pumped back to the fish tank.

A main blower was used to aerate, airlift, oxidize and circulate the water within the system. Seven air channels were designated for the aquacultural unit and 15 for the hydroponics part. The fish tank channels are used for circulation of water, aeration, and to airlift the water out of the tank towards the water treatment units. The protein skimmer and the biofiltration units operate with a continuous aeration. The biofilters were supplied with a separate air blower.

The rated values (power consumption in kW) of the water treatment components were reviewed and registered into a data sheet (Table 2). The actual power consumption of the system was scoped out for further investigation and nominal power consumption of the water treatment unit was determined based on the rated values of the components. The investigation had its focus only on the protein skimmer and the biofilter, excluding the solid filtration, UASB, and the UV sterilization

TABLE 2. Component specification of the novel multi-loop aquaponics water treatment system.

Component	Description	units	Power/unit (kW)
Main blower	145 m^3/h (28.7 m^3/h for RAS part)	1	0.85
Fish tank	Aeration from main blower	1	0.168
Drum filter ED-PP-30	Flow rate 30 m^3/h, roller type design Filter precision 80 μm (200 mesh) Automatic backwash, time, and water level control 800*730*750 mm	1	0.49
Protein skimmer	Flow rate 10 m^3/h Ozone input system 480 * 2000 mm	1	0.37
MBBR	Flow rate 8.5 m^3/h (aeration provided by the main blower)	2	0.05
UASB anaerobic Fermenter	Diameter 600 mm Height 2080 mm	1	0
UV sterilization	60 m^2/h 120W UV tubes	3	0.36

3.2. Pilot RAS overview and analysis

Project “Pilot” RAS is a system located within the same premises in the NCM, near the aquaponic construction site. The design and layout of the RAS is presented in the picture below (Figure 7).

The RAS served as a platform for the practical research done in this thesis since it shared a similar concept as in the studied aquaponics water treatment system (The addition of a protein skimmer for organic matter separation).

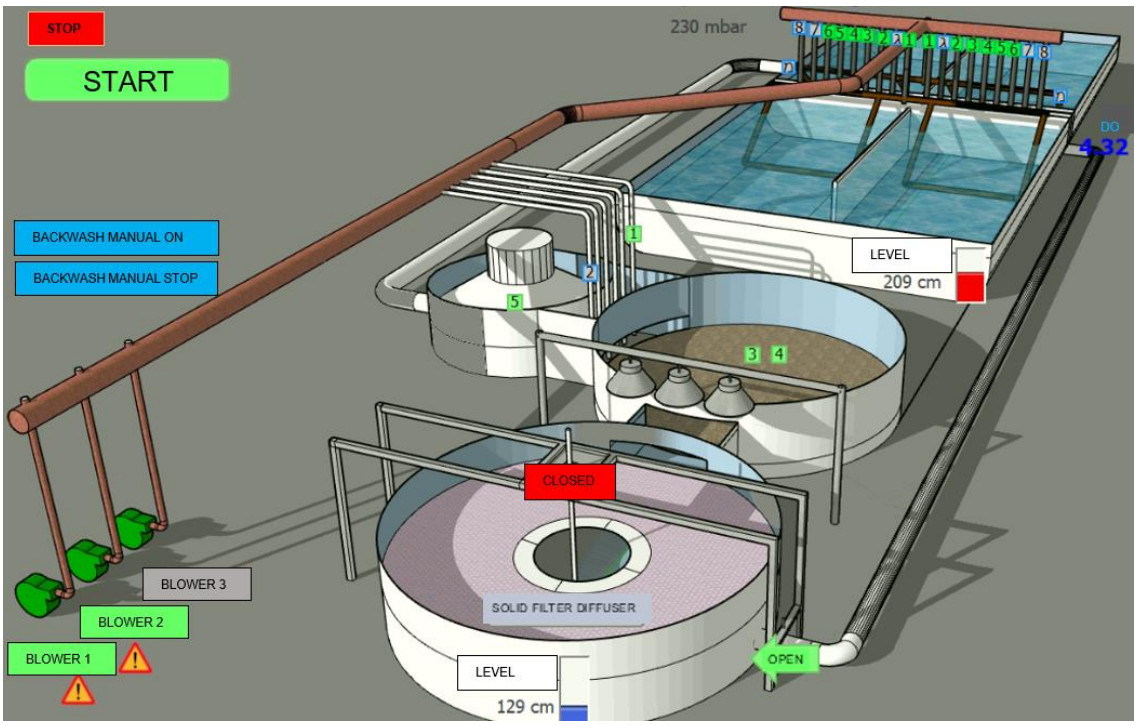


FIGURE 7. View of Pilot RAS control in “AnyDesk” remote software tool (NCM property 2022, edited)

The system has a fish tank with two airlifts, where aeration is supplemented via three main blowers. Circulation of the two pools occurs throughout the aeration. The rearing tank output is directed to a solid filter diffuser with a backwash function. UV light is sterilizing the water before it reaches a biofiltration unit where nitrifying bacteria break down the ammonia. Lastly, DP and part of the suspended solids are removed with foam fractioning unit (known as a protein skimmer). The water is then pumped back to the fish tank.

All the RAS pools in NCM have automated fish feeding systems, where feeding modes are either single, or continuous. The pilot RAS had a single feeding mode, where the fish got food three times, during daytime. During the experiment, the food was given manually twice a day.

Note, it is important to mention in this thesis that the RAS units are not in the right order from engineering point of view. The protein skimmer should be assembled before the biofiltration unit. Reasons for layout of the RAS, or unexpected feeding method changes, will stay within the organisation the work is done for. Nevertheless, the layout does not affect the research results and the unit analysed would express the same phenomena in any case.

The RAS was analysed for nominal-, power consumption; oxygen; flowrate; pH; temperature; DP concentration. The data was obtained via “Anydesk”, a remote control and monitoring software tool. Three months of data was extracted for upper mentioned parameters, and the system was analysed mainly for blower power consumption, DO and DP concentrations. The later was the only parameter utilized in the thesis and it was obtained via separate grab sampling and a laboratory analysis.

3.3. Evaluating water treatment functionality

The evaluation of the protein skimmer and the biofiltration unit functionality over time in terms of energy efficiency was carried out firstly by conducting an experiment.

The purpose of the experiment was to investigate the phenomenon of foam formation absence in the protein skimmer. The main aim was to evaluate the demand for a continuous aeration of the protein skimmer and biofiltration units.

3.3.1 Dissolved protein concentration – Bradford Protein Analysis

A “Hack Buhler 2000”, a portable automatic water sampler, collected one-litre grab samples in one-hour intervals from the rear tank. The samples were collected over a period of 24 hours. The samples were stored in a cooling compartment within the sampler during the sampling period. After 24 hours, the final grab sample was collected, and the samples were brought to the laboratory for further analysis.

The Bradford protein analysis is based on a dye-protein binding. Blue dye (Coomassie Brilliant Blue G-250) is mixed with the filtered water sample and color reaction is formed. Protein concentration is associated with color intensity, and at a 595mm wavelength, the concentration level is determined. (Bradford 1976)

After brought to the laboratory, the 24 grab sample bottles were poured over 24 vacuum cups (300 ml each) with a pre-assembled glass fibre filter. An air compressor was used to vacuum the samples through the filter. Each filtered sample was transferred to a sampling tube and then placed in a freezer. After six days, the samples were defrosted in a fridge and then liquidized at room temperature.

Excel table was prepared to mimic a 96 well cell culture cluster plate (max. 300 µl each). Bradford protein assay was carried out according to the protocol (Appendix 1). The plate was placed in a microplate reader for the analysis (Biotek, powerwave xs). Results were extracted to an excel table via “GEN5” software for further analysis.

3.3.2 Alternative for MBBR

Alternatives for the biofiltration unit were reviewed and non-electrical candidates were selected for the process. PBR method was suggested as an alternative to replace the MBBR.

An innovative approach to utilize recycled materials was combined with cost effective solution for the biofiltration process. A simple residential sand filter (Figure 8) was converted into a FBBR biofilter by filling the filtration compartment with nitrification bids instead of filtration sand.

FIGURE 8. Non-aerated and non-electrical residential pump used as the FBBR biofilter in the novel aquaponics (manufacturer catalog, from uri)

DO demand calculation was carried out to characterize the functionality and efficiency of the selected biofilter unit. The model below (Figure 9) was conducted to illustrate the fate of DO in the FBBR biofilter.

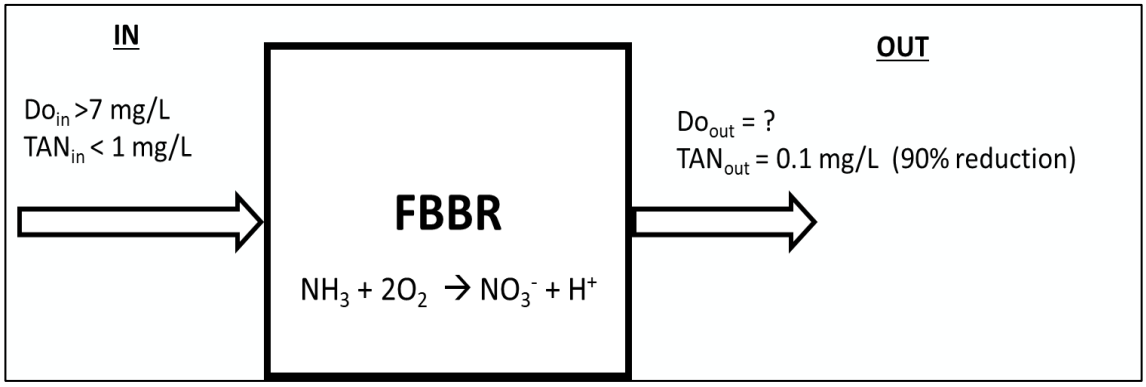


FIGURE 9. Flow model of dissolved oxygen (DO) and Total Ammonia Nitrogen (TAN) in the fixed bed biofilm reactor (FBBR).

A formula (5) was implemented in the model and the value of DO out was determined. The system layout was remodeled to adapt with the new component.

3.4. Data and key parameters

Data was collected from two studied systems. Nominal values from “Pilot” RAS and rated values from novel multi-loop aquaponics. The obtained data and collection methods are presented in Table 3 below.

TABLE 3. Key parameters for water treatment system analysis

Parameter	**System**	**Method**	**Measurement frequency**
DP (mg/L)	RAS	Bradford protein assay	1/h (24h)
Power / DO (mg/L)	AP	Rated values	1/h (365d)
DO (mg/L) / Power	RAS	Logger	1/m (90d)

4 RESULTS

4.1. Protein skimmer – operation time evaluation

The fish in RAS are fed automatically twice a day. In the graph below (Figure 10), one can observe two major peaks crossing the DP concentration limit of 10 mg/L where foam formation occurs, due to fish excretion after feeding.

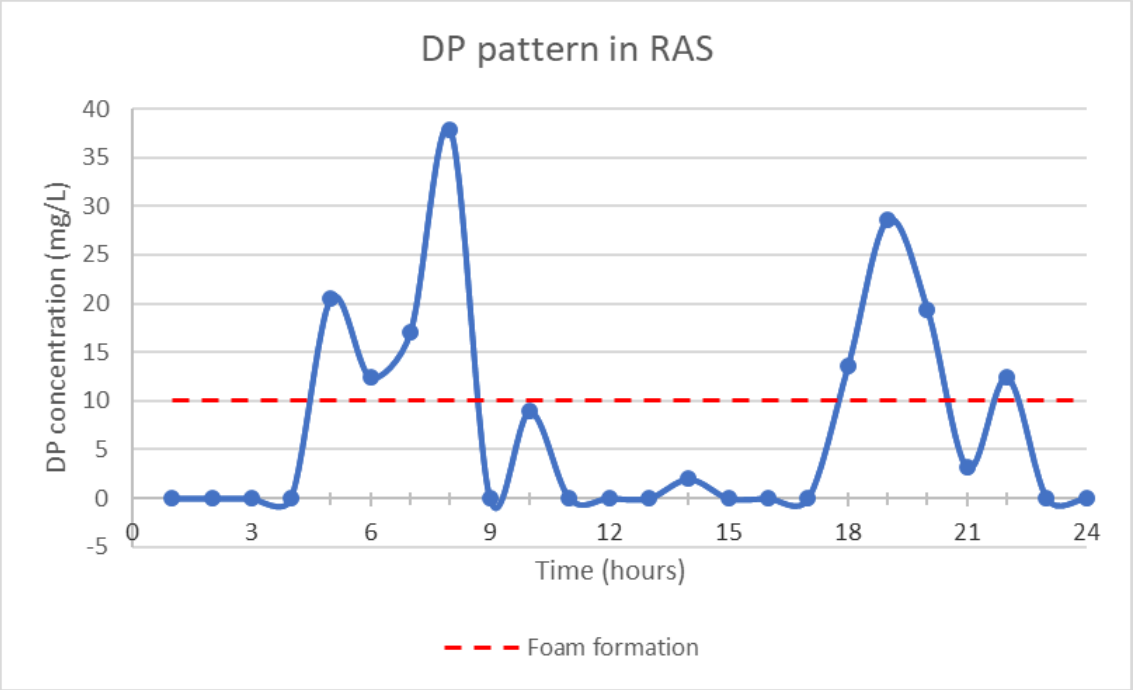


FIGURE 10. Daily pattern of the dissolved protein in the recirculating aquaculture system with single feed (given manually twice).

From the graph, one can determine that the demand for protein skimmer operation is between the first feeding and approximately two hours after the last feeding. In terms of hours, the protein skimmer in pilot RAS can be on hold for approximately 16 hours (or 67% of the time).

4.2. DO demand evaluation

Since the water from the protein skimmer is fully saturated with oxygen, it raises the question of the oxygen demand in a continuously aerated biofilter. To understand the fate of DO concentration in a non-aerated biofilter such as the FBBR, an equation (9) is set based on the nitrification formula (5), where the change in DO can be described as:

$$\Delta DO = 2 \cdot \Delta TAN \tag{9}$$

Oxygen mass balance is set (Equation 10) to calculate the DO leaving the biofilter.

$$\Delta DO = DOin - DOout \tag{10}$$

Using the removal rate efficiency, and the values of DO and TAN flow presented in the model of the FBBR (Figure 9), equations 9 and 10, one can solve for DO out.

$$DOout = \frac{7mg}{l} DOin - \frac{1.8mg}{l} TANin$$

The targeted DO concentration for the FBBR was calculated using excel table. The data is presented in a table found in the appendices (Appendix 2). The result for DO out is presented in the graph below (Figure 11), where DO flow of the unit is presented in five concentrations, between 4-8 mg/L. The concentration of DO reaching the unit in the novel aquaponics is coming from the protein skimmer, where the water is saturated with oxygen (7 mg/L).

The minimal DO concentration required for the nitrification process is approximately 3 mg/l. DO concentration out, is placed on the y-axis. TAN concentration within the biofilter unit is scaled from 0 to 2 mg/L on the x-axis.

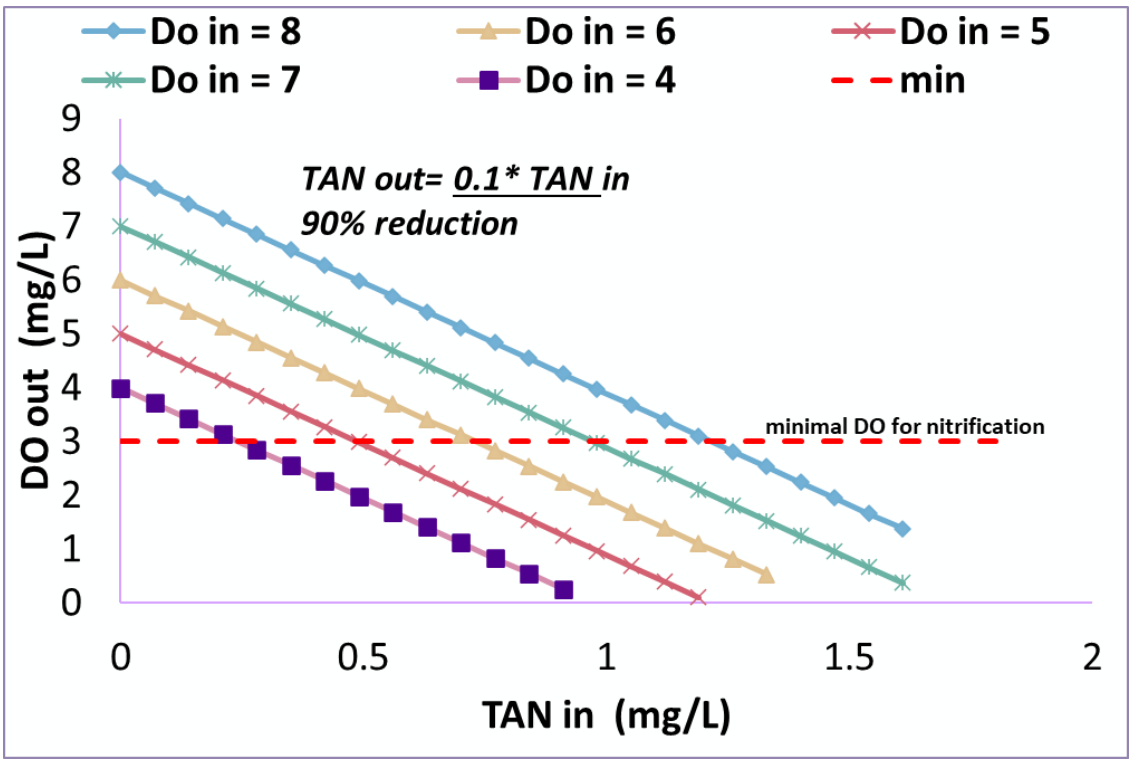


FIGURE 11. Model -based representation for flow of Total Ammonium Nitrogen (TAN) and Dissolved Oxygen (DO) in the fixed bed biofilm reactor (FBBR) with TAN removal rate of 90%.

Observing the graph, one can determine there is necessary DO out concentration of 3 mg/L, when DO in concentration is 7 mg/L. This result suggests that the DO concentration in the non-aerated biofilter is sufficient for the process.

4.3. Power consumption

The table below (Table 4) represents the nominal power consumption of the water treatment system in the novel multi-loop aquaponics calculated with the values given in Table 2.

TABLE 4. Novel aquaponics nominal power consumption

Component	Operation time (hours per day)	Effective power (kW)	Total daily consumption (kWh)	Total annual consumption kwh
Drum filter	2.4	0.49	1.18	429.24
UV sterilization	24	0.36	8.64	3153.6
Protein skimmer	24	0.37	8.88	3241.2
Blower	24	0.168	4.03	1473.79
Blower (Biofilters)	24	0.05	1.19	436.49

4.4. Power consumption of new model

Table 5 below represents the new power consumption of the water treatment components after altering the duration of protein skimmer operation and replacing the MBBR with the FBBR biofilter.

TABLE 5. Nominal power consumption of the redesigned model

Component	Operation time h/day	Power (W)	Total daily consumption (kWh)	Annual consumption (kwh)
Drum filter	2.4	0.49	1.18	429.24
UV sterilization Equipment	24	0.36	8.64	3,153.6
Protein skimmer	8	0.37	2.96	1,080.4
BLOWER	24	0.118	2.84	1,037.3

5 OUTCOMES

The direct outcome of this study enhanced the approach towards alternative solutions for the water treatment system of the initial model. The goals were successfully achieved, and aquaponics energy efficiency was improved.

The results of this thesis were applied in the final design of the novel multi-loop aquaponics. In addition, the results were utilized in a project for clean fertilizer production.

5.1. Energy reduction

The overall power consumption variation measured between the initial model and the modified model of the novel aquaponics water treatment apparatus is presented in Table 6 below, in terms of system power and annual power reductions.

TABLE 6. Summary of the overall energy consumption for novel multi-loop aquaponics water treatment apparatus before and after modifications.

SYSTEM	Initial aquaponics	Modified aquaponics	Reduction (kWh)	Reduction (%)
Power (kW)	1.39	1.34	0.05	3.6
Annual consumption (kWh)	8,297.83	5700.54	2,597.29	31.3

5.2. New model overview

The results indicate that the MBBR has no critical oxidation functionality in the studied system. Thus, the FBBR is suitable to carry out the nitrification process without energy consumption deriving from the blower. The backwash function of the FBBR is not covered in the research done in this thesis. The waters in the novel aquaponics are not typical RAS waters due to protein skimmer organic

matter separation. Therefore, it is assumed to have negligible impact on the power consumption of the system due to low clogging vulnerability with lower backwash demand.

The system layout was remodeled after the biofilter replacement (Figure 12). Gravity measures were considered, and the protein skimmer was placed in a separate loop with the sump tank. The system water flow, and more accurate water quality, was controlled and monitored with addition of a sump tank after the drum filter. The water is pumped partially to the biofilters and partially to the protein skimmer. The water from the protein skimmer flows back to the sump tank.

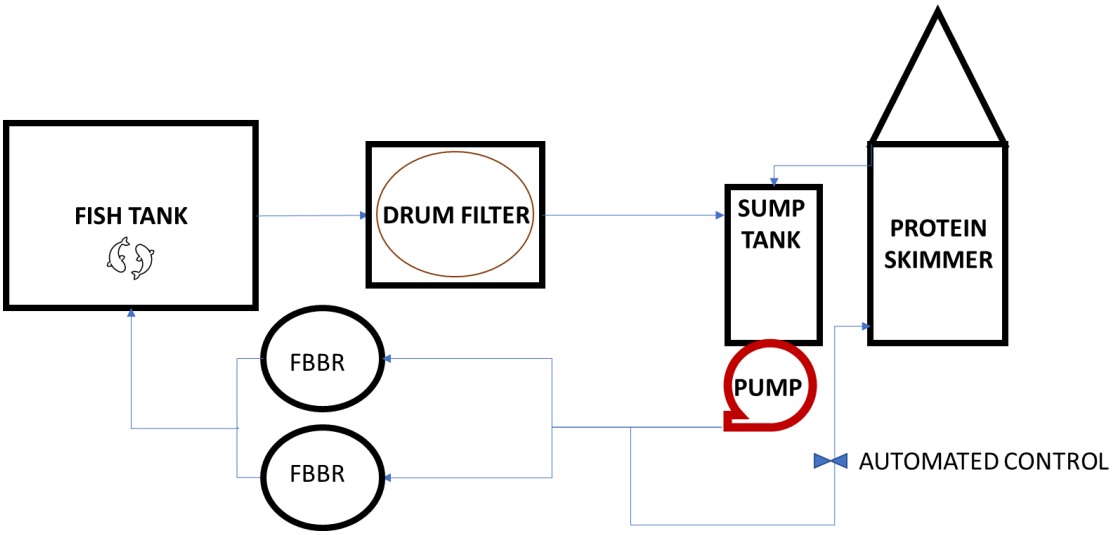


FIGURE 12. Layout of the remodeled water treatment unit (excluding the hydroponics and UASB)

The new model was characterized, and the energy consumption reduction from operations and component modification was determined (Table 6). Eventually, the novel multi-loop aquaponic system was constructed with the FBBR biofilter as part of the water treatment unit.

5.3. Future research

The results of the thesis were applied in the design of a Novel RAS with onsite nutrient recovery concept (Figure 13), where the waste treatment apparatus effluent was designed to produce high-purity crystalline fertilizers (e.g., Struvite).

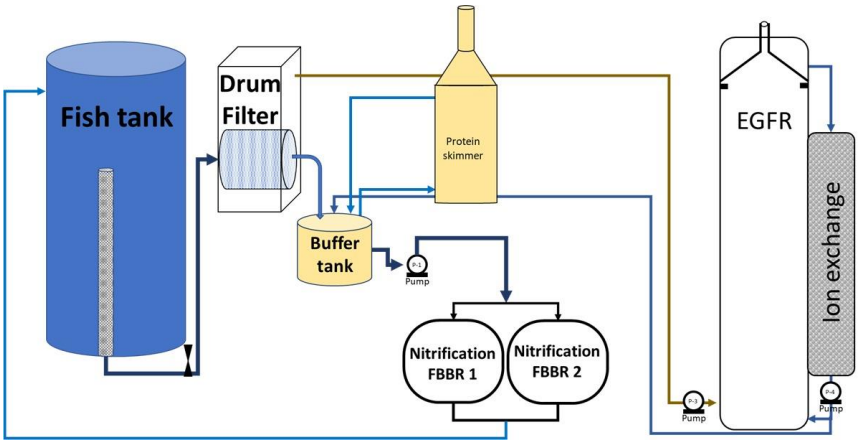


FIGURE 13. Model for a Novel RAS, based on the remodeled novel multi-loop aquaponics water treatment unit. (Yogev 2022).

Also, a plug flow reactor (PFR), type of PBR, was reviewed for the biofiltration alternatives. The PFR is a potential method for larger scales, where the unit is not limited to facility dimensions and larger flows of water is treated. PFR was suggested for the novel aquaponics, yet the viability and dimensions of the project were not suitable for the new technology. This method should be studied and applied in further aquaponics research. Information regarding the specific manufacturer and the method (including specification) of the component are left out from this thesis.

5.4. Challenges

The protein skimmer was analysed once. More accurate results would have been carried out with several sampling periods, yet the idea of operation duration responding to feed activity remains the same. Furthermore, the pilot RAS practiced single feeding with two daily portions given manually at the time. An experiment with single feed (1-3 feeding times) and continuous feed, would generate more information regarding the protein skimmer functionality for various

RAS that practice different feeding modes (e.g., continues feeding is typically used for grow-out and fattening).

The pilot RAS overall energy consumption was not feasible since aeration portion of protein skimmer and biofiltration were not accessible. This resulted in scoping out the reduction value for RAS from the thesis. However, the reduction of energy consumption can be estimated with further research. The aquaponics overall energy consumption reduction is a further research matter as well.

Due to Covid-19 global pandemic, the project was delayed frequently, and the actual results of an operating system were not feasible at the time. This is the reason for using the pilot RAS as a in-situ platform for practical research.

6 CONCLUSION

The outcome successfully optimized the power consumption of the water treatment apparatus. The results presented a significant reduction of 30 percent of the water treatment overall energy demand. According to the results, FBBR method is suitable for any aquaponic water treatment system within small to medium scale, in condition of a proper layout design and the utility of a protein skimmer in the system. For bigger systems, in industrial scale, the use of non-aerated biofiltration should be considered. The method might be feasible with PFR technology supplemented with Venturi pumps.

Characterizing the water treatment components of the novel multi-loop aquaponics, provided a better understanding of their functionality within the system and assisted in locating the strengths and weaknesses in each phase of the process. The optimization of the protein skimmer was a direct outcome of simple characterization. The very first step of reasoning the activity of the unit when there is no foam, resulted in the analysis that initiated the findings of the thesis. Testing alternatives for biofiltration revealed the major interest in aquaponics worldwide. Lot of research is published, progress is seen in many publications, and the progress accelerates each year.

Nevertheless, energy efficiency improvements in aquaponics should be rapidly addressed and further research is in demand to mitigate on time global food production challenges and to advance circular food production methods.

REFERENCES

Alkhalidi, A., Khawaja, M.K., Abusubaih, D. 2020. Energy efficient cooling and heating of aquaponics facilities based on regional climate. International Journal of Low-Carbon Technologies 15 (2), 287-298.

Bodenmiller, D. 2017. Effects of aeration on lettuce (Lactuca sativa) growth in deep water culture aquaponics. Degree programme in environmental engineering. Tampere university of applied sciences. Bachelor's thesis.

Bouwman, A.F. 1998. Nitrogen oxides and tropical agriculture. Nature 392, 866-867.

Boyd, C.E. 2015. Overview of aquaculture feeds: Global impacts of ingredient use. In Davis, D.A. (ed.) Feed and Feeding Practices in Aquaculture. 1st edition. Cambridge: Woodhead Publishing Ltd, 3-25.

Bracino, A.A., Concepcion, R.S., Dadios E.P., Vicerra, R.R.P. 2020. Biofiltration for recirculating aquaponic systems: A review. IEEE 12th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM), 1-6.

Braungart, M., McDonough, W., Bollinger, A. 2007. Cradle-to-cradle design: creating healthy emissions – a strategy for eco-effective product and system design. Journal of Cleaner Production 15 (13-14), 1337-1348.

Greiner, A.D., Timmons, M.B. 1998. Evaluation of the nitrification rates of microbead and trickling filters in an intensive recirculating tilapia production facility. Aquaculture Engineering 18, 189-200.

Guerdat, T.C., Losordo, T.M., Classen, J.J., Osborne, J.A., DeLong, D.P. 2010. An evaluation of commercially available biological filters for recirculating aquaculture systems. Aquaculture Engineering 42, 38-49.

Halvorson, H.O., Smolowitz, R. 2009. Aquaculture. In Schaechter, M. (ed.) Encyclopedia of Microbiology. 3rd edition. Academic Press, 17-22.

Heinsbroek, L.T.N., Kamstra, A. 1990. Design and performance of water recirculation systems for eel culture. Aquaculture Engineering 9, 187-207.
Junge, R., König, B., Villarroel, M., Komives, T., Jijakli, M. 2017. Strategic Points in Aquaponics. Water 9 (3), 182.

Karimanzira, D., Rauschenbach, T. 2018. Optimal utilization of renewable energy in aquaponic systems. Energy and Power Engineering 10, 279-300.

Malone, R.F., Beecher, L.E. 2000. Use of floating bead filters to recondition recirculating waters in warmwater aquaculture production systems. Aquaculture Engineering 22, 57-73.

Neori, A., Krom, M.D., van Rijn, J., 2007. Biogeochemical processes in intensive zero-effluent marine fish culture with recirculating aerobic and anaerobic biofilters. Journal of Experimental Marine Biology and Ecology 349 (2), 235-247.

Pfeiffer, T.J., Wills, P.S. 2011. Evaluation of three types of structured floating plastic media in moving bed biofilters for total ammonia nitrogen removal in a low salinity hatchery recirculating aquaculture system. Aquaculture Engineering 45 (2), 51–59.

Pulkkinen, J.T., Eriksson-Kallio, A.M., Aalto, S.L., Tiirola, M., Koskela, J., Kiuru, T., Vielma, J. 2019. The effects of different combinations of fixed and moving bed bioreactors on rainbow trout (Oncorhynchus mykiss) growth and health, water quality and nitrification in recirculating aquaculture systems. Aquacultural Engineering 85, 98-105.

Randall, D.J., Tsui, T.K.N. 2002. Ammonia toxicity in fish. Marine pollution bulletin 45 (1−12), 17-23.

Sardare, M.D, Admane, S.V. 2013. A review on plant without soil - Hydroponics. International Journal of Research in Engineering and Technology 2, 299-304.

Seerat, J., Zahida, R., Tanveer, A., Sadaf, I., Abbas, N., Shabina, M., Tauseef, B., Razia, G., Insha, N. 2020. Hydroponics - A review. International Journal of Current Microbiology and Applied Sciences 9, 1779-1787.

Shitu, A., Liu, G., Muhammad, A.I., Zhang, Y., Tadda, M.A., Qi, W., Liu, D., Ye, Z., Zhu, S. 2022. Recent advances in application of moving bed bioreactors for wastewater treatment from recirculating aquaculture systems: A review. Aquaculture and Fisheries 7 (3), 244–258.

Suhr, K.I., Letelier-Gordo, C.O., Lund, I. 2015. Anaerobic digestion of solid waste in RAS: Effect of reactor type on the biochemical acidogenic potential (BAP) and assessment of the biochemical methane potential (BMP) by a batch assay. Aquaculture Engineering (65), 65-71.

Thorarinsdottir, R. (ed.) 2015. Aquaponics Guidelines. Reykjavik: Haskolaprent, University of Iceland.

Tilman, D., Balzer, C., Hill, J., Befort, B.L. 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America 108 (50), 20260-20264.

Timmons, M.B., Ebeling, J.M. 2007. Recirculating aquaculture systems. 3rd edition. New York: North-eastern Regional Aquaculture Center.

Timmons M.B., Ebeling J.M. 2013. Recirculating Aquaculture. 3rd edition. New York: Ithaca Publishing Company LLC.

Van Rijn, J. 1996. The potential for integrated biological treatment systems in recirculating fish culture – A review. Aquaculture 139, 181-201.

Wongkiew, S., Hu, Z., Chandran, K., Lee, J.W., Khanal, S.K. 2017. Nitrogen transformations in aquaponic systems: A review. Aquaculture Engineering, 76-19.

Yogev, U., Barnes, A., Gross, A. 2016. Nutrients and energy balance analysis for a conceptual model of a three loops off grid, aquaponics. Water 8, 589.

Yogev, U., Sowers, K.R., Mozes, N., Gross, A. 2017. Nitrogen and carbon balance in a novel near-zero water exchange saline recirculating aquaculture system. Aquaculture 467, 118-126.

Yuen, K.I., Chew, S.F. 2010. Ammonia production, excretion, toxicity, and defense in fish: A review. Frontiers in Physiology 1, 1-20.

APPENDICES

Appendix 1. Protocol used for dissolved protein concentration analysis

a. Proteins

I. Range

1.25 – 10 ppm

I. Reagents

1. **Bradford reagent:** Purchased.
2. **Stock BSA solution:** Dissolve 250 mg BSA in 250 ml DDW (=1000 ppm BSA)

II. Procedure

1. Add equal amounts of sample and Bradford reagent.
2. Read with spectrophotometer at 595 nm between 10 – 60 minutes after reaction.
3. You can read with the plate counter in the microbiology dept.
    a. You must obtain permission and directions from Tali before using.
    b. Make sure it is available in the 60min following the analysis.
4. Recommendation: Run 4 standards each time you perform the analysis.

III. Recommended work solutions and standards

1. Dilute the stock 3 times as follows:

Name		**DDW**	**Conc.**
WS1	0.1 ml (stock)	0.9 ml (DDW)	100 ppm
WS2	0.1 ml (WS1)	0.9 ml (DDW)	10 ppm

2. Prepare standards as follows:

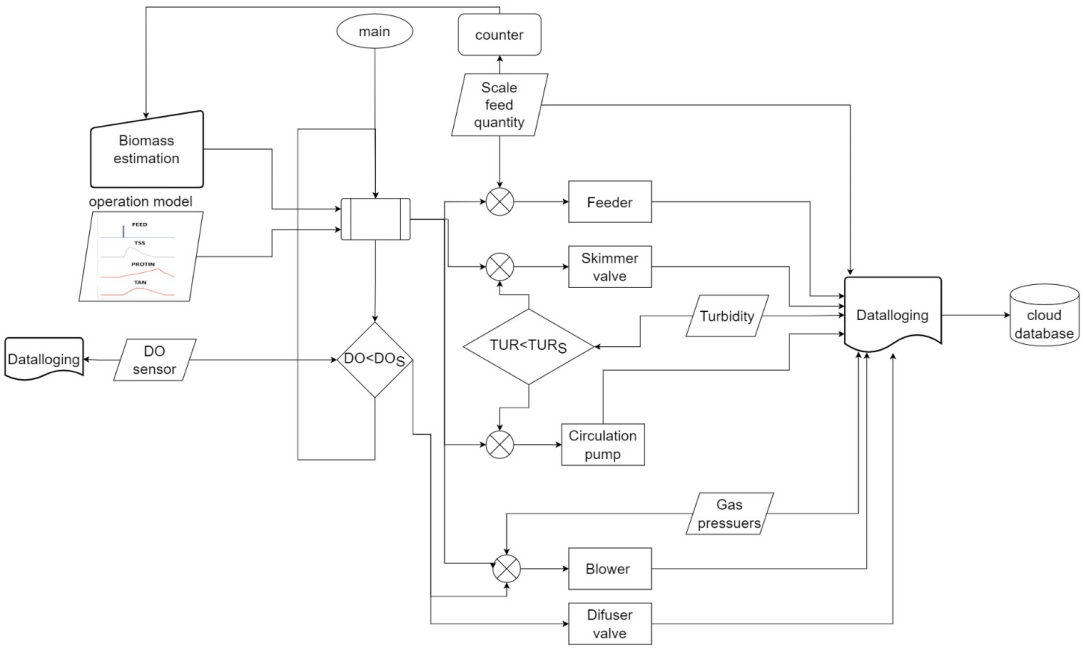
	Eppendorf Sample V = 500 µl		**Plate reader** Sample V = 150 µl		
	WS1 (µl)	**DDW (µl)**	**WS1 (µl)**	**DDW (µl)**	**Conc. (ppm)**
1	0	500	0	150	0
2	100	400	30	120	2
3	200	300	60	90	4
4	250	250	75	75	5
5	300	200	90	60	6
6	400	100	120	30	8

Appendix 2. Excel table for calculation of target DO concentration

Fate of DO concentration in the non-aerated FBBR was calculated with nitrification formula and modelled with DO and TAN flow values of the novel multi-loop aquaponics model. The calculation was implied in the excel table below (Table 1).

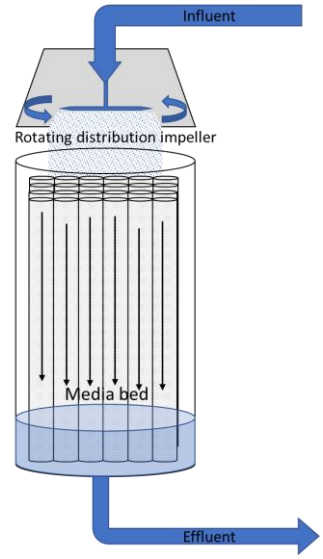
	target DO concentration			4	5	6	7	8
TAN in [mg/	TAN out [mg/L]	DO needed [mM]- 90%	DO needed [mg	DO out [mg/L]				
0	0	0	0	4	5	6	7	8
0.07	0.007	0.009	0.288	3.712	4.712	5.712	6.712	7.712
0.14	0.014	0.018	0.576	3.424	4.424	5.424	6.424	7.424
0.21	0.021	0.027	0.864	3.136	4.136	5.136	6.136	7.136
0.28	0.028	0.036	1.152	2.848	3.848	4.848	5.848	6.848
0.35	0.035	0.045	1.44	2.56	3.56	4.56	5.56	6.56
0.42	0.042	0.054	1.728	2.272	3.272	4.272	5.272	6.272
0.49	0.049	0.063	2.016	1.984	2.984	3.984	4.984	5.984
0.56	0.056	0.072	2.304	1.696	2.696	3.696	4.696	5.696
0.63	0.063	0.081	2.592	1.408	2.408	3.408	4.408	5.408
0.7	0.07	0.09	2.88	1.12	2.12	3.12	4.12	5.12
0.77	0.077	0.099	3.168	0.832	1.832	2.832	3.832	4.832
0.84	0.084	0.108	3.456	0.544	1.544	2.544	3.544	4.544
0.91	0.091	0.117	3.744	0.256	1.256	2.256	3.256	4.256
0.98	0.098	0.126	4.032	-0.032	0.968	1.968	2.968	3.968
1.05	0.105	0.135	4.32	-0.32	0.68	1.68	2.68	3.68
1.12	0.112	0.144	4.608	-0.608	0.392	1.392	2.392	3.392
1.19	0.119	0.153	4.896	-0.896	0.104	1.104	2.104	3.104
1.26	0.126	0.162	5.184	-1.184	-0.184	0.816	1.816	2.816
1.33	0.133	0.171	5.472	-1.472	-0.472	0.528	1.528	2.528
1.4	0.14	0.18	5.76	-1.76	-0.76	0.24	1.24	2.24
1.47	0.147	0.189	6.048	-2.048	-1.048	-0.048	0.952	1.952
1.54	0.154	0.198	6.336	-2.336	-1.336	-0.336	0.664	1.664
1.61	0.161	0.207	6.624	-2.624	-1.624	-0.624	0.376	1.376

Appendix 3. Flowgorithm for model-based RAS

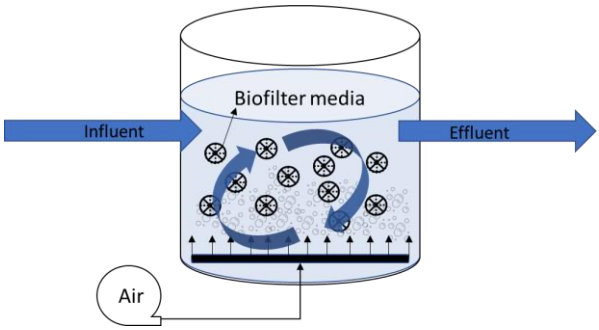


Appendix 4. Schematics of the studied biofiltration units

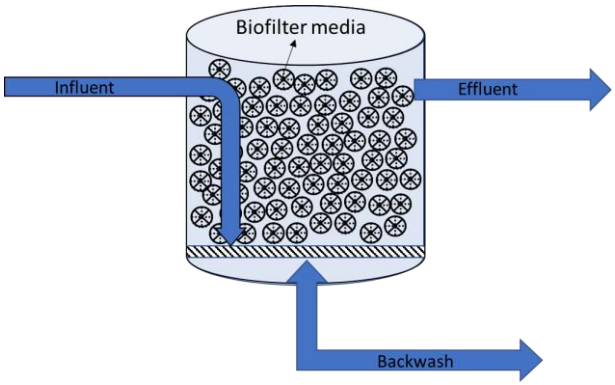
Considered methods and the initial biofilter (MBBR) are visualized in the figures below.



Trickling filter



MBBR



FBBR